VYACHESLAV SKRYPNYK, BAUYRZHAN YELEUSSINOV, ANATOLII SEMENOV

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CONDUCTIVE FRYING OF MEAT: CURRENT STATE AND PROSPECTS

Kyzylorda-Poltava
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The monograph analyzes the current state of processes and equipment for conductive meat frying. A methodology for evaluating the energy and resource efficiency of meat frying processes and equipment has been developed. Based on this methodology, potential directions for improving the energy and resource efficiency of these processes and devices have been identified.

A scientific concept is proposed, which involves creating conditions for intensified heat transfer during conductive frying by employing various physical and electrophysical methods—such as the application of electric current combined with compression, compression in a functionally closed volume, or in functionally closed chambers. The concept is supported by research results obtained from experimental prototype devices.

The monograph is intended for academic staff, postgraduate and master's students, researchers, and professionals in the field of food production.

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PREFACE

One of the major economic challenges for the countries of the former Soviet Union, including Ukraine and Kazakhstan, is the low energy efficiency of technological processes. Energy efficiency is one of the key integral indicators of the state and development of the economy, the fuel and energy sector, and energy management systems. It refers to the efficient use of fuel and energy resources at various stages of a product's life cycle: design and development of technical requirements, product development, manufacturing, quality control, testing and inspection, operation, and disposal. Energy efficiency is sometimes referred to as the "fifth" fuel because using energy more efficiently means using less energy to achieve the same level of energy supply in technological processes.

The food industry is a vital sector of the economies of Ukraine and Kazakhstan, and it faces the same challenges. However, between 2007 and 2024, the energy efficiency of the food industry increased by 6.5% – from 38.4% to 44.9% of the EU level – due to the implementation of new production methods, modern equipment, and improved quality control. Based on this, the minimum potential for energy savings in the food industry can be estimated at 55.1% of current energy consumption.

Fry ing meat products is one of the most widespread methods of thermal processing. This process is characterized by significant mass loss (up to 11–35%) and high specific heat consumption (up to 1000–1300 kJ/kg). The energy efficiency of this process largely depends on the method of heat supply and the design features of the equipment and is generally low. The process requires maintaining high-temperature conditions (423–473 K), and the equipment used is subjected to considerable thermal stress on the heating surfaces (up to 45 kW/m²).

An analysis of the development of conductive frying equipment and the scientific literature on the topic shows that issues related to energy efficiency of the process and its equipment, as well as yield improvement and product safety, have not received sufficient attention.

Conductive frying of meat is also limited by resource constraints. Only specific cuts of carcasses from slaughtered animals are suitable for frying: tenderloin, loin, sirloin, and top and inside round cuts of the hindquarter. These parts constitute no more than 10–20% of the total carcass weight of cattle. These cuts are characterized by a thin, delicate network of connective tissue composed mainly of collagen fibers. Other parts of the carcass (neck, hindquarter, shoulder) contain significantly more connective tissue and are therefore unsuitable for conductive frying. Instead, they are used to produce minced or chopped semi-finished products.

Each year, the cattle and pig population in Ukraine and Kazakhstan decreases by an average of 4.5%, significantly reducing the resource base for conductive frying processes. This negatively affects the cost of semi-finished products. To mitigate this, the governments of Ukraine and Kazakhstan import meat raw materials from various countries (Brazil, Poland, Germany, etc.). As a rule, the cost of imported raw materials, including customs duties, is lower than that of domestic products. However, the quality of such imported meat is often low, which negatively impacts the energy efficiency of thermal processing. Moreover, the presence of rabies virus and traces of genetically modified organisms (GMOs) in imported meat cannot be ruled out due to the use of GMO-based feeds.

This monograph addresses and proposes solutions to the pressing scientific and applied problems of low energy efficiency, low product yield, and insufficient resource base in the process of conductive meat frying.

The monograph is intended for a wide audience, including academic staff, researchers, higher education students, and practitioners in the food production industry, including the restaurant sector.

The authors express their sincere gratitude to the reviewers of the monograph and to their colleagues – academics and researchers – who provided valuable critical feedback on its content.

LEGEND / SYMBOLS

HCTC – high connective tissue content;
HA – heterocyclic amines;
FCC – functionally closed container
η_t – thermal efficiency;
b – specific consumption of energy resource, J/kg, J/unit;
b_t – specific thermal energy consumption, Gcal/kg, J/kg;
b_e – specific electricity consumption, kWh/kg, kWh/unit;
E_e – energy capacity of the product, J/kg, J/unit;
E_{sp} – specific energy capacity, J/m²;
ΔW – total energy change of the system, J;
ΔU – change in internal energy of the system, J;
Q – heat (energy absorbed by the system with a temperature increase ΔT, K; under no work conditions), J;
c – specific heat capacity of the system/body/product, J/(kg·K);
dq – heat input per unit mass in a system transitioning under isobaric conditions from state 1 to 2;
dI – change in enthalpy of the body/product, J/kg;
Q_w – energy supplied to the apparatus, J;
G – mass of raw material, kg;
q – specific heat consumption per unit mass of raw material, J/kg;
$\sum Q_{los}$ – total heat losses, J;

W_t^u – energy transferred to the working fluid and used in the process, J;
$\sum W_e^u$ – unused available energy leaving the apparatus, J;
Q_{fp} – heat used for product treatment, J;
$\sum W_{los}$ – total energy losses during thermal processing due to irreversible heat and mass transfer, J;
β – share of energy losses due to irreversible heat and mass transfer during thermal processing;
η_{ef} – efficiency of energy usage in an irreversible technological process;
η_{en} – energy efficiency;
S – entropy, J/K;
E_Q – exergy of heat flow transferred from the body;
Q – amount of heat flow, J;
T_{ws}^m – mean thermodynamic temperature of heat source, K;
T_0 – ambient absolute temperature, K;
E_m – mass exergy, J;
I, I_0, S, S_0 – enthalpy and entropy of the body at temperature T and reference T_0, respectively, J, J/K
e – specific exergy (per unit mass), J/kg;
E_{los} – exergy loss in process due to system entropy change ΔS, J;
P_{el} – power of electric heaters with ohmic resistance, W;
τ – duration of the process, s;
ΔE – change in exergy, J;

ΔE_{β} – exergy used to heat the product during conductive frying, J;
ΔE_{los} – total exergy losses, J;
Δe – change in specific exergy during heat input, J/kg;
i_1, i_2 – specific enthalpy at start and end of heating, J/kg;
s_1, s_2 – specific entropy at start and end of heating, J/(kg·K);
ΔS_v – entropy increase due to irreversibility during product heating, J/K;
η_{ex} – exergy efficiency of the process;
$\sum \Delta E_{los}$ – total exergy losses, all types, J;
ΔS_c – total entropy increase of all system elements (energy source, product, environment), J/K;
ΔE_{β} – exergy loss due to irreversible heat exchange during frying, J;
∇e – specific exergy loss due to irreversible heat transfer, J/kg;
e_1 – exergy of the upper heat source, J/kg;
e_2 – exergy of the heated product, J/kg;
q_1 – heat delivered by upper heat source, J/kg;
q_2 – heat that can be delivered by the heated product, J/kg;
T_{ws}^{m} – mean integral temperature of working surface, K;
T_{max}, T_{min} – maximum and minimum temperatures of the apparatus surface, K;
T_v – average product volume temperature, K;

∇E – total exergy loss of the apparatus; for electric devices – exergy of electrical energy, J;

$\Delta E_{\beta_{sp}}$ – specific exergy loss per 1 kg of product due to irreversible heat exchange, J/kg;

∇E_f – exergy loss to the environment through apparatus walls, J;

Q_{5i} – heat directly lost to the environment by the i-th external surface element, J;

α_i – heat transfer coefficient from i-th external surface element to the environment, W/(m²·K);

F_i – surface area of the i-th apparatus element, m²;

T_{wi} – temperature of the i-th apparatus surface element, K;

f – relative exergy loss through the apparatus walls;

$\Delta E_{f_{sp}}$ – specific exergy loss through the apparatus walls per kg of product, J/kg;

∇E_f^{prod} – exergy losses to the environment by the surface of the heated product, J;

$T_{ps_i}^{av}$ – average temperature of the i-th surface of the product, K;

f^{prod} – relative exergy loss from the product surface;

$\nabla E_{f_i}^{prod}$ - specific exergy loss from product surface per kg of product, J/kg;

∇E_γ – exergy loss from heating liquid migrating from the product and evaporating, J;

z – yield of the finished product;

c_ρ – heat capacity of product moisture, J/(kg·K);

T_f – boiling temperature of liquid on heating surface, K;

r – latent heat of vaporization, J/kg;

ε_r – phase transformation coefficient (moisture evaporated/total moisture loss);

γ – relative exergy loss from heating migrating liquid;

$\nabla E_{\gamma_{sp}}$ - specific exergy loss from heating migrating liquid per kg of product, J/kg;

ΔE_{prod} – total relative exergy loss to environment, J;

$\sum \Delta E_{los}$ – tal exergy loss of all types, J;

S_m – heating surface area of product (meat), m²;

λ_1, λ_2 – thermal conductivity of contacting bodies, W/(m·K);

$\frac{dT_1}{dx}$, $\frac{dT_2}{dx}$ – temperature gradients in contacting bodies, K/m;

q – heat flux through contact plane, W/m²;

R_{dc}– thermal resistance of direct contact zone, (m²·K)/W;

R_{env} – thermal resistance of medium in gaps, (m²·K)/W;

R_k – total thermal resistance of the system, (m²·K)/W;

$\bar{q}$ – heat flux density normal to isothermal surface, W/m²;

λ – thermal conductivity, W/(m·K);

$gradT$ – temperature gradient, K/m;

ω – heat propagation speed in meat, m/s;

ρ – density of meat, kg/m³;

τ_p – relaxation time, s;

a – thermal diffusivity of meat, m²/s;
A – volumetric internal energy (enthalpy) concentration, J/m³;
Θ – dimensionless product temperature;
ξ – dimensionless coordinate;
Bi – Biot number;
Fo – Fourier number;
Q_1 - heat input to product surface, J;
Q_2 - heat transfer from product surface to its center, J;
T_1– eating surface (medium) temperature, K;
T_{sur} – product surface temperature, K;
T_c – product core temperature, K;
Fo^I - duration of stage 1 (until T* reached at surface);
Fo^{II} - duration of stage 2 (surface at T*, center reaches T_c;
b – coefficient depending on product shape;
d_i – diameter of a single capillary, m;
h_i – vapor-filled height of a single capillary, m;
n – vapor-filled height of a single capillary, m;
δ_{ef} – effective thickness of meat, m;
i_2, i_1 – enthalpy of vapor at points 2 and 1 in T-S diagram, J/kg;
v_2, v_1 – specific vapor volume at points 2 and 1 in T-S diagram, m³/kg;
$\bar{V}_v$ – average vapor volume in capillary meniscus, m³;
α_1 – heat transfer coefficient from frying surface to liquid in meniscus, W/(m²·K);
F^m– average integral surface area of meniscus during evaporation, m²;

F_{min} – minimum meniscus surface area due to moisture displacement, m²;

F_{max} – maximum meniscus surface area, m²;

${T_{sur}}^m$ – average integral frying surface temperature in process 1-2 (T-S), K;

${T_{liq}}^m$ – average integral liquid temperature at meniscus in process 1-2 (T-S), K;

τ_{vap} – evaporation time (process 1-2 in T-S), s;

v_3, v_1 – vapor volume at points 3 and 1 (T-S), m³/kg;

α_2 - heat transfer coefficient from vapor to meniscus liquid, W/(m²·K);

T_{vap}– vapor temperature in meniscus during condensation (process 3-1), K;

T_{liq} – liquid temperature during process 3-1, K;

τ_{con} – condensation time (process 3-1 in T-S), s;

k – heat transfer coefficient during one 1-2-3 thermodynamic cycle in T-S diagram, W/(m²·K);

d_c – capillary diameter during frying, m;

ρ_m – meat density, kg/m³;

λ – thermal conductivity, W/(m·K);

c – heat capacity of meat, J/(kg·K);

τ_r – relaxation period, s;

a – thermal diffusivity, m²/s;

a – thermal diffusivity of the product, m²/s;

Fo – Fourier number;

d_{i} – diameter of individual capillary, m;

h_{i} – height of vapor-filled space in capillary, m;

n – number of capillaries per unit meat area, pcs/m².

CHAPTER 1. ANALYSIS OF THE CONDUCTIVE FRYING PROCESS OF MEAT, EQUIPMENT FOR ITS IMPLEMENTATION, AND THEIR ENERGY EFFICIENCY

1.1. Features of the Processes Occurring During Conductive Frying of Meat

A significant share of food industry products consists of items that have undergone thermal processing [1]. Among them, meat and meat-based products occupy a prominent place.

The purposes of thermal processing of meat and meat products are [2, 3]:

- to bring the product to a state of culinary readiness;
- to initiate color-forming reactions and the development of flavor and aroma compounds;
- to transform the visco-plastic properties of meat systems into elastic-plastic ones;
- to destroy vegetative forms of microorganisms;
- to enhance the digestibility of the final product.

When meat products are heated to a temperature of 333–343 K, about 99% of the initial number of vegetative-form microorganisms are destroyed within 300–600 seconds. Up to 90% of the remaining microflora consists of spore forms. The absolute number of microorganisms that remain after thermal treatment largely depends on the initial microbial contamination of the meat products and typically ranges from 10^3 to 10^4 per 10^{-3} kg. Therefore, to effectively neutralize microorganisms during thermal processing, it is necessary to maintain meat products at a specific temperature for a certain period [4, 5].

One of the most common methods of thermal processing of food products is frying. Frying is a thermal culinary treatment of products carried out without the addition of water, at a temperature that ensures the formation of a specific crust on their surface [6-9].

Frying is a non-stationary thermal process and can be implemented using various methods [3, 6, 7, 10]:

– conductive heating on a heated surface with a small amount of fat or without it;

– convective heating in a heated air medium with natural or forced movement;

– infrared heating by irradiating the product's surface;

– convective heating in a large amount of fat (deep frying) at temperatures of 423–473 K.

The frying process is characterized not only by the variety of methods for heat transfer to the product but also by the unevenness of the temperature field on the heating surface (environment) and the influence of many factors on the internal heat transfer [11, 12]. However, compared to other thermal processing methods, frying stands out for its higher thermal efficiency, as heat transfer occurs directly to the product's surface.

Conductive frying (the main frying method) is carried out on heated surfaces using a small amount of fat (5–10% of the product's weight) or without it, at temperatures of 423–473 K, until a browned crust is formed. Fat, due to its high thermal resistance, helps:

- smooth out the unevenness of the temperature field on the frying surfaces and ensures uniform heating of the surface of the product in contact with it;
- protect the product from excessive local overheating and ensure a full crust [4-6, 12-15].

Some of the fat is absorbed by the product during frying and accumulates in the crust and the layer directly adjacent to it. However, the thermal processing of meat products in the presence of fat changes the content of active substances in it, and the moisture that is removed from the product into the fat and air accelerates its oxidation and the accumulation of polymerization products [6].

During conductive frying without the use of fat, the heating surface is made from non-stick materials or coated with a special non-stick coating to prevent the product from sticking to the heating surface [16]. Since the surface of the meat in contact with the heating surface deforms during thermal processing, uneven conditions for heat transfer and its distribution inside the product are created, which negatively affects the speed of reaching culinary readiness and its quality.

The rate of processes occurring in the meat during frying depends on the type, shape, and size of the product, its physical and chemical properties, the temperature of the fat, heat exchange conditions between the fat and the product, and other factors [11, 17, 18].

During the frying of meat and meat products, two periods of heat and mass exchange are distinguished [11, 12, 17]. In the first period, after ensuring contact between the product and the heated fat or heated surface, the temperature in the outer layer quickly rises to 373 K and is maintained at this level due to intense evaporation of moisture. Moisture is released on the surface in the form of meat juice as a result of the compression of the outer layer of muscle fibers caused by denaturation changes in proteins [2, 4, 5]. At the same time, the processes of moisture evaporation from the outer layer and its migration to the center of the product begin [12, 13]. During this period, moisture in the form of liquid migrates to the surface of the product due to the temperature gradient, while under the pressure gradient, both liquid and steam migrate into the product. Along with the liquid and steam, heat transfer occurs under the action of the pressure gradient, which leads to the heating of the product.

When the temperature in the meat reaches 318–323 K, denaturation affects the majority of structural proteins: myosin, actomyosin, actin, and others [5, 19, 20], which is accompanied by a 25–30% reduction in the diameter of muscle fibers and a 2–2.5 times decrease in the thickness of connective layers [2, 14, 21, 22]. Due to compression caused by denaturation, meat juice is released, with losses reaching 25–35% [2, 14]. The main proteins of the sarcoplasm (myogen and myoglobin) begin to denature when the temperature reaches 323–327 K [5], which is indicated by the change in the color of the meat to gray-brown [14]. At temperatures of 333–338 K, about 90% of the proteins in the meat denature, and at 343 K, almost all of them do [19]. During the denaturation of muscle proteins, their hydrophilicity decreases, which is associated with a shift in the pH value toward the neutral range (from 5.3–5.7 to 6.1–6.6). This process begins at 323 K [5, 23]. During this process, the amount of strongly bound moisture in the muscle tissue decreases by 15–20%, which in turn leads to an increase in moisture loss and a decrease in the juiciness of the meat [2, 5].

From the moment the temperature of the contact layer reaches 373 K, the rate of moisture evaporation from the surface begins to exceed the rate of its diffusive suction from deeper layers [11]. This marks the beginning of the second period of heat and mass transfer. During this period, the evaporation zone is located at some distance from the surface and no longer deepens [24], while the movement of vapor is directed toward the inner layers of the product due to a significant temperature gradient between the heat carrier (fat) and the boiling point of the liquid. As the vapor penetrates inward, it condenses and transfers its heat to the less heated layers of the product [24]. The intensity of internal heating during the second period is lower compared to the first.

An increase in the temperature of the outer layer to 375–378 K initiates the thermal degradation of components of the raw product, resulting in the formation of chemical compounds, some of which are volatile and have specific aromas and flavors [4, 5, 11, 14]. Further increase in surface temperature above 408 K leads to the formation of substances with an unpleasant bitter taste and odor.

Studies [5, 9, 12, 25–34] examine the influence of technological factors such as meat storage conditions, the temperature of the heating surface or heating medium, method of heat transfer, frying temperature, medium reactions, and others on the physical, chemical, and biochemical processes occurring in meat during frying. These factors affect the quality of the finished meat products and may also contribute to the formation of harmful substances. The main criteria for changes caused by technological factors include the nutritional value of the product and the formation of undesirable and harmful substances in the finished product.

According to the literature [14, 19, 22], the appetizing crust on the surface and the characteristic aroma of fried products are the result of the formation of melanoidins – dark brown polymers that are products of the interaction between reducing sugars (monosaccharides and disaccharides) and amino acids, peptides, and proteins. The impact of melanoidins on food products from consumer, technological, and biomedical perspectives is mixed [14, 22]. Their positive role lies in the formation of color, taste, and aroma of fried products under moderate heating conditions. However, high-temperature or prolonged heating may cause excessive darkening, as well as undesirable taste and odor [14, 19]. Food melanoidins formed during culinary processing reduce the nutritional value of products, as they are not digested by human gastrointestinal enzymes and, therefore, are not absorbed [14, 22, 35].

From the standpoint of reducing the duration of the conductive frying process for meat and meat products, increasing the temperature is desirable, as it shortens the thermal processing time. However, from a technological point of view, increasing the process temperature above 425 K leads to the formation of carcinogenic compounds in the crust—heterocyclic amines (HA) [36–40], namely IQx (2-amino-3-

methylimidazo[4,5-f]quinoxaline) and MeIQx (2-amino-3,8-dimethylimidazo[4,5-f]quinoxaline).
Studies [41, 42] have shown that the consumption of meat products containing heterocyclic amines causes cancer in mice and monkeys, indicating a high probability of similar effects in humans. The main factors influencing the formation and accumulation of HA and mutagenic substances are the temperature and duration of thermal processing [43–47]. The mutagen content in finished products increases proportionally with processing temperature, and the mutagenicity of minced meat fried at 473 K is nearly twice as high as that fried at 423 K [46, 48]. Other factors influencing HA formation include fat and sugar content, various amino acids, antioxidants, vegetable fillers, water content, cooking method [30, 32, 49–52], and the number of product flips during cooking [53]. The authors of [54] proposed an analytical model for HA formation, according to which the rate of their formation is a function of the absolute surface temperature of the product. The analytical model is recommended as an alternative to experimental determination of HA content in finished meat products.

The doneness of fried meat can be evaluated organoleptically by the formation of a crust. However, a more reliable and objective quality indicator is the reduction in the weight of the semi-finished product during frying, referred to as visible cooking loss [12].

During frying, two opposing mass transfer processes occur simultaneously: moisture removal and fat absorption [12, 23].

The change in nutritional and biological value of meat products after thermal treatment is due to both positive and negative effects. Moderate protein denaturation increases their digestibility and bioavailability [3, 14, 19]. At the same time, prolonged or intense heating can increase the resistance of proteins to proteolytic enzymes. Furthermore, heating leads to inactivation and destruction of vitamins. Due to moisture loss during frying, meat loses up to 10% of its proteins, 30% of its fats, around 20% of its minerals and vitamins B and PP, 40% of vitamin A, and 60% of vitamin C. It has been established that the main factor influencing the loss of nutrients is the heating temperature. For example, increasing the temperature in the range of 348–363 K by 1 K increases mass losses by an average of 0.37%; when heating from 338 to 348 K, the increase is 0.25%; and from 328 to 338 K, the increase is 0.14% [55]. According to M.A. Yaremachenko [56], the doneness of pork products is achieved when the center of the piece reaches a temperature of 343–345 K, and for beef products, 353–355 K.

1.2. Features of Thermal Processing of Meat with High Connective Tissue Content

One of the key factors during thermal processing that determines the culinary readiness of meat products is the softening of connective tissue. In this context, changes in one of the main connective tissue proteins—collagen—are of particular importance, since elastin and reticulin undergo little to no significant changes under known methods of thermal processing of meat products. Under the influence of heat and moisture, collagen transforms into water-soluble gelatin, which leads to a reduction in the mechanical strength of the connective tissue and a weakening of the bonds between muscle fibers and bundles. This is crucial, as gelatin is easily digested by proteolytic enzymes and is highly soluble in water. According to data [57, 58], cutting resistance decreases by approximately tenfold.

Research [59, 60] has shown that the rate of collagen hydrolysis does not depend on its chemical nature, but rather on other factors—primarily the morphological structure of the meat's connective tissue. Connective tissue in the muscles of the limbs consists of large and coarse formations, where collagen fibers are interwoven with a higher number of elastin and fewer reticulin fibers. In contrast, in tender cuts of meat (such as the loin and tenderloin), the connective tissue is a fine, delicate network composed mainly of collagen fibers. Additionally, significant collagen hydrolysis occurs only under intense thermal processing conditions. During conventional frying and boiling, an increase in temperature and heating duration more significantly promotes the aggregation of muscle proteins than collagen hydrolysis. This results in the shrinkage of the meat piece and juice loss.

Research [27] indicates that the triceps brachii and semitendinosus muscles achieve optimal consistency when collagen is broken down by an average of 25–45% of its total content. Thus, for these muscle types, collagen hydrolysis is the main factor determining culinary readiness.

It is known that the amount of moisture present in the meat at the start of thermal processing, and the amount lost by the end of the process, affects the rate at which collagen gelatinizes. Whole muscle tissue with an undisturbed structure can be characterized as a coagulation-type dispersed colloidal system [21], in which part of the moisture is retained due to high osmotic pressure and the structure of the material. It is known [61] that muscle tissue contains 0.35–0.40 kg of water per 0.10 kg of protein, but only about 0.04 kg is tightly bound. The remaining water is immobilized in intra- and intercellular spaces. It is believed that a small amount of water is bound to proteins, while most of it behaves like free water. Therefore, developing thermal processing methods that minimize native moisture losses is particularly important, as this promotes more efficient collagen hydrolysis in meat with high connective tissue content (HCCT).

During traditional frying, substantial moisture loss occurs, and the remaining amount in the meat is insufficient to achieve the level of collagen hydrolysis required for the culinary readiness of HCCT meat.

Among technological factors influencing the rate of collagen-to-gelatin conversion, the most important are temperature, duration of heat exposure, presence of water, and the reaction of the medium [62–65].

According to [4, 66, 67], collagen gelatinization is accompanied by heat absorption of $(8{,}5–22{,}5)\cdot 10^3$ J/kg due to the breakdown of hydrogen bonds, and the heat capacity of both gelatinized and non-gelatinized collagen is about 1700 J/kg within the temperature range of 293–343 K. Furthermore, gelatinization of collagen should be viewed as a denaturation process of a fibrillar protein. There is also a known correlation between the gelatinization temperature and the hydroxyproline content in the collagen structure: the higher the hydroxyproline content, the higher the gelatinization temperature.

Research [29] shows that the hydrothermal stability of intramuscular connective tissue collagen increases with the animal’s age. For example, under identical frying conditions, collagen breakdown in young animals averages 43% (ranging from 29.2% to

52.3%), whereas in 8–10-year-old animals, it averages only 22% (ranging from 13% to 28%).

Studies of beef quality indicators [68] show that technologically important parameters such as pH, tenderness, and water-holding capacity depend significantly on the age of the animal. It has been established that tenderness correlates with juiciness and flavor. Generally, tender meat is juicy, but not always flavorful. In dry meat, no significant correlation is observed between tenderness and flavor. Tough meat, although less juicy, may still receive varied flavor assessments.

A correlation analysis between organoleptic and physicochemical characteristics of beef before and after thermal processing was conducted in [69]. It was found that tenderness positively correlates with pH, moisture content after thermal treatment, and labile collagen content. Negative correlations were observed between tenderness and the amount of juice released during heating, mass loss from heating, cutting force, bite force, and number of chewing motions. Flavor negatively correlates with collagen content.

The nutritional value of connective tissue is closely linked to its chemical composition, particularly its relatively high protein content. Due to the limited ability of digestive enzymes to break down collagen, meat with high connective tissue content has lower nutritional value. This serves as the basis for meat grading—higher-grade meats contain minimal connective tissue.

Neck, hip, and shoulder cuts contain significant amounts of structurally strong collagen (2,4–3,3%) [57]; the strength of these tissues is further increased by higher elastin content. These parts are typically boiled or stewed, as the moisture retained during conventional frying is insufficient for adequate collagen hydrolysis to reach culinary readiness in HCCT meat.

However, the commonly held notion that food should be high in calories and easy to digest is not entirely appropriate, as easily digestible food may weaken digestive functions. Hence, the idea that meat with the least amount of connective tissue protein is the most beneficial should be reconsidered [70–72]. Moreover, in proper proportion to other muscle proteins, these proteins can compensate for a lack of essential amino acids, which they contain in substantial quantities [5].

The quality of finished meat products is largely influenced by the internal temperature achieved during heating, which ensures protein denaturation and a certain bactericidal effect. For HCCT meat, this temperature is 358 K [57]; only the tenderloin can be heated to lower temperatures due to its particularly delicate structure and low microbial contamination.

A study [30] of changes in organoleptic properties, chemical composition, and biological value of natural beef cuts (tenderloin and ribeye) revealed that during frying, the structural and mechanical properties of meat are influenced by two opposing factors. Collagen breakdown softens connective tissue formations and tenderizes the meat (reducing cutting resistance along the muscle fibers). On the other hand, moisture loss due to protein denaturation compresses muscle fibers, increasing meat toughness (cutting resistance across the fibers). For the studied semi-finished products, the cutting resistance across the fibers was $28.7 \cdot 10^4$ Pa for tenderloin and $31,9 \cdot 10^4$ Pa for ribeye. The degree of collagen-to-gelatin conversion was 21,7% for tenderloin and 21,4% for ribeye. The authors also noted that after frying, the temperature in the center of portioned meat pieces continued to rise by 2–3 K due to retained heat. It was also established that a recommended heating surface temperature for frying portioned semi-finished products is 433 K.

Raw beef is structurally close to a liquid. During heating, due to the processes of protein coagulation and denaturation, it begins to transition toward a solid state. The heat capacity of solids is lower than that of liquids (due to a change in the number of degrees of molecular freedom), which explains the slight decrease in the heat capacity of beef when its temperature reaches 313–333 K—i.e., the range in which the coagulation (solidification) of proteins is mostly completed [73].

Fried natural portioned beef products (such as minute steak, beefsteak, and roast beef) are made from the most tender and soft parts of the carcass (tenderloin, dorsal, and lumbar sections), which account for about 14% of the carcass mass in cattle [74, 75]. In contrast, lower-grade cuts with high connective tissue content (HCCT), such as the hip and shoulder sections, are not suitable for this purpose and are used for the production of diced semi-finished products.

One of the approaches [19, 76–78] to increase the volume of HCCT beef that can be used for the production of fried natural portioned products is its preliminary treatment, namely: mechanical tenderization, loosening, marinating, and treatment with enzyme preparations. However, such preliminary processing significantly affects the quality of the final product, as it disrupts cell structure, leading to moisture loss and, consequently, a reduction in the nutritional value of the finished product.

1.3. Methods of Heat Supply during Conductive Frying and Equipment for Their Implementation

Traditionally, during the conductive frying of meat and meat products, heat is supplied to the surface of the product unilaterally through contact with a surface heated to 423–493 K [5, 6, 12–15], either featuring anti-adhesive properties or coated with fat. During frying, products require flipping to achieve the desired organoleptic characteristics. The basic frying method is implemented using frying pans, direct-heat cooking plates (frying surfaces), and stoves with cookware placed on top.

Frying pans are classified by energy source into electric and gas types. In electric frying pans, the heat-generating elements include spiral heaters in ceramic beads or tubular electric heaters (TENs) embedded in aluminum. In gas pans, low-pressure injection burners are used [17]. The VarioCooking Center from Rational [79], which supports boiling, frying, grilling, deep-frying, and pressure cooking, features the VarioBoost heating system, similar to flat foil heaters based on mica-plastic – HEF. Temperature field non-uniformity in frying pans is significant, reaching up to 120 K in Soviet models СЭСМ-0.2 and СЭСМ-0.5 [13], Russian models СЭС-0.55 and СЭС-0.2 [80], and Ukrainian model CE-30 [81], and up to 60 K in other models like СЭ-0.22, СЭ-0.45 (USSR) [6], Bertos E7BR8/I (Italy) [82], and Garland E24 series (Canada) [83]. This unevenness is due to the pan's side surfaces drawing heat from the bottom and the irregular placement of heating elements. As a result, frying speed and product quality vary between the center and edges of the pan, requiring manual repositioning during frying and resulting in reduced product yield.

To reduce temperature non-uniformity to 15–20 K, indirect bottom heating is applied through a jacket filled with high-temperature heat transfer fluids (mineral or silicone-based) [84] in models like СКЭ-0.3 [6–8, 12], СКГ-0.3 [7, 8, 12], double-surface roasters [85], and universal frying devices [86]. However, such pans have higher metal consumption than those with direct heating, leading to longer warm-up times and greater thermal inertia. Thanks to electronic temperature control and the VarioBoost system, the VarioCooking Center [79] achieves a temperature uniformity within 20 K. Structurally, all frying pans are fundamentally similar; the differences lie in the bowl materials, tilting mechanisms, heating systems, and lid designs.

Direct-contact cooking plates such as ПЕСМ-1Н and ПЕСМ-2НШ (USSR) [17], ПЭ-6,0/380Н (Ukraine) [80], Garland's 36ES32-3 (Canada) [83], KOVINASTROJ's EZ-7/P-L (Slovenia) [87], Kogast's EZT40R (Slovakia) [88], and Gastrorag's GH-VEG-833 (China) [89] are of similar design, consisting of rectangular burners with flat or ribbed cooking surfaces bordered on three sides, sharing the same shortcomings as frying pans. Surface temperature is regulated within 373–623 K using thermostats or thermal relays.

A theoretical model for conductive frying of hamburgers on a pan surface was proposed by the authors of [54], based on solving the heat conduction equation using the Galerkin finite element method.

Many of the drawbacks of traditional frying equipment are resolved through double-sided heat supply. In this method, frying time is reduced by at least half (down to 180–220 s) due to a twofold increase in heat exchange surface area. Product yield increases by 10–20%, flipping is no longer required, and energy consumption is reduced by 50–60% [90]. Equipment for implementing double-sided frying (contact grills) is produced only in electric versions due to the complexity of supplying heat to the upper surface [17].

Fundamentally, double-sided frying devices [91–105] consist of a stationary lower and one or two movable upper flat or ribbed surfaces connected via a system of levers and hinges, allowing the upper plate to open from 90 to 180°. Opening to 180° allows both surfaces to act as a single flat surface for basic frying. Heating surfaces may be removable [92–96] or made of anti-adhesive materials or non-stick coated plates. Heating elements include TENs [92–96, 101–103] or enclosed electric heating elements. Temperature control is carried out either by single-position thermal relays or multi-position thermostats within the range of 363–573 K, depending on the thermal properties of the product, and can be regulated independently for the lower or upper surface [99]. However, regulating only the lower surface may lead to overheating of the upper one due to uneven heat removal by the product, and vice versa—regulating only the upper surface may cause the lower one to cool excessively. This results in uneven crust formation and decreased product quality.

Heat can also be supplied to the entire surface of the product. The author of [25] proposes conducting conductive frying in a functionally closed environment, formed between upper and lower heating surfaces with recesses matching the geometric dimensions of the meat patties. Frying in such a closed environment significantly equalizes the temperature field within the product and reduces frying time by 57–59%. The presence of a sealed space prevents vapor from escaping, increasing product yield by 2.9–3.1%. Additionally, vapor condensation inside the product during cooling in the same closed environment raises the yield by another 6.3–6.7%, provided the condensate is cooled to serving temperature.

A theoretical model for double-sided frying of frozen and chilled hamburger patties was proposed in [106], based on solving the heat conduction equation using the Galerkin finite element method. A theoretical model for frying meat patties in a functionally closed environment was proposed by the authors in [12].

1.4. Use of Physical and Electrophysical Methods for the Intensification of Conductive Frying of Meat and Meat Products

It is known that the factors contributing to the intensification of thermal processing of food raw materials include:

- increasing the process temperature level;
- increasing the heat exchange surface between the raw material and the heating medium (or surface);
- increasing the heat transfer coefficient from the heating medium (or surface) to the raw material;
- changing the thermophysical properties of the product.

Raising the temperature above 423 K, as previously noted, significantly intensifies the conductive frying process, but adversely affects the quality of the final product and leads to the formation of harmful substances such as heterocyclic amines (HA) in the crust [36-40]. Due to these undesirable technological consequences, increasing the temperature beyond 423 K is considered impractical.

Increasing the heat exchange surface in conductive frying can be achieved through double-sided heat supply. This significantly reduces frying duration, decreases specific energy consumption, and increases product yield.

Enhancing the heat transfer coefficient from the frying surface to the meat and altering its thermophysical properties can be achieved using certain physical and electrophysical methods, such as pressure and electric current.

Touba A. R. [107] patented a method of double-sided meat frying under pressure. The optimal process parameters include: surface temperature of 477–588 K, pressure on the product ranging from (6.9–345) x 10^3 Pa, and frying duration of 15–100 s. Under these conditions, the optimal temperature that ensures intense surface steam formation without burning the meat is 533 K, and the pressure for adequate contact ranges from (13.8–207) x 10^3 Pa. Steam generated at the surfaces penetrates the meat. However, this method has drawbacks: surface temperatures of 477–588 K can lead to the formation of HA; no data is provided on product yield or energy efficiency; and with rigid fixation of the top plate, uncontrolled steam pressure buildup may damage the meat structure and reduce yield.

Studies by the author [90] determined the critical pressure level above which the connective tissue of meat begins to break down, reducing yield. A proposed method involves double-sided frying under pressure using semi-finished products placed between two surfaces heated to 423 K, with pressure applied close to the critical threshold and maintained via non-rigid fixation [90, 108]. This method increases yield by up to 20%, reduces frying time 7–10 times, and lowers specific energy consumption 3–7 times compared to the basic frying method. The setup ensures optimal compression without structural damage. Meat juice fills all pores, improving contact area and thermal conductivity, enabling frying in 50–120 s. Moisture expelled to the surface prevents overheating and HA formation, ensuring a safe, high-quality product. Studies confirmed sufficient collagen hydrolysis [90, 110] and acceptable microbiological quality [90, 111]. However, determining the critical pressure for each product is challenging due to factors like animal age, gender, storage, and freezing cycles. Compression mechanism complexity also limits usability.

Conductive frying is a surface heating method where heat penetrates the product via thermal conduction, which restricts intensification. Acceleration is possible using electrocontact heating, where current passes directly through the product, generating heat via its electrical resistance [112].

Known methods of electrical heating for meat [113, 114] have not been widely applied in frying, as water-salt solutions (main conductors in meat) typically heat only to 373 K [115, 116]—sufficient for doneness but not crust formation.

To overcome this, a combined electrocontact heating method was proposed [117], supplemented by traditional or electrophysical heat transfer methods.

Surface or infrared heating forms a crust, while electric current intensifies internal heating.

Authors in [118] suggest combining low-frequency electrocontact heating with double-sided surface heating. Voltage is determined by the product's composition and resistance [119].

Another method [120, 121] involves simultaneous surface, infrared, and electrocontact heating. Conductive and infrared heating form a desirable crust with good organoleptic properties, while electric current ensures uniform internal heating, reducing processing time, increasing yield, and lowering energy use.

These methods [113, 117-121] are applicable mainly to minced multicomponent meat products. Their use for natural meat is less effective due to non-uniform structure and fat inclusions. Also, using open electrodes with voltage above 36 V poses safety risks for operators.

Electrokinetic phenomena, particularly electroosmosis, show promise for removing moisture from the surface layers of meat during double-sided frying, helping to prevent HA formation. Electroosmosis involves liquid movement toward the negatively charged electrode under an externally applied potential [122-125].

Modern understanding of electroosmosis in dispersive systems involves a diffuse double electric layer at the phase boundary [126, 127], consisting of ions bound to the solid and liquid phases [125, 128, 129]. Electric fields in capillaries drive solvated counterions toward the opposite electrode [130]. Experiments show transferred liquid volume is proportional to current and independent of membrane cross-section or thickness, increasing with solution resistance [130].

Electroosmosis is used in construction and agriculture for drainage [131, 132], irrigation [133], wall drying [134-138], and low-temperature seed drying [139], reducing drying time and energy use. In medicine, it aids in drug delivery for tumor treatment [140]. In the food industry, it is used for water purification [141], dehydration of pastes [142], cryoground bone tissue [143], and plant materials [144].

Dehydration of plant materials via electroosmosis was studied in [145]. Application of a 6–12 V DC field initiates electroosmotic filtration—directed moisture movement from anode to cathode due to electric and hydrodynamic forces [146]. Initially, moisture from intercellular spaces is removed, followed by mechanically bound and then physicochemically bound water. A method [147] and device [148] were developed for electroosmotic dehydration, which can remove up to 60% moisture, but with 30–60% loss of valuable dry matter [145, 150]. Thus, this method is best for drawing moisture to the surface before removal via heat. An electroosmotic-convective solar dryer developed by the author [151] enables such combined drying.

Though electroosmosis is generally used for dehydration, reversing the current during meat frying could retain moisture inside the meat. Therefore, using electric current to control internal moisture movement shows promise for advancing conductive frying technologies. It could improve energy efficiency, and combining double-sided heating with alternating electric current would reduce moisture loss and prevent overheating and HA formation in surface layers.

1.5. Existing Methods for Assessing the Energy Efficiency of Thermal Processing Processes and Equipment for Food Raw Materials

Technological thermal equipment uses the energy supplied to it for physical-chemical, thermal, and other transformations that affect the input raw materials. The evaluation of the efficiency of thermal equipment operation is related to accounting for various types of energy losses: irreversible heat exchange, loss of mass (moisture) from the input raw material, losses to the environment, etc. [152].

Existing methods for assessing the energy efficiency of thermal processing of food raw materials and the equipment used for it are based on determining and analyzing a large number of indicators [153–156], among which the most significant for conductive frying are:

- thermal efficiency coefficient (η_t) – the ratio of usefully consumed energy to the total energy consumption;
- specific energy consumption (b) – the amount of energy resource used per unit of product (J/kg, J/unit, etc.).

Most conductive frying equipment is electric, so for such devices, the indicator is either:

- specific electricity consumption (b_e) – the amount of electrical energy consumed per unit of product (kWh/kg, kWh/unit, etc.), or
- specific heat energy consumption (b_t) – the amount of thermal energy consumed per unit of product (Gcal/kg, J/kg, etc.);
- energy intensity of the product (E_e) – the amount of electricity used to produce one unit of product (J/kg, J/unit, etc.);
- specific energy intensity (E_{sp}) – the amount of energy consumed per primary parameter characterizing the device (J/m², etc.).

The efficiency of heat use in equipment, regardless of complexity or technological purpose, is typically based on the first law of thermodynamics. For a thermal system, the law is formulated as follows: the change in internal energy during any process equals the difference between the energy supplied to the system and the energy removed from it. The transition from initial state 1 to final state 2 can occur directly or through intermediate states, allowing the total energy change ΔW to be expressed as:

$$\Delta W = \sum \Delta W_i = W_2 - W_1, \text{ J.}$$

For each state, the change in internal energy ΔU is:

$$\Delta U = \Delta W = U_2 - U_1, \text{ J.}$$

Heat Q is the energy absorbed by the system as its temperature increases (without doing work):

$$\Delta Q = c \cdot \Delta T, \text{ J,}$$

The amount of heat supplied per unit mass of a body being heated in a system undergoing an isobaric process from state 1 to state 2 is equal to the difference in enthalpy; that is, the heat supplied to the body during an isobaric process is used for changing its enthalpy.

$$dq = di, \text{ J/kg.}$$

The energy balance of a thermal apparatus (heat utilization) can be written as [157]:

$$Q_w = G \cdot q + \sum Q_{los}, \text{ J,}$$

Energy use Q_w can be represented as energy flows summing to Q_w:

$$Q_w = W_t^u + \sum W_e^u, \text{ J},$$

With this energy and heat balance, the degree of heat use is evaluated by thermal efficiency η_t [153, 157, 158]:

$$\eta_t = \frac{Q_{fp}}{Q_w} = 1 - \frac{\sum Q_{los}}{Q_w}. \qquad (1.1)$$

The heat consumption Q_{fp} is independent of the heating regime or apparatus design and depends solely on product properties and the technological process.

Comparisons of the efficiency [158] of different types of thermal equipment based on energy and heat balances using the first law of thermodynamics are impossible. These balances only show relationships between components and reflect the quantitative aspect of thermal processes but do not account for differences in energy conversion potential. Calculated η□ values do not indicate how fully the system's potential is utilized. Only internal irreversibility is accounted for, while losses due to the finite temperature difference between the heat source and the heated medium (or product) are not. Despite this, efficiency coefficients are widely used in practical thermal calculations [153, 157, 158] because external irreversibility does not affect quantitative analysis. The same heat quantity will be transferred regardless of temperature difference, though this results in loss of thermal potential.

All energy transformations in thermal processing equipment are irreversible. Each irreversibility lowers process efficiency. Thus, for energy W□ᵘ:

$$W_t^u = G \cdot q + \sum W_{los}, \text{ J},$$

W_t^u exceeds enthalpy $G \cdot q$ since a higher thermal potential must be maintained than that obtained in the product.

Therefore, the energy supplied to the apparatus is:

$$Q_w = G \cdot q + \sum W_{los} + \sum W_e^u, \text{ J}.$$

The coefficient of energy transformation is:

$$\eta_t = \frac{G \cdot q}{Q_w}. \quad (1.2)$$

The share of energy losses during thermal processing due to irreversible heat and mass transfer will be:

$$\beta = \frac{\sum W_{los}}{Q_w},$$

Energy loss fraction from irreversible heat and mass transfer:

$$\eta_{ef} = 1 - \frac{\sum W_{los}}{Q_{\text{p}}} = 1 - \beta. \quad (1.3)$$

Overall apparatus efficiency (energy efficiency coefficient):

$$\eta_{en} = \eta_t + \eta_{ef}. \quad (1.4)$$

This coefficient considers both quantitative and qualitative aspects of energy conversion. However, to determine these coefficients, concepts from the second law of thermodynamics must be used.

Irreversibility is addressed by the second law of thermodynamics [158]. It states that energy transfer with a finite potential difference (temperature, pressure, etc.) incurs losses due to irreversibility—something not reflected in energy balance equations. A thermally efficient device under the first law may be inefficient under the second law. This imperfection is evaluated by the entropy method.

For processes involving heat transfer, temperature serves as the potential factor. Heat transfer dq at temperature T [158]:

$$dq = T \cdot dS, \text{ J}.$$

Entropy S measures irreversibility:

$$dS = \frac{dq}{T}, \qquad \text{or} \qquad S_2 - S_1 = \int_1^2 \frac{dQ}{T} = \Delta S, \frac{J}{K}.$$

Entropy is an additive caloric state function. For G kg of substance, entropy is G times that of 1 kg.

Since $dS = \frac{dq}{T}$ and $T > 0$: if $dq > 0$ i $dS > 0$ then $dS > 0$; if $dq < 0$ then dS<0. Thus, entropy increase indicates heat input; decrease indicates heat removal.

If the process is internally irreversible, entropy change includes internal entropy generation $d_\text{i}S$.

$$dS = d_\text{e}S + d_\text{i}S, J/K$$

or

$$dS = \frac{dQ}{T} + d_\text{i}S, \frac{J}{K}.$$

$T \cdot d_\text{i}S$ represents energy dissipation due to irreversible heat, mass transfer, or transformations.

In evaluating process efficiency in thermal equipment, the concept of "useful energy" becomes less meaningful. Instead, the actual energy transformations must be considered [158].

Thus, developing a methodology based on both the first and second laws of thermodynamics, accounting for energy resource quality and process irreversibility, is essential for analyzing equipment performance.

1.6. Conclusions for the Chapter

A critical analysis of the conductive frying process of meat, the specific features of thermal treatment of meat with high connective tissue content (HCCT), methods of heat supply in conductive frying using applicable equipment, and existing methodologies for evaluating their energy efficiency, as well as previous research, allows us to formulate the main objective of this study: the development of scientifically grounded energy- and resource-efficient processes and equipment for conductive frying of meat.

Achieving this goal is possible through solving the following research tasks:

- scientifically substantiate and develop a new methodology for assessing the energy efficiency of conductive frying processes and equipment;
- analyze the energy efficiency of existing conductive frying processes and equipment using the newly developed methodology;
- based on energy efficiency analysis, scientifically justify directions for intensifying the conductive frying process and formulate technological requirements for the equipment needed for its implementation;
- scientifically substantiate the influence of physical and electrophysical actions on the intensification, energy, and resource savings in the conductive frying process;

– determine the mass transfer patterns in meat under the influence of electric current, heat flow from the heater, excess pressure, and their combined action;

– identify the patterns of heat and mass transfer processes during conductive frying of meat under the influence of the specified factors and scientifically justify and develop an analytical and theoretical thermal model;

– develop scientifically grounded energy- and resource-efficient technological processes for the production of natural portioned fried meat products and evaluate their quality;

– design equipment for implementing the proposed conductive frying processes using physical and electrophysical methods, prepare project documentation, transfer it to manufacturing enterprises for the production of pilot batches, study its functional capabilities, and determine its technical-operational and energy efficiency indicators;

– evaluate the socio-economic effectiveness of the scientific and technical developments and implement measures for their industrial adoption.

The object of the research is the conductive frying processes of meat under the influence of physical and electrophysical methods, and the heat and mass transfer occurring during frying, as well as the equipment used for implementation.

The subject of the research includes semi-finished natural portioned meat products, including those with high connective tissue content, the finished products, and the equipment for conductive frying of meat.

CHAPTER 2. SCIENTIFIC SUBSTANTIATION OF THE ANALYTICAL AND THERMAL MODELS OF ENERGY- AND RESOURCE-EFFICIENT PROCESSES IN CONDUCTIVE MEAT FRYING

2.1. Development of a Methodology for Analyzing the Energy Efficiency of Thermal Equipment

The method of analyzing the operation of thermal equipment based on the combined use of the first and second laws of thermodynamics, taking into account the quality of energy resources and the irreversibility of real working processes, is called the exergetic method [159].

Heat exergy is the maximum amount of heat that can be converted into work when the lower heat source is the surrounding environment [159, 160]. Every phenomenon of irreversibility causes an irreversible loss of exergy.
The concept of exergy proves to be quite convenient for analyzing the degree of thermodynamic perfection of a particular thermal apparatus [161].
By evaluating these losses in individual sections of a thermal installation, one can quantitatively determine the reasons for the decrease in process efficiency.

With regard to thermal devices for heating food products, we can consider the exergy of the heat flow

E_Q and the exergy of the mass of the working medium E_m.

The exergy of the heat flow released by a body at temperature TTT is determined as follows:

$$E_Q = Q \cdot \left(1 - \frac{T_0}{T_{ws}^m}\right), \text{J},$$

where Q is the amount of heat flow, J; T_{ws}^m is the mean thermodynamic temperature of the heat source, K; T_0 is the absolute temperature of the surrounding environment, K.

The mass exergy is determined by the expression:

$$E_m = I - I_0 - T_0 \cdot (S - S_0), \text{J}.$$

The exergy referred to the unit mass mmm of a body is called the specific exergy [158]:

$$e = \frac{E_m}{m}, \text{J/kg}.$$

For thermal equipment that does not perform mechanical work and is intended to carry out a specific irreversible technological process, the energy balance can be represented as follows:

$$E_Q^{ex} + E_m^{ex} = E_Q^{\text{en}} + E_m^{\text{en}} + E_{los}, \text{J}.$$

Loss of exergy E_{los} in a process accompanied by a change in the system's entropy ΔS is given by:

$$E_{los} = T_0 \cdot \Delta S, \text{ J.}$$

Since in real irreversible processes the system's entropy increases, i.e., $\Delta S > 0$ and $E_{los} > 0$, it follows that $\sum E^{ex} < \sum E^{en}$.

The exergetic balance [158] reflects the reduction of a system's exergy during the irreversible processes occurring within it. It should be noted that the energy balance presented earlier, based on the first law of thermodynamics, indicates the constancy of exergy at the system's inlet and outlet, namely:

$$\sum \mathrm{E}^{ex} = \sum \mathrm{E}^{en}, \text{ J.}$$

Exergy losses in equipment for the thermal processing of food products consist of:

–exergy losses due to the irreversibility of heat exchange between the heating medium and the product being heated;

–exergy losses due to the irreversibility of heat exchange between the system (the apparatus, the heating medium, the product) and the surrounding environment.

In heating processes, the absolute exergy value *E*, is not considered; rather, its difference Δ*E* (the change in exergy) is used.

In technological apparatus where thermal energy is obtained by converting electrical energy into heat (heaters with ohmic resistance), the exergy of the electrical energy always equals the amount of that energy.

$$P_{el} \cdot \tau = W_{el} = \Delta E, \text{ J.}$$

Therefore, for electric conduction frying appliances with direct heating of the working chamber (surface), the exergy balance can be expressed as:

$$\Delta E = \Delta E_{\beta} + \Delta E_{los}, \text{ J.}$$

The change in the specific exergy of a substance when heat is supplied to it can be determined by the expression:

$$\Delta e = (i_1 - i_2) - T_0 \cdot (s_1 - s_2), \text{ J/kg,}$$

where i_1, i_2 are the specific enthalpies of the substance being heated at the start and end of the process, J/kg; s_1, s_2 are the specific entropies, J/(kg·K); T_0 is the absolute temperature of the surrounding environment, K.

In differential form:

$$de = di - T_0 ds, \text{ J/kg.}$$

The increase in the substance's enthalpy at constant pressure equals the amount of heat input, $di = c_\rho \cdot dT = dq$, and under reversible conditions a $dq = T \cdot ds$.

Then:

$$de = c_\rho \cdot dT - T_0 \cdot c_\rho \cdot {}^{dT}/_{T}, \text{ J/kg},$$

where c_ρ is the specific heat capacity of the substance (product), J/(kg·K).

Integrating this expression for the heating process from T_1 to T_2:

$$\int_1^1 de = \int_1^2 c_\rho \cdot \left(1 - {}^{T_0}/_{T}\right) dT$$

and assuming $c_\rho = const$, we obtain

$$e_2 - e_1 = \Delta e = c_\rho \cdot (T_2 - T_1) - c_\rho \cdot T_0 \cdot ln\frac{T_2}{T_1}, \text{ J/kg}.$$

In the general case, the total increase in the exergy of the product being heated is:

$$\Delta E_{prod} = G \cdot \Delta e, \text{ J}.$$

Heat transfer to the product being heated is associated with irreversibility caused by the finite temperature difference between the heating medium (surface) and the product.

Thus, the exergy expenditure for heating the product is:

$$\Delta E_{\beta} = G \cdot \Delta e + T_0 \cdot \Delta S_v, \text{ J},$$

where $T_0 \cdot \Delta S_v$ is the exergy loss due to irreversibility, J.

Knowing the increase in the exergy of the product being heated and the exergy loss in the process, one can determine the exergetic efficiency of the process:

$$\eta_{ex} = \frac{G \cdot \Delta e}{\Delta E} = \frac{\Delta E - T_0 \cdot \Delta S_v}{\Delta E} = 1 - \frac{T_0 \cdot \Delta S_v}{\Delta E}.$$

The exergetic efficiency η_{ex} is a measure of the exergetic losses arising from the irreversibility of the product heating process. It must be noted that the losses due to irreversibility in the process can be internal (heat and mass transfer) or external. Therefore, the general expression for exergetic efficiency is:

$$\eta_{ex} = 1 - \frac{\sum \Delta E_{los}}{\Delta E}.$$

The amount of exergetic losses is calculated by the general expression:

$$\Delta E_{los} = T_0 \cdot \Delta S_c, \text{ J.}$$

If the change in entropy in any element of the system is determined, then the exergy loss for that element is thereby determined.

The irreversibility losses of heat exchange during the heating of the product (body) by the heating medium (surface) can be represented as follows: the temperature of the medium (wall) changes from T_1 to $T_1{}'$, the temperature of the product being heated changes from T_2 to $T_2{}'$, and heat exchange takes place with a finite temperature difference.

Since the temperatures of the heating medium and the body (product) being heated both change during heat exchange, one can use the mean thermodynamic (mean integral) temperatures of heat input T_1^{av} and heat removal T_2^{av} (Fig. 1) to evaluate the irreversibility losses of heat exchange. The mean integral temperature [161] for any process is defined as the ratio of the amount of heat participating in the process to the change in entropy of the heating medium or heat source caused by that process.

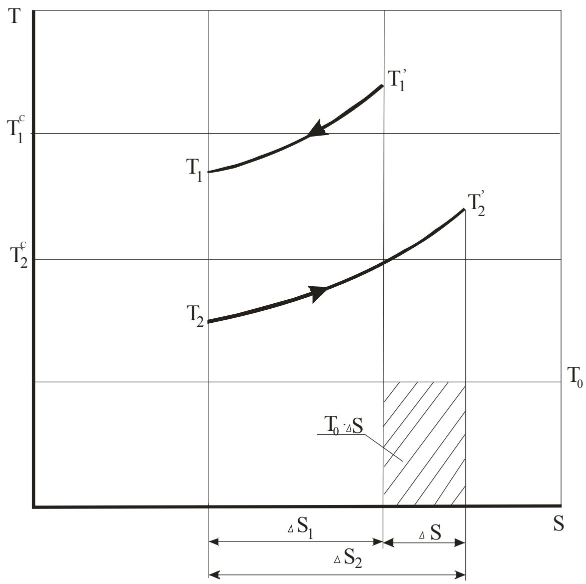


Fig. 1. Diagram for determining the mean dynamic temperatures and irreversibility losses of heat exchange

$$T^{av} = \frac{Q}{s_2 - s_1}, \text{ K}; \ \Delta S = c_\rho \cdot ln\frac{T_2}{T_1}, \text{ J/K}; \ Q = c_\rho \cdot (T_2 - T_1), \text{ J}.$$

Given Q and ΔS, we determine T^c

$$T^{av} = \frac{T_2 - T_1}{ln\frac{T_2}{T_1}}, K,$$

where T_1 and T_2 are, respectively, the initial and final temperatures of the body (product) being heated or the heating medium in the process (K).

Then

$$T_1^{av} = \frac{T_1 - T_1'}{ln\frac{T_1'}{T_1}}, \text{ K, a } T_2^{av} = \frac{T_2 - T_2'}{ln\frac{T_2'}{T_2}}, \text{ K.}$$

If, in the heating process, the body (product) is heated by a wall (surface) whose temperature is maintained at a specified level, then $T_1^{av} = T_1$.

If heat exchange in the system is accounted for by internal heat sources supplying heat dQ per unit time at temperature T_1^{av}, then the exergy of the heating medium decreases by $\left(1 - \frac{T_0}{T_1^{av}}\right) \cdot dQ$, and the exergy of the body (product) being heated increases by $\left(1 - \frac{T_0}{T_1^{av}}\right) \cdot dQ$.

The exergy loss will be:

$$dE_{prod} = \left(1 - \frac{T_0}{T_1^{av}}\right) \cdot dQ - \left(1 - \frac{T_0}{T_2^{av}}\right) \cdot dQ = T_0 \cdot \left(\frac{1}{T_2^{av}} - \frac{1}{T_1^{av}}\right) \cdot dQ, \text{ J,}$$

since

$$\frac{dQ}{T_1^{av}} = dS_1, \text{ J/K}, \frac{dQ}{T_2^{av}} = dS_2, \text{ J/K i } dS_v = dS_2 - dS_1, \text{ J/K,}$$

Hence,

$$dE = T_0 \cdot dS_v, \text{ Дж},$$

and thus

$$dS_v = dQ \cdot \left(\frac{1}{T_2^{av}} - \frac{1}{T_1^{av}}\right), \text{ J/K.}$$

The exergy loss due to irreversible heat exchange (loss of work capacity) ΔE_β during product frying [158] in the corresponding equipment can be calculated by the following formula:

$$\Delta E_\beta = G \cdot \nabla e = G \cdot [e_1 - e_2] = G \cdot \left[q_1 \cdot \left(\frac{T_{ws}^m - T_0}{T_{ws}^m}\right) - q_2 \cdot \left(\frac{T_v - T_0}{T_v}\right)\right] =$$

$$= G \cdot \left[\frac{P \cdot \tau}{G} \cdot \left(\frac{T_{ws}^m - T_0}{T_{ws}^m}\right)\right] - c_\rho \cdot (T_v - T_0) \cdot \left(\frac{T_v - T_0}{T_v}\right) =$$

$$= P \cdot \tau \cdot \left(\frac{T_{ws}^m - T_0}{T_{ws}^m}\right) - G \cdot c_\rho \cdot \frac{(T_v - T_0)^2}{T_v}, J, \qquad (2.1)$$

where

$$T_{ws}^m = \frac{T_{max} - T_{min}}{ln\frac{T_{max}}{T_{min}}}, K. \qquad (2.2)$$

The relative exergy loss due to irreversible heat exchange during product heating can be calculated by the following formula:

$$\beta = \frac{\Delta E_{\beta}}{\nabla E} = \frac{\Delta E_{\beta}}{P \cdot \tau} = \left(\frac{T_{ws}^{m} - T_{0}}{T_{ws}^{m}}\right) - \frac{G \cdot c_{\rho} \cdot (T_{v} - T_{0})^{2}}{T_{v} \cdot P \cdot \tau}. \quad (2.3)$$

The specific exergy loss per 1 kg of finished product due to irreversible heat exchange during frying can be calculated by:

$$\Delta E_{\beta_{sp}} = \frac{\Delta E_{\beta}}{G_{fp}}, \text{ J/kg} \quad (2.4)$$

where G_{fp} is the mass of the finished products after frying, kg.

The exergy loss to the environment through the apparatus walls [158–160] can be calculated using:

$$\nabla E_{f} = \sum_{i=1}^{i=n} \left[Q_{5i} \cdot \left(\frac{T_{wi} - T_{0}}{T_{wi}} \right) \right] = \sum_{i=1}^{i=n} \left[\alpha_{i} \cdot F_{i} \cdot (T_{wi} - T_{0}) \cdot \tau \cdot \left(\frac{T_{wi} - T_{0}}{T_{wi}} \right) \right] =$$

$$= \sum_{i=1}^{i=n}\left[\alpha_i \cdot F_i \cdot \frac{(T_{wi}-T_0)^2}{T_{wi}} \cdot \tau\right], \text{J}. \qquad (2.5)$$

The relative exergy loss to the environment through the apparatus walls [158] can be found by:

$$f = \frac{\sum_{i=1}^{i=n} \alpha_i \cdot F_i \cdot (T_{wi}-T_0)^2 \cdot \tau}{T_{wi} \cdot P \cdot \tau}. \qquad (2.6)$$

The specific exergy loss to the environment through the apparatus walls per 1 kg of finished product is calculated by:

$$\Delta E_{f_{sp}} = \frac{\Delta E_f}{G_{fp}}, \text{J/kg}. \quad (2.7)$$

During frying on an open surface, the exergy losses to the environment must also include the losses from the heated product itself. Specifically, these are the losses from the part of the product's surface that is in contact with the surrounding air (assuming that heat is supplied from below and above the product, the losses are determined only by the product's lateral surfaces).

$$\nabla E_f^{prod} = \sum_{i=1}^{i=n} \alpha_i \cdot F_i \cdot \frac{\left(T_{ps_i}^{av}-T_0\right)^2}{T_{ps_i}^{av}} \cdot \tau, \text{J} \qquad (2.8)$$

where F_i is the i-th surface of the product that does not come into contact with the heating surfaces, m^2:

$$T_{ps_i}^{av} = \frac{T_v - T_{in}}{ln\frac{T_v}{T_{in}}}, \text{K.}$$

The relative exergy loss to the environment through the product's surface can be calculated by:

$$f^{prod} = \frac{\nabla E_f^{prod}}{\nabla E} = \frac{\sum_{i=1}^{i=n} \alpha_i \cdot F_i \cdot \left(T_{ps_i}^{av} - T_0\right)^2 \cdot \tau}{T_{ps_i}^{av} \cdot P \cdot \tau}, \qquad (2.9)$$

The specific exergy loss to the environment through the product's surface per 1 kg of the finished product can be calculated by:

$$\nabla E_{f_i}^{prod} = \frac{\nabla E_f^{prod}}{G_{fp}}, \text{J/kg.} \qquad (2.10)$$

When frying meat products, various methods are used to heat the product: contact or conductive (through thermal conduction), convective, and radiative heating, carried out at different temperatures, pressures, and electrical potentials. Each heating method, under the optimal frying conditions, is characterized by certain product mass losses (moisture losses, partial moisture conversion to steam) and, consequently, different irreversibility losses. For heating processes that involve phase transformations, heating of the liquid migrating out of the product—part of which is converted into steam—should be considered among the exergy losses to the environment. It is not justified to regard these exergy losses as "useful" i.e., contributing to heating the product, changing the enthalpy of the finished product, and increasing its internal energy.

Therefore, it can be asserted that the efficiency of the product heating processes that occur with lower moisture losses (i.e., a higher yield of the finished product z) is always greater.

The exergy loss due to heating the liquid migrating out of the product during frying and turning into steam lost to the environment [154] can be calculated by the following formula:

$$\nabla E_{\gamma} = G \cdot (1 - z) \cdot \left(c_{\rho} \cdot (T_{к} - T_0) + r \cdot \varepsilon_r\right) \cdot \frac{T_{к} - T_0}{T_{к}} =$$

$$= G \cdot (1 - z) \cdot \left(c_{\rho} \cdot \frac{(T_{к} - T_0)^2}{T_{к}} + r \cdot \varepsilon_r \cdot \frac{T_{к} - T_0}{T_0}\right), \text{J.} \qquad (2.11)$$

The relative exergy loss for heating the liquid migrating from the product during frying and converting into steam that is lost to the environment can be calculated by the formula:

$$\gamma = \frac{\nabla E_{\gamma}}{\nabla E} = \frac{G \cdot (1 - z) \cdot \left(c_{\rho} \cdot (T_{к} - T_{0})^{2} + r \cdot \varepsilon_{r} \cdot (T_{к} - T_{0})\right)}{T_{к} \cdot P \cdot \tau}. \quad (2.12)$$

The specific exergy loss for heating the liquid migrating from the product during frying and converting into steam lost to the environment, per 1 kg of the finished product, can be calculated by:

$$\nabla E_{\gamma_{пит}} = \frac{\nabla E_{\gamma}}{G_{fp}}, \text{ J/kg.} \quad (2.13)$$

The total relative exergy loss to the environment is:

$$\Delta E_{prod} = \Delta E_{f_{sp}} + \nabla E_{f_{i}}^{prod} + \Delta E_{\gamma}, \text{ J.}$$

The total exergy loss of all types is:

$$\sum \Delta E_{втрат} = \Delta E_{\beta} + \Delta E_{f} + \Delta E_{f}^{prod} + \Delta E_{\gamma}, \text{ J.}$$

The exergetic efficiency of the apparatus is

$$\eta_{ex} = 1 - \frac{\Delta E_{\beta} + \Delta E_{f} + \Delta E_{f}^{prod} + \Delta E_{\gamma}}{\Delta E},$$

or

$$\eta_{ex} = 1 - (\beta + f + f^{prod} + \gamma). \quad (2.14)$$

The quantity $(1 - \beta)$ represents the ratio of the amount of heat transferred to the product to the maximum possible amount of heat that the working medium (heating medium or surface) can release. Clearly, this quantity corresponds to the efficiency coefficient η_{ef} (Equation 1.3), i.e.,

$$\eta_{ef} = 1 - \beta. \quad (2.15)$$

Thus, the equation for exergetic efficiency takes the following form:

$$\eta_{ef} - (f + f^{prod} + \gamma) \quad (2.16)$$

The specific thermal load on the heaters and the temperature level of the process have a significant influence on the apparatus efficiency. The relationships presented make it possible to determine the optimal conditions for thermal processing that correspond to the maximum energy efficiency [162–164].

2.2. Analysis of the Energy Efficiency of Meat Conductive Frying Processes and Equipment

Under the conditions of the energy crisis, the economies of Ukraine and Kazakhstan have become practically insolvent, caused by insufficient domestic energy resources, the non-competitiveness of domestic goods and products due to high energy consumption and outdated production methods, and the lack of a culture of energy consumption. In Ukrainian and Kazakh food industry enterprises, according to the authors [165], the specific energy consumption for the production of food products is 2–4 times higher than the European average and 3–6 times higher than in France. The authors of [165] suggest introducing at the state level the foundations of an energy strategy for the development of agro-industrial complex (AIC) enterprises, which consist of two main areas: increasing the culture of energy use and creating an energy monitoring system. The result of these two areas should be programs to increase energy efficiency at individual enterprises and in the industry as a whole. The first stage in the work of an energy monitoring center or group, which should be established at AIC enterprises, is an energy audit of specific production sites in order to obtain information on the levels of consumption of all types of resources and to determine the specific energy expenditure for production.

The restaurant industry is part of the AIC and shares all of the sector's drawbacks. One of the most common processes for the thermal treatment of food products in the restaurant industry is the conductive frying of meat products. This process is characterized by high energy consumption, significant losses of raw materials (up to 40%), and high manual labor costs. In most cases, this process is carried out in restaurant enterprises using stove tops with cookware and pans; only some enterprises are equipped with direct-contact grills or dual-sided cooking equipment. This widespread use of stoves is due to their versatility, while pans are popular for their convenience in use and hygiene, as well as a mentality inherited from the Soviet era when energy was cheap.

The technical characteristics of conductive frying devices (Table 2.1) do not reflect their energy efficiency.

Table 2.1

Technical Characteristics of Conductive Frying Equipment

Name of Indicator	SESM-0,2	PE-0,17-01	SEB	GH-VEG-833	Elio L	PUSKU-1
Working surface area, m²	0,2	0,17	0,0314	0,22	0,0612	0,048

Power, kW	6	4	1,5	2,75	1,55	1,4
Time to heat up to operating temperature, min	45	-	-	25	7	8
Duration of the frying cycle, s	-	-	-	-	180	60
Overall dimensions, mm, mm length width height	1050 840 860	500 800 330	350 600 50	550 400 240	260 500 500	345 400 300
Weight, kg	185	50	5	18	15	15,5

Determining energy efficiency under production conditions involves certain difficulties, associated with the lack of appropriate methodologies and devices. The data found in the scientific literature relate only to certain types of equipment and various products subjected to thermal processing.

For the calculation of energy efficiency indicators, data obtained during experimental studies were used.

The results of studies on the utilization factor k_{sa} of the frying surface area and the specific surface power of batch-type conductive frying equipment are presented in Table 2.2.

An analysis of the data in Table 2.2 indicates that the surface area utilization factor for batch conductive frying equipment during the frying of portioned meat semi-finished products does not differ significantly, falling within the range of 0.718–0.792.

Table 2.2

Results of studies on the frying surface utilization factor and specific power in electric conductive frying equipment

Name of Indicator	SESM-0,2	PE-0,17-01	SEB	GH-VEG-833	Elio L	PUSKU-1
bottom area of the stovetop cookware, m²	-	0,168	0,0346	-	-	-
coefficient of area utilization by the stovetop cookware	-	0,988	1,102	-	-	-
product area, m²	0,0088	0,0088	0,0088	0,0088	0,0088	0,0088
number of products on the surface, pcs	18	15	3	19	5	4

total area of products on the surface, m²	0,1584	0,132	0,0264	0,1672	0,044	0,0352
surface area utilization factor k_{sa}	0,792	0,786	0,763	0,76	0,718	0.733
specific surface power, kW/m² - relative to the bottom surface - relative to both surfaces	30,00	23,52	47,77	12,50	25,32	29,16 14,58

The specific surface power of batch-type equipment used for conductive frying varies significantly. The high specific surface power of stovetops used with cookware – 23.52 kW/m² for the PE-0.17-01 and 47.77 kW/m² for the SEB – can be explained by their versatility. The fairly high specific surface power of the SESM-0.2 pan – 30.00 kW/m² - also stems from its inherent versatility based on its intended purpose. In contrast, equipment designed specifically for direct conductive frying has a relatively low specific surface power, ranging from 12.5 kW/m² for the GH-VEG-833 to 12.66 kW/m² for the Elio L, and 14.58 kW/m² for the PUSKU-1.

The results of experimental studies on the conductive frying of meat in the equipment designed for this process are presented in Table 2.3.

As can be seen from Table 2.3, the duration of the frying process τ in the various pieces of equipment differs significantly, ranging from 150 s in the PUSKU-1 device to 720 s in the GH-VEG-833 direct-frying grill. The yield of the finished product also varies considerably—ranging from 0.90 in the PUSKU-1 device to 0.629 in the GH-VEG-833 direct-frying grill. Thus, it can be concluded that the yield of the finished product depends on the frying duration.

Table 2.3

Results of determining the indicators of the frying process for portioned natural meat products in the respective equipment

Name of Indicator	SESM-0,2	PE-0,17	SEB	GH-VEG-833	Elio L	PUSKU-1
1	2	3	4	5	6	7
initial temperature of the products, K	288	288	288	288	288	288
Temperature of the						

products during turning: – in the center, K – in the crust on one side, K – in the crust on the other side, K	333 405 323	333 412 324	333 408 323	333 411 324	-	-
Frying duration before turning, s	300	298	288	530	-	-
Temperature of the products at the end of the process: – in the center, K – in the crust on one side, K – in the crust on the other side, K	353 405 373	353 412 373	353 408 377	353 411 373	353 398 393	353 398 393
Average final temperature of the vertical sections of	373	373	373	373	364,75	364,75

the products at the end of the process, K						
Average volumetric temperature of the products at the end of the process, K	367,1	367,9	367,8	367,5	364,75	364,75
Frying duration after turning, s	200	194	192	370	254 всього	150 всього
Mass of semi-finished products, kg	1,79	1,5	0,3	1,5	0,3	0,4
Mass of finished products, kg	1,234	1,009	0,222	1,183	0,407	0,36
Yield of finished product, kg/kg	0,689	0,673	0,697	0,629	0,81	0,90
Electricity consumption, kWh	0,672	0,547	0,102	0,688	0,109	0,058

Area of the horizontal heat transfer surfaces of the products, m²	0,1584	0,132	0,0264	0,167	-	-
Area of the vertical heat transfer surfaces of the products, m²	0,0684	0,057	0,0114	0,072	0,0190	0,0152
Initial temperature of the fat, K	453	453	453	453	-	-
Maximum temperature of the working surfaces, K	463	623	593	463	423	423
Minimum temperature of the working surfaces, K	413	517	517	389	401	379
Surface area of the fat mirror not covered by the product, m²	0,04	0,036	0,0082	0,053	-	-

Area of vertical heat transfer sections connected to the working surface, m², at a temperature of K	0,38	0,0855	0,0754	0,189	0,0202	0,0038
Area of horizontal heat transfer sections connected to the working surface, m², at a temperature of K	0,0650	0,0171	0,0003	0,004	0,0494	-
Area of vertical cladding sections, m², at a temperature of K	0,65	0,91	0,0576	0,304	0,1554	0,033 333

Area of lower horizontal cladding sections, m², at a temperature of K	0,34	0,4	0,128 298	0,22 298	0,1131 298	0,048 298
Area of horizontal cladding sections, m², at a temperature of K	-	0,23	0,0573 333	-	-	-

The average power during the frying process, the calculated usefully consumed heat, the calculated thermal efficiency, and the specific electricity consumption for preparing 1 kg of finished products using conductive frying equipment are presented in Table 2.4.

As seen from Table 4.4, the highest thermal efficiency values are observed in double-sided frying devices – 0.8839 for the Elio L and 0.9377 for the PUSKU-1. The lowest thermal efficiency values are found in the SEB stovetop with a Tefal pan and the SESM-0.2 pan (0.7039 and 0.7205, respectively), which can be explained by the presence of large heat-loss surfaces heated to relatively high temperatures (open lid, pan walls, flanged edges, etc.). Among the appliances using conventional frying methods, the highest efficiency – 0.8430 - is shown by the GH-VEG-833 direct-contact grill by Gastrorag.

Table 2.4

Results of determining the thermal efficiency of the process, average power during the process, and specific electricity consumption

Name of Indicator	SESM-0,2	PE-0,17-01	SEB	GH-VEG-833	Elio L	PUSKU-1
electricity consumption for the frying process, kWh	0,672	0,547	0,102	0,688	0,109	0,058
average power of heating elements during the process, W	4838	4000	864	2750	1549	1392
usefully utilized heat, J	1743129,92	1520962	258477,6	2087968,4	346858,04	195808

thermal efficiency, η_t	0,7205	0,7724	0,7039	0,8430	0,8839	0,9377
specific electricity consumption, b_e, kWh/kg	0,5446	0,5421	0,4595	0,5816	0,2678	0,1611

According to the experimental data obtained, the average power during the frying process is lower than the rated power in the following devices: the SESM-0.2 pan (4838.4 W versus 6000 W) and the SEB stovetop with an infrared burner (864 W versus 1500 W).

This is due to the periodic switching on and off of the heating elements using a thermostat or temperature relay, which indicates that the rated power of the heating elements is sufficient to compensate for both the usefully utilized heat and the heat losses to the environment.

The low thermal efficiency of 0.7205 for the SESM-0.2 pan indicates that it is not advisable to use it for frying portioned meat semi-finished products. In the PE-0.17-01 stovetop, the average process power matches the power of the heating elements (4000 W versus 4000 W), but the relatively low thermal efficiency of 0.7724 indicates significant heat losses to the environment through the surfaces of the burner, the functional container, the loose contact between the bottom of the container and the burner, as well as the considerable thermal resistance to heat transfer between the heating surface and the product being cooked.

The GH-VEG-833 device demonstrates relatively high thermal efficiency – 0.8430. The average process power corresponds to the rated power (1550 W versus 1550 W), but the extremely long frying duration – 720 s – and the low yield of the finished product – 0.629 – indicate insufficient power of the heating elements. This leads to extended frying time and, in fact, evaporation of moisture from the products at a relatively low surface temperature.

In the Elio L and PUSKU-1 devices, the average power during the process matches the rated power (1550 W and 1392 W versus 1550 W and 1400 W, respectively). However, the discrepancy between the declared frying cycle duration (Table 2.1) and the actual duration (Table 2.3) also points to insufficient power of the electric heating elements.

The actual thermal efficiency values under real operating conditions for the devices considered are even lower, due to additional energy losses during loading of the semi-finished products, unloading of the finished products, and cleaning of the frying surfaces from burnt residues. This is especially true for stovetops, which, in addition to the mentioned losses, also lose heat through the burner surface due to the low surface area utilization coefficient by the cookware (no more than 0.6…0.7).

The lowest specific electricity consumption is shown by the PUSKU-1 and Elio L devices (0.1611 and 0.2678 kWh/kg, respectively), while the highest is seen in the GH-VEG-833 direct-contact grill (0.5816 kWh/kg), although it has the highest thermal efficiency (0.8430) among the appliances using the conventional frying method. Among these conventional frying devices, the SEB stovetop with a Tefal pan has the lowest specific electricity consumption (0.4595 kWh/kg). The specific electricity consumption of the SESM-0.2 pan and the PE-0.17-01 stovetop with GN-1/1 functional container are nearly the same (0.5446 kWh/kg versus 0.5421 kWh/kg). The specific electricity consumption of the PUSKU-1 device is 2.85 to 3.61 times lower than that of conventional frying appliances and 1.66 times lower than that of the Elio L double-sided fryer.

The results of the organoleptic evaluation of the finished products after thermal processing in electric conductive frying devices of batch operation, rated on a five-point scale, are presented in Table 2.5.

Table 2.5

Results of the organoleptic evaluation of finished products after thermal processing

Name of Indicator	Number of points awarded to finished products after thermal processing in the appliances					
	SESM-0,2	PE-0,17-01	SEB	GH-VEG-	Elio L	PUSKU-1
Appearance	4	3	3	4	4	4
Color	4	3	3	3	5	5
Aroma	4	3	3	4	5	5
Taste	4	3	3	3	5	5
Texture (Consistency)	3	3	3	3	4	5
Average score	3,8	3	3	3,4	4,6	4,8

As shown by the data in Table 2.5, the appearance and color of the finished products were the poorest after frying in the PE-0.17 and SEB appliances: the product surfaces were significantly deformed, burnt, and the taste resembled that of charred meat. This can be explained by the elevated crust temperatures – 412 K and 411 K, respectively – due to the lack of temperature control during the process. The texture was tough and dry.

The finished products after frying in the GH-VEG-833 appliance also had a tough and dry consistency due to the low yield of the finished product. The best organoleptic characteristics were observed in the products fried using the Elio L and PUSKU-1 devices, although the upper and lower crusts differed in color due to varying final temperatures.

The results of the calculation of the relative exergy losses due to irreversible heat exchange β (loss of work capacity), determined by formula (2.3); the thermal efficiency η_t from Table 2.4; the process efficiency coefficient η_{ef} calculated using formula (2.15); and the energy efficiency η_{en} of the appliances, calculated using formula (1.2), are summarized in Table 2.6.

Table 2.6

Values of thermal efficiency η_t, process efficiency coefficient η_{ef}, and energy efficiency η_{en} of appliances for conducting meat conductive frying

Name of Indicator	SESM-0,2	PE-0,17	SEB	GH-VEG-833	Elio L	PUSKU-1
B	0,2922	0,4445	0,4285	0,2710	0,2266	0,1756
η_t	0,7212	0,7718	0,7832	0,8434	0,8861	0,9378
η_{ef}	0,7078	0,5555	0,5715	0,7290	0,7734	0,8244
η_{en}	0,5105	0,4287	0,4476	0,6148	0,6854	0,7731

As seen from Table 2.6, the values of the process efficiency coefficient η_{ef} for various batch-type appliances used for conductive meat frying differ significantly from the values of thermal efficiency η_t. A more advanced direct-contact grill (GH-VEG-833), which has a thermal efficiency of η_t = 0,8434 based on the first law of thermodynamics, shows a process efficiency coefficient nearly equal to that of the SESM-0.2 pan (η_t = 0,7212) when evaluated from the perspective of the second law of thermodynamics (η_{ef}= 0,7290 vs. η_{ef} = 0,7078). The lowest efficiency coefficients were observed for stovetops with cookware: η_{ef}= 0,5555 for the PE-0.17 and η_{ef}= 0,5715 for the SEB. In contrast, significantly higher efficiency coefficients were recorded for the double-sided frying appliances Elio L and PUSKU-1, with η_{ef}= 0,7734 and η_{ef}=0,8244, respectively.

The data in Table 2.6 indicate that lowering the temperature level of the frying process, from the standpoint of the second law of thermodynamics, leads to an increase in the thermodynamic perfection of the process.

The energy efficiency (η_{en}=0,7731) of the PUSKU-1 double-sided frying device (0.7731) is higher than that of the Elio L double-sided fryer (η_{en}=0,6854), the GH-VEG-833 direct-contact grill, the SEB stovetop with a Tefal pan, the PE-0.17-01 stovetop with GN-1/1 functional container, and the SESM-0.2 pan by 8.77%, 15.83%, 32.55%, 34.44%, and 26.26%, respectively.

Interestingly, the less efficient SESM-0.2 pan in terms of the first law of thermodynamics (η_t=0,7212) demonstrates an energy efficiency that is 8.18% and 6.29% higher than the more thermodynamically efficient PE-0.17-01 (η_t=0,7718) and SEB (η_t=0,7832) stovetops, respectively. This suggests that the most effective frying process occurs in equipment with double-sided heat input under conditions of axial compression.

Exergy losses to the environment through the surface of the appliances (∇E_f) were calculated using formula (2.5); exergy losses to the environment through the product surface during frying (∇E_f^{prod}) using formula (2.8); and exergy losses from heating the liquid migrating from the product and turning into steam lost to the environment (∇E_γ) using formula (2.11). Based on the obtained data, the relative exergy losses f, f^{prod} and γ were determined using formulas (2.6), (2.9), and (2.12), respectively. The results of calculating the relative exergy losses and the exergetic efficiency η_{ex} of the conductive frying process in the respective appliances, according to formula (2.16), are presented in Table 2.7.

Table 2.7

Results of the calculation of relative exergy losses by components and the exergetic efficiency values of appliances for conductive meat frying

Name of Indicator	SESM-0,2	PE-0,17	SEB	GH-VEG-833	Elio L	PUSKU-1
β	0,292	0,445	0,429	0,271	0,227	0,176
f	0,081	0,031	0,095	0,069	0,031	0,004
f^{prod}	0,006	0,006	0,006	0,011	0,0004	0,00008
γ	0,128	0,139	0,138	0,157	0,135	0,106
η_{ex}	0,493	0,379	0,332	0,492	0,607	0,714

As shown in Table 2.7, the largest share in the structure of relative exergy losses is accounted for by the relative losses due to irreversible heat exchange (loss of work capacity), heating of liquid migrating from the product during frying and turning into steam lost to the environment, and losses to the environment through the heat-radiating surfaces of the appliance. Reducing these specific losses would lead to improved energy efficiency of the equipment.

The data in Table 2.7 indicate that the smallest relative exergy loss to the environment through the appliance surface is f=0,004 for the PUSKU-1 device, while the largest is f=0,095 and f=0,081 for the SEB stovetop with a Tefal pan and the SESM-0.2 pan, respectively. This is explained by the presence of surfaces heated nearly to the frying process temperature that contribute to heat loss (vertical walls of the pan, flanges, etc.). The greatest relative exergy losses to the environment through the product surface during f^{prod}=0,006 are observed for the SEB stovetop with Tefal pan and the PE-0.17-01 unit with GN1/1 functional container. This is due to significant overheating of the product surface during conventional frying, caused by the absence of process temperature control.

Very low values of relative exergy loss through the product surface during f^{prod}=0,00008 and f^{prod}=0,0004f – were recorded for the PUSKU-1 and Elio L units, respectively. This is due to the much smaller product surface area exposed to the environment, as a result of double-sided heat input and short process duration – 150 s and 254 s, respectively. The smallest specific exergy loss for heating liquid migrating from the product and turning into steam lost to the environment is γ=0,106 for the PUSKU-1 device, while the largest is γ=0,157 for the GH-VEG-833 grill. This is explained by the high yield of finished product – 0.9 – in the PUSKU-1, and the much lower yield – 0.629 – in the GH-VEG-833. The significant difference in product yield – 27.1% - and relatively small difference in relative exergy losses from migrating moisture – 5.02% - indicate that evaporation of liquid is the most energy-intensive component of the frying process.

Increasing the yield of the finished product is primarily achieved by reducing liquid losses (mainly in the form of vapor), which in turn reduces energy consumption for the frying process.

For the above reasons, the highest exergetic efficiency of the frying process, η_{ex}=0,714, is achieved by the double-sided compression fryer PUSKU-1, while the lowest values – η_{ex}=0,332 and η_{ex}=0,379 – are found in the SEB stovetop with Tefal pan and the PE-0.17-01 with GN1/1 functional container, respectively. The specific exergy losses per 1 kg of finished product $\Delta E_{\beta_{sp}}$, $\Delta E_{f_{sp}}$, $\nabla E_{f_i}^{prod}$, $\nabla E_{\gamma_{sp}}$ – were calculated using formulas (2.4), (2.7), (2.10), and (2.13). The results of the calculations of specific exergy losses per 1 kg of finished product by component for the frying process in the respective appliances are presented in Table 2.8.

Table 2.8

Results of the calculation of specific exergy losses per 1 kg of finished product (J/kg) by components for batch-type appliances used for implementing conductive meat frying

Name of Indicator	SESM-0,2	PE-0,17	SEB	GH-VEG-833	Elio L	PUSKU-1
$\Delta E_{\beta_{sp}} \cdot 10^{-3}$	572,76	867,54	708,75	567,45	218,43	101,84
$\nabla E_{f_{sp}} \cdot 10^{-3}$	157,99	60,39	157,81	143,84	29,52	2,52
$\nabla E_{f_i}^{prod} \cdot 10^{-3}$	11,12	11,89	8,69	23,90	0,40	0,05
$\nabla E_{\gamma_{sp}} \cdot 10^{-3}$	250,95	270,42	227,77	327,97	130,26	61,74
$\nabla E_{sp} \cdot 10^{-3}$	1960,45	1951,64	1654,05	2093,66	964,13	580,00

As seen from Table 2.8, the specific exergy loss per 1 kg of finished product due to irreversible heat exchange in the PUSKU-1 device is $\Delta E_{\beta_{sp}}$=101,84·10^3 J/kg, which is 2.14 to 8.52 times lower than in the Elio L, GH-VEG-833, SESM-0.2, SEB, and PE-0.17-01 units. The SESM-0.2 pan shows practically the same level as the GH-VEG-833 grill (572.76 × 10^3 J/kg vs. 567.45 × 10^3 J/kg). The highest value is observed in the PE-0.17-01 with GN1/1 container – 867.54 × 10^3 J/kg. Raising the temperature level of the frying process due to the use of components with high thermal resistance (such as stainless-steel containers, stovetop cookware, and fat layers on surfaces) leads to an increase in specific exergy losses per 1 kg of finished product due to irreversible heat exchange.

The specific exergy loss per 1 kg of finished product to the environment through the surfaces of the appliance in the PUSKU-1 device is $\nabla E_{f_{\text{пит}}}$= 2,52·$10^3$ J/kg, which is 11.72 to 62.70 times lower than in the Elio L, PE-0.17-01, GH-VEG-833, SEB, and SESM-0.2 devices. The highest values are observed in the SESM-0.2 pan and the SEB stovetop with a Tefal pan—157.99 × 10^3 J/kg and 157.81 × 10^3 J/kg, respectively. This, as mentioned earlier, is due to the presence of surfaces heated almost to frying process temperature (vertical sections of the pan, flanges, etc.) that contribute to heat loss.

The specific exergy loss per 1 kg of finished product to the environment through the product surface during frying in the PUSKU-1 is $\nabla E_{f_i}^{prod}$ = $0{,}05 \cdot 10^3$ J/kg, which is 8.56 to 511.72 times lower than in the Elio L, SEB, SESM-0.2, PE-0.17-01, and GH-VEG-833 appliances. The GH-VEG-833 direct-contact grill shows the highest value – 23.90×10^3 J/kg - due to the longest frying duration (900 s). The minimal specific exergy losses in the PUSKU-1 and Elio L appliances are explained, as previously noted, by the significantly smaller product surface exposed to the environment, thanks to double-sided heat input and the short process duration.

The specific exergy loss per 1 kg of finished product due to heating the liquid migrating from the product and turning into steam lost to the environment in the PUSKU-1 appliance is $\nabla E_{\gamma_{sp}}$=$61{,}74 \cdot 10^3$ J/kg, which is 2.11 to 5.31 times lower than in the Elio L, SEB, SESM-0.2, PE-0.17-01, and GH-VEG-833 devices. The highest value is observed in the GH-VEG-833 direct-contact grill – 327.97×10^3 J/kg—due to the longest process duration (900 s), caused by insufficient power of the electric heating elements.

The results of the evaluation and analysis of energy efficiency indicators for the conductive frying processes of meat in the respective appliances allow us to state the following:

- the duration of the conductive frying process, the yield of portioned natural meat products, and the specific electricity consumption significantly depend on the specific surface power of the frying surfaces. Insufficient specific surface power leads to longer frying times, reduced product yield, lower thermal, exergetic, and energy efficiency, and increased specific electricity consumption;

- in direct-contact grills, particularly the GH-VEG-833 grill by "Gastrorag", due to the low yield of the finished product, long process duration, and high specific electricity consumption, the existing specific surface power needs to be significantly increased;

- in appliances for double-sided frying, including those operating under compression, the current specific surface power also requires a significant increase;

- the use of frying pans for conducting the process of conductive frying of portioned natural meat semi-finished products in foodservice enterprises is not advisable due to high specific electricity consumption and low thermal, exergetic, and energy efficiency;

- conductive frying of portioned natural meat semi-finished products in appliances that lack temperature control during the process—i.e., stovetops—is not advisable due to significant overheating of product surfaces, resulting in the formation of endogenous carcinogenic substances (heterocyclic amines, HA), as well as due to high specific exergy and electricity consumption and low thermal, exergetic, and energy efficiency;

- conductive frying of portioned natural meat semi-finished products is most advisable in appliances for double-sided frying under compression—such as the PUSKU-1—because of the lowest specific exergy and electricity losses (0.1611 kWh/kg);
- regulating the frying surface temperature in double-sided appliances—particularly under compression—only by the bottom surface leads to overheating of the top frying surface and, as a result, uneven doneness of the product's top and bottom surfaces;
- the design of double-sided frying appliances, including those operating under compression, needs improvement by adding separate thermostats or a dual-position electronic thermostat to regulate the temperature of both the top and bottom surfaces.

Based on all the above, the following recommendations can be made for foodservice establishments to implement the conductive frying process:

- equip enterprises with double-sided frying appliances, prioritizing those operating under compression (contact grills);
- avoid using electric stovetops with cookware, frying pans, and direct-contact frying surfaces;
- implement a set of organizational measures to improve overall energy consumption culture by

raising staff qualifications and enforcing strict control to ensure the frying process is carried out only in the recommended appliances.

When developing new or improving existing equipment for conductive frying, the following guidelines should be followed:

- minimize the temperature level of the process (not exceeding 423 K), which, in addition to increasing energy efficiency, will effectively eliminate the formation of harmful endogenous substances in the finished product—such as heterocyclic amines (HA);
- enhance the heat exchange surface area with the product by implementing double-sided heat input and, where applicable, use physical or electro-physical methods to improve process efficiency (compression, electric current, etc.), which will reduce heat loss through the product surface and shorten frying time;
- minimize the number and surface area of structural components heated to frying process temperatures;
- to increase product yield and reduce moisture and vapor losses, use functionally enclosed volumes. These can be created by adding flanges to the heating surfaces made from materials with high thermal resistance or by using functionally enclosed containers made from materials with minimal resistance to heat transfer to the product.

According to the analysis of energy efficiency [164, 166], the most energy-efficient method of thermal processing of meat is the use of double-sided frying appliances under compression. The reasons for their high energy efficiency are as follows.

Double-sided heat input during the conductive frying process increases the heat exchange surface area by at least 2 times. In addition, the degree of contact pressure between the meat and the heat exchange surfaces affects the thermal resistance of heat transfer: greater pressure reduces thermal resistance. Thus, the efficiency of heat transfer from the heated surface to the product can be enhanced through compression of the meat raw material.

During double-sided heat input under compression, the meat semi-finished product is compacted; steam, gases, and air along with moisture are expelled toward the frying surfaces into the surface layers of the meat, thereby increasing its overall thermal conductivity – that is, its thermophysical properties are altered.

Analysis of the energy efficiency of the processes and equipment for conductive meat frying [164] has shown that increasing the temperature level of the process on the one hand intensifies it, but on the other hand reduces the energy efficiency of the process and the equipment due to increased exergy losses from irreversible heat exchange.

From a technological point of view, increasing the temperature level of the process above 423 K leads to the formation of carcinogenic compounds -

heterocyclic amines (HA) – in the crusts of meat products [36–41].

Due to the aforementioned reasons, in order to prevent the formation of heterocyclic amines (HA) during the organization of the conductive frying process for meat products, it is necessary to adhere to the previously formulated technological requirements.

These technological requirements essentially align with the directions for improving energy efficiency and resource conservation in the conductive frying process, as justified by the conclusions from the analysis of the energy efficiency of conductive frying processes and equipment [164]. They can be summarized as follows:

– reducing moisture loss during frying, which will lead to a decrease in the amount of heat required for evaporation of liquid from the product and an increase in the yield of the finished product;

– lowering the temperature level of the process, which will reduce heat losses to the environment and, as a result, decrease the specific energy consumption for the frying process;

– reducing the duration of the process at a low temperature level, which will decrease specific energy losses and increase the yield of the finished product;

– minimizing the number of surfaces heated to frying temperature in the equipment, thereby reducing the specific energy consumption;

– reducing the number of product turnovers during frying, which will help reduce heat loss to the environment through the product surface [167].

These directions for improving the energy efficiency of the conductive frying process are effectively implemented in the double-sided compression frying appliance PUSKU-1 [90]. However, both the frying method and the appliance itself have significant drawbacks.

Driving moisture into the surface layer of the product for the majority of the frying process to prevent HA formation can be achieved not only by compression as described by the author [90], but also by using electrokinetic phenomena during double-sided heat input. This approach would eliminate the need to determine the optimal compression pressure for each type of semi-finished product, significantly simplify the design of the appliance for double-sided meat frying, and make its operation easier.

Meat with high collagen content (HCCT) could serve as an alternative to imported raw materials for conductive frying. When frying HCCT meat, the previously formulated technological requirements must also be followed. These requirements can be implemented through double-sided heat input under compression in a functionally sealed volume (FSV). FSV would help reduce steam and heat losses to the environment. Moreover, the vertical surfaces of the products would no longer be heat-releasing but rather become heat-absorbing, taking in heat from the moist saturated steam formed in the surface layer of the product.

2.3. Factors for Intensifying the Conductive Frying Process of Meat

The analysis of the processes occurring during conductive frying of meat, aimed at preventing the formation and accumulation of heterocyclic amines (HA) in the finished products, allows us to formulate, as additions or clarifications to existing recommendations [13, 17], the following technological requirements:

- the temperature of the frying surfaces should not exceed 423 k;
- the frying process duration should be minimized;
- the number of product flips during frying should be minimal;
- the surface layer of the product should retain moisture as long as possible and have minimal contact with fat [167].

An analysis of the feasibility of conductive frying of HCCT (high collagen connective tissue) meat allows us to formulate the following technological requirements:

- ensure the closest possible contact between the product surface and the heating surface;

– avoid deformation of the product surface during frying;

– maximize retention of native meat moisture during frying, which is sufficient for collagen denaturation and disaggregation;

– eliminate the need to flip the product during thermal processing;

– prevent the formation of product surfaces that release heat into the environment;

– avoid conditions conducive to the formation of HA [167].

The implementation of these technological requirements will allow for an expanded resource base for the conductive frying process, the production of safe finished products for human consumption, and a reduction in production costs.

To expand the resource base, we propose using HCCT meat in double-sided frying processes under compression in functionally sealed volumes (FSV). To improve energy efficiency, increase the yield of finished products, and significantly simplify the design of double-sided meat frying equipment under compression, we propose the use of electric current [167].

One of the most important parameters of heat exchange processes, which are unsteady thermal processes, is their rate. To further improve the frying processes of meat products, it is necessary to determine and compare the significance of key factors influencing the rate of heat transfer from the heating surface to the product center and the time required to achieve culinary readiness. These include:

- size and mass of the product being heated;
- method of heat input to the product surface;
- quality of contact between the product and the heating surface;
- pressure applied to the product during heating (contact force during thermal treatment), etc.

Based on the above, a scientific problem emerges, the essence of which lies in the low energy and resource efficiency of the conductive meat frying processes in existing appliances.

The intensity of heat exchange during frying depends on the shape, size, and physical properties of the product being heated, as well as the temperature and physical properties of the heating surface (or medium).

Semi-finished products subjected to thermal treatment have a specific mass and geometric dimensions. For a given mass, the geometric dimensions (b – width, l – length, δ_m – height or thickness) can be varied within certain limits. There is practical interest in studying the effect of the surface-to-volume ratio S_m/V_m at a given mass on the duration required to heat the product to a target temperature.

According to the Newton-Richmann equation, under otherwise equal heat exchange conditions, in order to reduce the time required to heat a semi-finished product to a given temperature, it is necessary to maximize its heating surface area SmS_mSm. This can be achieved by altering the proportions of the product's dimensions and applying heat to the entire or most of its surface.

If the height (thickness) of the semi-finished product δ_m is halved, the heating surface (assuming bottom-only heating) becomes $S_m = 2 \cdot b \cdot l$, and for double-sided heating (top and bottom), it becomes $S_m = 4 \cdot b \cdot l$.

Analysis shows that the standard dimensions of semi-finished meat products used in culinary production provide either a minimal or nearly minimal S_m/V_m ratio. This leads to a reduction in process speed and an increase in thermal processing time under otherwise equal conditions.

In conclusion, increasing the heat-receiving surface area of the semi-finished product by reducing its height (thickness) while maintaining volume can accelerate the thermal processing and reduce its duration. However, it is important to consider that excessive reduction in thickness and increase in surface area may lead to greater moisture loss and lower finished product yield [90, 168].

Thus, one way to intensify the frying process is to increase the contact surface area between the semi-finished product and the frying surface. The use of double-sided frying can at least halve the process duration due to heat input from both sides, proving its greater efficiency compared to single-sided heat input. However, it does not fully resolve the issue of efficient heat transfer from the heating surface to the product.

When frying directly on a heated surface without fat under ideal contact conditions, heat is transferred solely by conduction. However, achieving ideal contact when frying meat on an open surface is practically impossible. Additionally, during heating, thermal deformation of the meat reduces the contact area with the heating surface and causes the formation of air or steam-air gaps, which increase thermal resistance in the heat transfer zone [169].

Therefore, one of the ways to reduce the thermal processing time is to ensure effective contact between the heated product and the heating surface.

Heat exchange through the contact surface is described by Fourier's law of heat conduction for bodies 1 and 2 (see Figure 2).

$$dQ = -\lambda_1 \cdot \frac{dT_1}{dx} \cdot df \cdot d\tau = -\lambda_2 \cdot \frac{dT_2}{dx} df \cdot d\tau, \text{ J.}$$

If within the plane area df the contact between the two bodies is ideal, then at this location $T_1 = T_2$, and the temperature distribution curve is continuous (Fig. 2a). The temperature gradient is determined only by the internal thermal resistance of the bodies transferring and receiving heat: when $\lambda_1 > \lambda_2$, the slope of temperature curve AK will be steeper than that of curve KB.

In areas where actual contact is absent, air or steam–air gaps are formed. The thermal conductivity of the medium filling these gaps is significantly lower than that of the product and the heating surface in contact. As a result, thermal contact resistance arises. Depending on the number of such gaps, the contact resistance can significantly increase the total thermal resistance of the heat transfer system.

Due to the small thickness of the contact break zones, the temperature distribution in them can be represented by straight lines AK and BD, with a temperature jump at the contact plane (Fig. 2a).

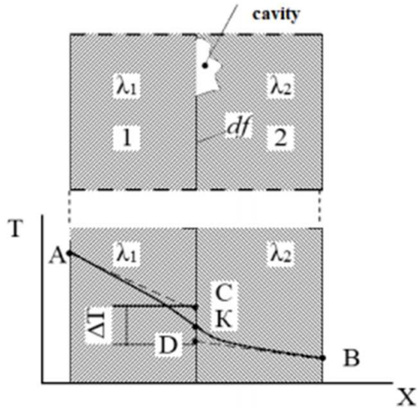
The magnitude of this jump is determined by the thermal contact resistance $R_к$:

$$\Delta T_к = q \cdot R_к, \text{ K},$$

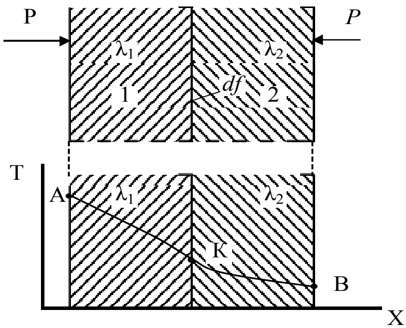
where q – heat flux through the contact plane, W/m².

The total thermal resistance of the system is determined by two components – the thermal resistance of direct contact zones (where no gaps exist) R_{dc}, and the thermal resistance of the medium R_{env} in the gap zones:

$$\frac{1}{R_k} = \frac{1}{R_{dc}} + \frac{1}{R_{env}}, \text{ W/(m}^2\cdot\text{K)}.$$



a



b

Fig. 2. Temperature distribution pattern during thermal contact between the heating surface (1) and the product (2) being heated during the frying process:
a – without pressure applied to the product;
b – with compression force P applied to the product

Thermal resistance of the system can be reduced by pressing the product against the heating surface using an external force *P*. In this case, some air gaps may be eliminated or reduced, thereby minimizing R_c to the lowest possible value under the applied pressure. As a result, the temperature distribution curve becomes nearly continuous and takes the form shown in Fig. 2b.

The reduction of thermal resistance and the increase in contact area between the product and the heating surface partially explain the significant decrease in frying time when the product is compressed against the surface.

Thermal treatment time can be reduced by applying pressure to the product during frying to ensure ideal contact with the heating surface.

However, the approaches discussed above for intensifying the thermal treatment of meat ultimately reduce to increasing the heat exchange surface of the product and the heating surface (or medium), i.e., intensifying heat input to the product surface, but they do not influence the internal heat transfer processes within the product. It is well known [22, 170–173] that during all types of frying, conductive heat transfer within the product dominates over other modes of heat exchange, and it is the determining factor in the heating rate and the time required for the product to reach the desired temperature.

Heat transfer inside the meat during thermal treatment is complex. This is due to the fact that during frying, mass transfer processes also occur within the product. The speed of these processes depends on the product's properties, shape, dimensions, temperature, and other factors [173, 174].

Heat and mass transfer within the product are interrelated and act simultaneously, influencing each other and affecting the overall rate of the process.

Heating leads to both quantitative and qualitative changes in the physicochemical properties of meat. One sign of this is deformation. The stresses arising during deformation of the meat—particularly those associated with structural changes in muscle proteins and collagen—affect moisture distribution within the product and, as a result, lead to moisture being squeezed out along with dissolved substances into the surrounding environment. This also alters the thermal conductivity of the product being heated [175].

A significant advantage of thermal processing under external pressure is the ability to influence the structural and mechanical properties of the product, and thereby its thermophysical and mass transfer characteristics in the desired direction.

The thermophysical characteristics of meat products are affected by their physical parameters (density and temperature) and technological parameters (moisture and fat content). These parameters change under the influence of external pressure applied during heating, and therefore it can be assumed that the thermophysical characteristics also change under pressure [175].

The influence of pressure on the heat exchange process is explained by its effect on mass transfer, and in colloid-capillary-porous bodies, heat distribution is directly linked to moisture transport. These two processes occur simultaneously and interact with each other. Their ratio determines the numerical values of thermophysical properties and, consequently, the intensity of internal heat transfer and the time required for the product to reach the target temperature [176, 177].

During high-intensity thermal processes, the rate of steam generation exceeds the rate of its relaxation, which causes a rise in pressure and, accordingly, a slight increase in temperature. If a pressure gradient is created within the product, moisture may move through the material due to this gradient [24].

Analytical study of heat distribution processes is based on approximate solutions of the heat conduction equation – namely Fourier's law – which establishes a direct proportional relationship between heat flux density and the temperature gradient [176].

$$\bar{q} = -\lambda gradT, \qquad (2.17)$$

where $\bar{q}$ – heat flux density in the direction normal to the isothermal surface, directed toward decreasing temperature, W/m²; λ – thermal conductivity coefficient, W/(m·K); $gradT$ – temperature gradient, characterized by the change in temperature T per unit distance between isothermal surfaces along the normal in the direction of decreasing temperature, K/m.

The nature and rate of heat propagation during the thermal treatment of meat and meat products are determined by their thermophysical properties (specific heat capacity, thermal conductivity, and thermal diffusivity).

For the meat frying process, the main goal is to reach a specified temperature at the center of the finished product. A rational process in this case is one in which the target temperature in the center is achieved in the shortest possible time while complying with technological requirements.

The rate of heat propagation in meat is determined by the following formula:

$$\omega = \sqrt{\frac{\lambda}{c \cdot \rho \cdot \tau_{\mathrm{p}}}} = \sqrt{\frac{a}{\tau_{\mathrm{p}}}}, \mathrm{m/s}, \qquad (2.18)$$

The properties of meat, according to this formula, indicate a fairly high resistance to heat propagation. For meat products, the thermal conductivity coefficient is on the order of 10^{-1} W/(m·K). A characteristic feature of meat products is that the value of the thermal conductivity coefficient may vary depending on the direction (for example, along versus across the muscle fibers) [177].

The thermal diffusivity coefficient can be considered as a characteristic of the product that depends on its specific heat capacity, thermal conductivity, and density, or as a parameter determined experimentally. In the latter case, it equals the amount of heat transferred per unit time through a unit surface area under a gradient of internal energy [178].

$$a = \frac{Q}{\frac{\partial A}{\partial x} F\tau} = \frac{\lambda}{c\rho}, \text{ m}^2/\text{s}, \qquad (2.19)$$

where A – volumetric concentration of internal energy (enthalpy), J/m³.

Since meat contains up to 75% water, its thermal conductivity is close to that of water. Therefore, as temperature increases, thermal conductivity also increases, in most cases following a linear relationship. Water and products with higher water content have greater thermal conductivity than those with high fat content. The thermal conductivity coefficient is determined using Fourier's equation:

$$\lambda = -\frac{Q}{\frac{dT}{dx} \cdot F\tau}, \text{ W/(m·K)}, \qquad (2.20)$$

where Q – amount of heat, J; F – cross-sectional area through which heat is transferred, m^2; τ – duration of the process, s;

$\frac{dT}{dx}$ – temperature gradient, K/m.

Specific heat capacity varies within a narrower range than the thermal conductivity coefficient.

The description of thermal treatment processes can be generally expressed as [172, 178]:

$$\Theta = f(\xi; Bi; Fo), \qquad (2.21)$$

where Θ – dimensionless temperature of the product,

$$\Theta = \frac{T-T_0}{T_{av}-T}; \qquad (2.21a)$$

ξ -dimensionless coordinate, $\zeta = {}^{x}/_{\delta_m}$; (2.21b)

Bi – Biot number, $Bi = \alpha \cdot \delta_m/\lambda$; (2.21c)

Fo-Fourier number, $Fo = {}^{a \cdot \tau}/_{\delta_m{}^2}$. (2.21d)

The amount of heat Q_1 supplied to the product surface and the amount of heat Q_2 transferred from the surface to the center of the product are calculated using the following formulas [172]:

$$Q_1 = \alpha[T_1(Fo) - T_{sur}], \qquad (2.22)$$

$$Q_2 = \frac{\lambda}{\delta_м}[T_{sur} - T_c(Fo)], \qquad (2.23)$$

where T_1 – temperature of the heating surface (medium), K; T_{sur} – temperature of the product surface; T_c – temperature at the center of the product, K.

To maintain the product surface temperature at a given level, the condition $Q_1 = Q_2$, must be satisfied. Then:

$$T_1(Fo) = T_{sur} + \frac{1}{Bi}[T_{sur} - T_c(Fo)]. \qquad (2.24)$$

The duration of the first stage Fo^I, defined as the time at which the product surface reaches the allowable temperature T^*, is calculated by the formula:

$$Fo^I = \frac{Bi+3}{3Bi} ln\left(\frac{2\cdot(T_{sur}-T_0)}{(\mathrm{Bi}+2)\cdot(T_{sur}-T^*)}\right) + Fo^v. \quad (2.25)$$

During the second stage, the surface temperature of the product remains constant at T^*, and the duration is determined by the time it takes for the center of the product to reach the target temperature T_c:

$$Fo^{II} = \frac{1}{b} ln\left(\frac{Bi\cdot(T_{sur}-T^*)}{2\cdot(T^*-T_c)}\right) + Fo^v, \quad (2.26)$$

where b – coefficient; for a flat plate, b=3 [178].

The duration of the process at a known Fourier number *Fo* is calculated using the formula:

$$\tau_0 = \frac{Fo\cdot{\delta_m}^2}{a}, \quad (2.27)$$

2.4. Analytical Model of the Conductive Meat Frying Process Under the Influence of Physical and Electrophysical Methods

To expand the resource base, we propose the use of meat with a high content of connective tissue (HCCT) in the process of double-sided frying in functionally sealed chambers under axial compression. To increase energy efficiency, improve the yield of the finished product, and significantly simplify the design of devices for double-sided meat frying under compression, the use of electric current is proposed [167, 173].

Factors contributing to the intensification of the conductive frying process include increasing the contact surface area between the semi-finished product and the heating surface by ensuring effective contact and, as a result, increasing the heat transfer coefficient from the heating surface to the product. Another is the change in thermophysical properties of the product during frying through the application of physical (pressure) and electrophysical (electric current, pressure) methods.

The goal of these intensification factors is to create in the meat, of total thickness δ_m, an effective layer of reduced thickness δ_{ef}, which has the thermal conductivity characteristics of liquid (meat juice). Achieving this effective layer δ_{ef} during double-sided frying is possible by compressing the meat between the heating surfaces with sufficient force to generate excess steam pressure in the surface layers of the meat at the critical limit p_{lim}, where the capillaries and pores of the meat are filled with liquid, or by generating a substance flow defined by: $J_s = V_s/(S_m \cdot \tau)$, where V_s – volume of substance transported through the meat cross-section S_m per unit time τ, under the influence of alternating current.

According to sources [122–144], in capillary-porous bodies, the application of a potential difference generates a flow of matter, the magnitude of which depends on the physicochemical properties of the material. The use of alternating current during double-sided frying, under conditions that create an internal substance flow J_s and hence an effective layer δ_{ef} , makes it possible to significantly reduce processing time (according to formula 2.27) and increase the product yield. Under these conditions, steam generated in each crust as a result of thermal input from the heating elements Q begins to act as an intermediate heat carrier: initially, water evaporates from the meniscus surfaces in capillaries, generating excess vapor pressure due to compression force; then it condenses on other meniscus surfaces, forming an effective heat transfer layer within the meat that is thinner than the full product thickness (see Fig. 3). The thermal conductivity of this effective layer is significantly higher than that of meat and is approximately equal to that of meat juice.

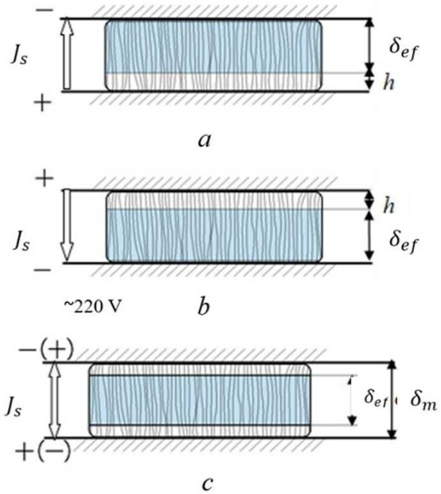


Fig. 3. Diagram of effective meat thickness formation during double-sided frying under the influence of electric current:
a, *b* – movement of liquid depending on current polarity; *c* – comparison of effective thickness with actual meat thickness δ_{ef} with actual meat thickness δ_m

Under combined exposure to the heat flow from the heater and the electric current, the volume of the dehydrated layer on the heating surface side increases by an amount V_p. This volume consists of the cavities filled with steam in each capillary of the meat sample, that is:

$$V_p = \sum_{i=1}^{i=n} \left(\frac{\pi \cdot d_i^{\,2}}{4} \cdot h_i + \frac{\pi \cdot d_i^{\,3}}{12} \right), \text{ m}^3,$$

Knowing the distribution law of capillaries and pores, the porosity of the body, and their proportion, the height h_i [179, 180] as follows:

$$h_i = \frac{V_\text{p} - \sum_{i=1}^{i-n} \frac{\pi \cdot d_i^3}{12}}{\sum_{i-1}^{i=n} \frac{\pi \cdot d_i^3}{4}}, \text{m}. \qquad (2.28)$$

From which the thickness of the effective meat layer is:

$$\delta_{ef} = \delta_m - h_\text{i}, \text{ m}. \qquad (2.29)$$

Conducting the cooking process under pressure higher than atmospheric (e.g., heat treatment in an autoclave or pressure cooker), as reported in sources [5, 27], leads to the intensification of the hydrothermal breakdown of collagen. However, information regarding the effect of pressure on the amount of collagen hydrolyzed is not available.

During double-sided frying of HCCT meat, heat is supplied only to the surfaces of the product in direct contact with the heating surfaces. No heat is supplied to the lateral (side) surfaces of the product in this case, and heating of those areas occurs only via internal heat conduction within the product. Moreover, the product loses heat through these lateral surfaces.

To make fuller use of the heat energy delivered by the heating surfaces and to ensure heat input to all product surfaces, it is necessary to organize the frying process in such a way that the steam, which would otherwise be lost to the environment along with the latent heat of vaporization, remains in contact with the lateral surfaces of the product. In this case, if the steam comes into contact with the cooler lateral surfaces of the product (which remain at a lower temperature than the steam throughout the process), condensation will occur. This can be achieved by creating a functionally closed chamber (FCC) and conducting the frying process within it with the meat placed inside [181–185]. Furthermore, displacing air from the FCC with steam will significantly increase the heat transfer coefficient from steam to the side surfaces of the product.

The optimal compression force applied during frying is considered to be the value that generates steam pressure in the crusts and displaces (or compresses) the air from the meat's capillaries and pores, without causing irreversible deformation. Under such conditions, the meat's thermal conductivity will increase to values approaching that of liquid (meat juice). Exceeding the optimal compression force, which would cause moisture loss due to structural destruction, would negatively impact frying efficiency and final product quality.

Additionally, during double-sided frying at an excess steam pressure close to the critical level, meat with HCCT will experience virtually no internal moisture flow, preserving native moisture and thus creating favorable conditions for sufficient collagen hydrolysis.

The limit of intensification for the double-sided frying of HCCT meat under compression in an FCC is determined by the thermal conductivity coefficient of the liquid in the meat at the given pressure.

In the case of non-rigid fixation of the heating surfaces, any loss of moisture from the product will be compensated by a reduction in the meat's height (thickness) due to compression. Thus, it can be concluded that steam pressure in the contact zone is maintained constant, meaning the temperature will equal that of saturated steam under the created pressure.

The frying process should therefore be conducted by placing semi-finished meat products made from HCCT meat into an FCC and applying a specific compression force PPP between two heating surfaces, as shown in Figure 4. The upper and lower surfaces of the product, in contact with the heating surfaces, are heated by heat fluxes q1q_1q1 and q2q_2q2. Additionally, heat will also be transferred to the lateral surfaces due to condensation of moist steam on them. Thus, the proposed method ensures heat is supplied to the entire surface of the product. Moreover, as the steam displaces air from the working volume of the FCC, the heat transfer coefficient from steam to the lateral surfaces of the product increases significantly.

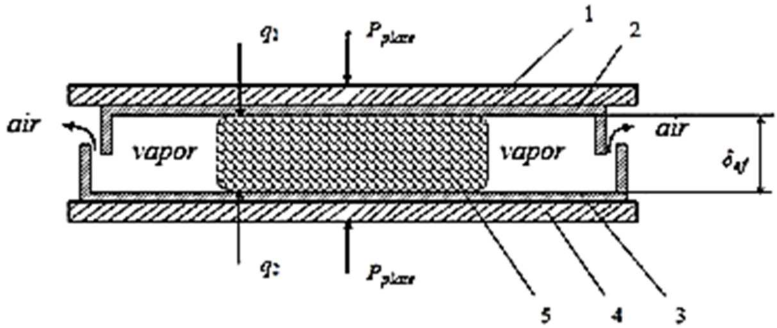


Fig. 4. Diagram of the process of two-sided frying under pressure in FCC of meat with HCCT: 1, 4 – upper and lower heating surfaces of the apparatus; 2, 3 – upper and lower parts of the FCC; 5 – product

Since phase transitions from "liquid to vapor" occur in the contact zone between the product surface and the heating surface (with a temperature of 423 K), this ensures intensive heat transfer to the product's surface. Given that the product is compressed between two heating surfaces, phase transitions in the contact zone occur at a pressure higher than atmospheric, and therefore at a temperature above 373 K. Meanwhile, condensation on the lateral surface of the product takes place at atmospheric pressure, and evaporation of liquid at the contact surface acts as resistance to mass filtration transfer. Part of the vapor generated during frying will escape into the surrounding environment due to the imperfect sealing of the FCC.

Heat transfer from the heating surfaces to the product occurs through continuous evaporation and condensation of moisture on the surfaces in contact with the FCC, as well as condensation on the lateral surface of the product.

The entire two-sided frying process—whether under pressure or with electric current—can be divided into three stages (see Fig. 5):

- stage I – heating of the thin surface layers of the semi-finished product to the water evaporation temperature. This stage is short and occurs almost instantly. During this stage, a sharp decrease in the temperature of the heating surfaces above and below the semi-finished product is observed;
- stage II is the main stage of the frying process in terms of energy consumption. Heat transfer in the surface layers occurs through vapor layers and ends when the temperature in the center of the product reaches about 338–343 K, at which point the meat transitions from a viscoplastic to a solid state due to the completion of thermal transformations of meat proteins;
- stage III involves the formation of a browned crust on the product surface due to increased temperature. The duration of this stage can be used to regulate the organoleptic properties of the final product: a longer Stage III results in a more

pronounced browning, while a shorter stage allows for a high-quality, potentially dietary product with minimal or no dried crust [186].

Meat with HCCT has an extremely complex structure consisting of muscle fibers grouped into primary bundles, which are further grouped into larger bundles. The spaces between these structures contain significant layers of connective tissue and are filled with liquid. The diameters of various capillaries can vary widely. For instance, the diameter of a muscle fiber may range from 45 to $60 \cdot 10^{-6}$ m [187], depending on the type of muscle, age, sex of the animal, its feeding and watering conditions, storage conditions, etc. Additionally, capillaries exist between fibers and bundles, and their diameters also vary based on the arrangement of capillaries and the aforementioned factors.

The capillaries and pores of meat, including that with HCCT, contain cavities filled with gases (steam, air, etc.). Compressing the meat with a certain force P, or applying electric current, leads to the formation of an effective thickness δ_{ef} of the heated product, reduces steam losses to the environment, shortens the frying process, and increases the yield of the final product [179, 180]. The analytical model of the two-sided frying process under electric current or compression in FCC, with the formation of an effective layer δ_{ef} in the meat, is expressed by Equation (2.27).

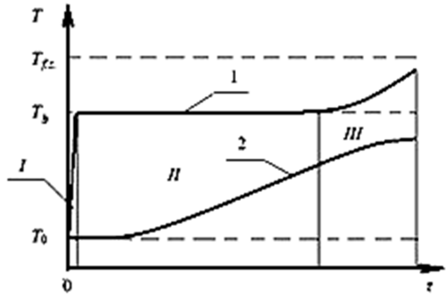


Fig. 5. Theoretical temperature kinetics of the surface (1) and central (2) layers of the product during two-sided frying under the influence of physical and electrophysical methods

To practically validate the justification of the analytical model (2.27), it is necessary to conduct studies of the processes of mass transfer in meat under the influence of heat flux, as well as under the combined influence of heat flux and alternating electric current voltage, in order to determine the patterns of substance flow formation and to establish the optimal parameters of the two-sided frying process, including for meat with high connective tissue content (HCCT) [188].

2.5. Heat Transfer in the Surface Layers of Meat Products During Two-Sided Frying Under the Influence of Physical and Electrophysical Methods

Boiling and evaporation processes are well-known and theoretically well-founded, yet heat transfer through steam layers during frying requires further investigation.

The essence of the processes occurring in the meniscus of each meat capillary during two-sided frying under the influence of electric current can be conveniently explained using a *T-S* diagram for water vapor, the schematic of which is shown in Fig. 6.

When liquid is drawn to the upper surface (Fig. 3a), a thermodynamic process *1-2-3* begins in the capillary menisci under the vapor pressure generated by the weight of the upper heating surface (Fig. 6).

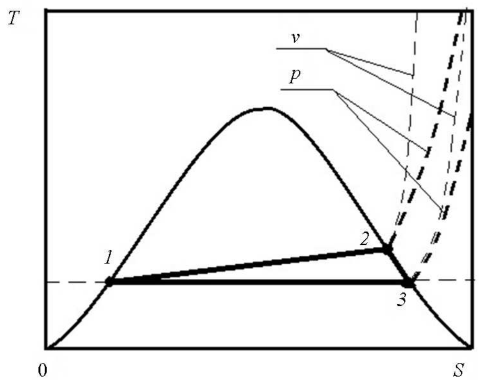


Fig. 6. Thermodynamic process diagram of water vapor in the meniscus of a capillary in the surface layer of the product during frying, shown in a *T-S* diagram

The amount of heat received by the liquid in each capillary meniscus from the heating surface during this process is:

$$Q = \frac{(i_2 - i_1) \cdot \bar{V_v}}{(v_2 - v_1)}, \text{J};$$

where i_2, i_1 – enthalpy of the vapor at points 2 and 1, J/kg; v_2, v_1 – specific volume of the vapor at points 2 and 1, m³/kg; $\bar{V_v}$ – – average vapor volume in the capillary meniscus during evaporation, m³.

$$\bar{V_v} = {\pi \cdot d_c}^3 / 24,$$

d_c – capillary diameter, m.

The heat transfer coefficient from the frying surface to the liquid on the meniscus surface during evaporation α_1 is:

$$\alpha_1 = \frac{Q_{1-2}}{F^c \cdot \left({T_{sur}}^m - {T_{liq}}^m\right) \cdot \tau_{vap}}, \text{W}/(m^2 \cdot \text{K}),$$

where F^m– average integral area of the meniscus surface during evaporation, m²,

$$F^m = \frac{F_{max} - F_{min}}{ln\frac{F_{max}}{F_{min}}} = 1{,}1331 \cdot {d_c}^2;$$

F_{min} – minimum area of the capillary meniscus surface, m², due to fluid displacement into the surface layer under the influence of electric current:

$$F_{min} = \pi \cdot {d_c}^2/4,$$

F_{max} – maximum surface area of the capillary meniscus, m²:

$$F_{max} = \pi \cdot {d_c}^2/2,$$

${T_{sur}}^m$ – average integral temperature of the frying surface during process 1-2, K; ${T_{liq}}^m$ – average integral temperature of the liquid on the meniscus surface during process *1-2*, K; τ_{vap} – duration of the evaporation process (*1-2*).

The amount of heat received by the liquid on the meniscus surface during condensation (process 3-1) in the capillary is:

$$Q_{3-1} = \frac{(i_3 - i_1) \cdot \bar{V}_v}{(v_3 - v_1)}, J;$$

where v_3, v_1 – specific volume of the vapor at points 3 and 1, m³/kg.

The heat transfer coefficient from vapor to liquid on the meniscus surface α_2 is:

$$\alpha_2 = \frac{Q_{3-1}}{F^m \cdot (T_{vap} - T_{liq}) \cdot \tau_{con}}, \text{ W/(m}^2\cdot\text{K)},$$

where T_{vap} – vapor temperature in the meniscus during process *3-1*, K; T_{liq} – liquid temperature on the meniscus surface during process 3-1, K; τ_{con} – condensation time (process *3-1*).

The heat transfer coefficient from the frying surface to the liquid on the meniscus surface during the thermodynamic cycle *1-2-3*, W/(m²·K):

$$k = \frac{1}{1/\alpha_1 + 1/\alpha_2} =$$

$$= \frac{1}{F^m \cdot ({T_{sur}}^m - {T_{liq}}^m) \cdot \tau_\text{в} / Q_{1-2} + F^m \cdot (T_{vap} - T_{liq}) \cdot \tau_{con} / Q_{3-1}}$$

$$=$$

$$= \frac{\bar{V}_{п}}{F^m \cdot \left(\left(T_{sur}{}^m - T_{liq}\right) \cdot (v_2 - v_1) \cdot \tau_{vap} / (i_2 - i_1) + \left(T_{vap} - T_{liq}\right) \cdot (v_3 - v_1) \cdot \tau_{con} / (i_3 - i_1) \right)}$$

After condensation of the vapor in the peripheral meniscus from the adjacent one, vapor breakthrough occurs due to excess pressure difference. As a result, the peripheral meniscus receives heat Q_{2-3}, and upon reaching the excess pressure *p*, due to further evaporation of the liquid from the meniscus surface, it is vented into the environment.

Thus, after the first *1-2-3* process, both in the peripheral and in all other capillaries, $\alpha_1 = \alpha_2 = \alpha$, and the heat transfer coefficient from the frying surface to the liquid on the meniscus surface equals:

$k = \alpha / 2$, or

$$k = \frac{Q_{3-1}}{2 \cdot F^m \cdot \left(T_{sur}{}^m - T_{liq}{}^m\right) \cdot \tau_c} = \frac{(i_3 - i_1) \cdot \bar{V}_{п}}{2 \cdot F^m \left(T_{sur}{}^m - T_{liq}{}^m\right) \cdot \tau_c \cdot (v_3 - v_1)} =$$

$$= \frac{(i_3 - i_1) \cdot \pi \cdot d_c{}^3}{48 \cdot 1{,}1331 \cdot d_c{}^2 \left(T_{sur}{}^m - T_{liq}{}^m\right) \cdot (v_3 - v_1) \cdot \tau_c} = \frac{0{,}05776 \cdot (i_3 - i_1) \cdot d_c}{\left(T_{sur}{}^m - T_{liq}{}^m\right) \cdot (v_3 - v_1) \cdot \tau_c} =$$

$$= \frac{0{,}05776 \cdot r \cdot d_c}{\Delta \bar{T}^m \cdot \Delta v \cdot \tau_c}, W/(m^2 \cdot К), \qquad (2.30)$$

where r – total latent heat of condensation of steam at atmospheric pressure, J/kg;

Δv – change (reduction) in the specific volume of steam during complete condensation at atmospheric pressure, m³/kg;

τ_c – duration of the thermodynamic process 1-2-3, s.

In the menisci near the lower surface, continuous and intense evaporation of steam occurs not only due to the action of the heat flux from the heater but also due to the action of electric current. The condensation of steam near the upper frying surface causes a sharp expansion of steam in the menisci near the lower surface and, as a result, its condensation on the meniscus surfaces. In effect, a thermodynamic process analogous to *1-2-3* occurs.

When the polarity is reversed, the same processes take place in the opposite direction.

From formula (2.30), it follows that the heat transfer coefficient is directly proportional to the ratio d_c/τ_c.

The average integral temperature difference $\Delta \bar{T}^m$ (mean integral temperature head) during the frying process depends on the specific surface power of the frying surface. Obviously, a decrease in the specific surface power leads to a reduction in $\Delta\bar{T}^m$, and conversely, an increase in the specific surface power leads to an increase in $\Delta\bar{T}^m$.

It can be stated that to enable the thermodynamic processes during the second stage to occur under a constant temperature difference $\Delta\bar{T}^m$, the specific surface power of each frying surface should be:

$$\mathrm{P}_{sp} = k \cdot \Delta\bar{T}^m = \frac{0{,}05776 \cdot r \cdot d_c}{\Delta v \cdot \tau_c}, W/m^2. \quad (2.31)$$

Given the known specific surface power P_{sp}, the average integral temperature difference $\Delta\bar{T}^m$, and the duration of the thermodynamic process *1-2-3* τ_c, the capillary diameter during the frying process is calculated using formula (2.31) as follows [189, 190]:

$$d_c = \frac{\mathrm{P}_{sp} \cdot \Delta v \cdot \tau_c}{0{,}05776 \cdot r} = \frac{17{,}3125 \cdot P_{sp} \cdot \Delta v \cdot \tau_c}{r}, m. \quad (2.32)$$

To calculate the heat transfer coefficients α, thermal conductivity k using formula (2.30), the duration of the first and second frying stages τ, the required specific surface power P_{sp}, the ratio d_c/τ_c, and the capillary diameters d_{c_i} using formula (2.32) during the frying process, it is necessary to determine the durations of the thermodynamic processes *1-2-3* τ_{c_i} and the average integral temperature difference $\Delta\bar{T}^m$ (average integral temperature gradient).

During two-sided frying of meat with high connective tissue content (HCCT) under compression, the effective meat layer δ_{ef} is achieved through compression. Heat transfer in the surface layers due to compression will be analogous to that described above.

2.6. Thermal Model of Meat Conductive Frying Processes Under the Influence of Physical and Electrophysical Methods

Let us consider the classical form of the unsteady heat conduction equation.

The heat conduction equation in general form can be written as [191, 192]:

$$\frac{\partial T}{\partial \tau} - a \cdot \left(\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2}\right) = f(x, y, z, \tau) \qquad (2.33)$$

or

$$\frac{\partial T}{\partial \tau} - a \cdot \nabla^2 T = f(x, y, z, \tau) \qquad (2.33^*)$$

or

$$\frac{\partial T}{\partial \tau} = \frac{1}{c \cdot \rho} div\big(\lambda \cdot grad(T)\big) + \frac{1}{c \cdot \rho} f(x, y, z, \tau), \qquad (2.33^{**})$$

where $T \equiv T(x, y, z, \tau)$ – temperature, K;

$a = \frac{\lambda}{c \cdot \rho}$ – thermal diffusivity of meat, m²/s;

$f(x, y, z, \tau)$ – heat source function;

$\frac{\partial^2}{\partial x^2} + \frac{\partial^2}{\partial y^2} + \frac{\partial^2}{\partial z^2} = \nabla^2$ – Laplace operator in Cartesian coordinates.

Two-sided frying of meat under compression conditions can be considered as the heating process of an infinite plate, and thus only one spatial coordinate needs to be considered.

Therefore, $x=\delta$, (δ,τ): $0 \le \delta \le \delta_{ef}$, $0 \le \tau \le \tau_{\kappa}$ i $T=T(\delta,\tau)$, where δ_{ef} – is the effective thickness of the meat, m.

It is known that the general solution of the heat conduction equation (2.33) can be obtained using the Fourier method, analytically represented as an infinite series [171, 189, 190]. However, this form is not practical for applied problems, particularly for the two-sided frying process of HCCT meat under physical and electrophysical influence. Therefore, it becomes relevant to develop a practical approach to solving real-world problems.

The most appropriate approach for solving this problem is through computational (experimental) modeling and calculating the temperature dependencies on the effective sample thickness δ_{ef} over time τ.

We used an approximation based on the least squares method, with the objective functional of optimization being the mean squared deviation (MSD) in the form:

$$F(a) = \sum_{\tau=1}^{\tau=n} [T_\tau - \hat{y}_\tau(a)]^2,$$

That is, the nonlinear optimization problem is solved with respect to the parameter vector *a*

$$F(a) \Rightarrow \min_a,$$

where $T_\tau = T(\tau, \delta_{ef}^*)$ – temperature kinetics for a fixed δ_{ef}; $\hat{y}_\tau(a)$ – the target model function (possible dependency).

To solve this, various software packages can be used such as MathCad, Excel, Curve Expert, etc. The simplest and most accessible is MS Excel, which includes the Solver optimization tool. We propose using a search method such as the nonlinear generalized reduced gradient method, which is effective for smooth nonlinear problems.

The heat transfer function in the two-sided frying process can be represented as a multiplicative dependency:

$$T(\tau, \delta_{ef}) = F[y(\tau), z(\delta_{ef}), \mathrm{a}] = \mathrm{A} \cdot y(\tau) \cdot z(\delta_{ef}), \quad (2.34)$$

where $T(\tau, \delta_{ef}) \equiv T_\tau(\delta_{ef})$ – temperature function; τ – process duration, s; δ_{ef} – meat thickness, m; $y(\tau) \equiv y_\tau$ – process trend; $z(\delta_{ef})$ – thermal conductivity model component as a function of δ_{ef}; A – scaling coefficient; a – model parameter vector.

Based on the theoretical kinetics of surface and center layer temperatures in the product during two-sided frying under compression in FCC (Figure 5), general patterns of thermal conductivity component changes in the form of (2.34) were obtained. To construct these, several function classes are considered: second-order polynomials, modified exponentials, and saturation-type curves (S-shaped curves: Gompertz and logistic curves) [193–195].

– Second-order polynomial (Figure 7):

$$y_\tau = a_0 + a_1 \cdot \tau + a_2 \cdot \tau^2, \quad (2.35)$$

–Modified exponential (Figure 8):

$$y_\tau = k + a \cdot b^\tau, \quad (2.36)$$

where $y = k$ is the horizontal asymptote.

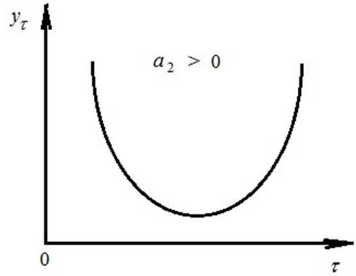


Fig. 7. General view of the second-order polynomial

If the parameter a is negative, then the asymptote lies above the curve; if a is positive, it lies below. In most practical applications, the commonly used form is when $a < 0$ and $b < 1$. In this case, the increase in values slows down and approaches a certain limit. To estimate the parameters of the modified exponential, one can use either the nonlinear least squares method or various other methods. The modified exponential accurately describes processes influenced by a limiting factor, where the effect of this factor increases as the current value grows.

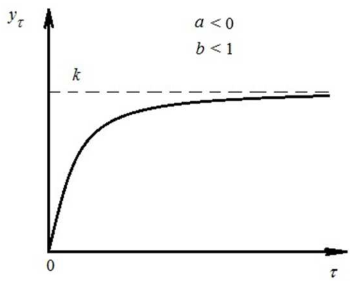


Fig. 8. General view of the modified exponential

–S-shaped curves.

If the impact of the limiting factor starts to become significant only after a certain point (inflection point), up to which the process follows an exponential law, S-shaped curves are used for modeling. The most well-known among them are the Gompertz curve and the logistic curve (Pearl-Reed curve):

–Gompertz curve (Fig. 9):

$$y_\tau = k \cdot a^{b^\tau}, \tag{2.37}$$

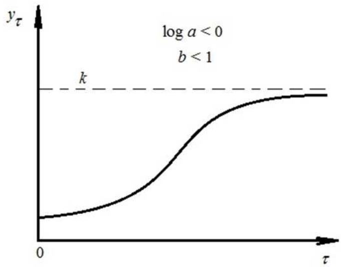


Fig. 9. General view of the Gompertz curve

–Logistic curve (Fig. 10):

$$y_\tau^{-1} = k + a \cdot b^\tau \text{ або } y_\tau = \frac{1}{k+a \cdot b^\tau}, \tag{2.38}$$

Specifically:

$$y_\tau = \frac{1}{k+a \cdot exp(c \cdot \tau)}. \tag{2.38*}$$

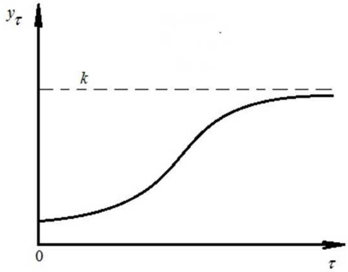


Fig. 10. General view of the logistic curve

Other forms of the logistic function are also used in practice, such as:

$$y_t = \frac{a}{1+b\cdot exp(-c\cdot\tau)}. \qquad (2.39)$$

The corresponding dynamic equation is the classical Verhulst model, which reflects the phenomenological behavior of complex (chaotic) processes:

$$\frac{dx}{d\tau} = \lambda x(1-x), x = y/a, \lambda \equiv c > 0.$$

In general, the two-sided meat frying process can be described by a logistic curve defined by the following differential equation:

$$\frac{dy}{d\tau} = \alpha(y-k_1)(k_2-y), \qquad (2.40)$$

where τ – a parameter expressing the cumulative costs of a technological process (time, energy, etc.); $y(\tau)$ – the technologically significant result achieved by the process; α – a positive constant (scaling parameter);

k_1 and k_2 – positive constants that define the lower and upper bounds of the process efficiency. Here, k_1 – represents the initial limitation (e.g., starting temperature) and k_2 – represents the technological ceiling (e.g., final temperature limit).

As the investment (in any form) into the mastery and improvement of the process increases, its output also grows. Therefore, $y(\tau)$ is a monotonically increasing function over its domain. The fact that the first derivative (rate of change) of y is proportional to its deviation from initial capabilities implies that $y(\tau)$ grows faster the further it is from k_1. On the other hand, its proportionality to $(k_2 - y)$ implies the growth slows as it nears the upper limit $y(\tau)$.

The logistic (S-shaped) curve that describes the lifecycle of a particular technology [191–193] can be viewed as a model of the kinetics of cumulative quantities—those that accumulate over time. Their growth rate is proportional to their current value.

Such variables characterize processes like development, perception, and learning. Logistic curves describe cumulative growth with saturation, meaning the accumulated quantity has an upper limit and slows as it approaches it. These curves can be used not only to describe technological kinetics but also broader phenomena like the scientific and technological progress of humankind.

This function satisfies a differential equation with fixed constants k_1 i k_2 ($k_2 > k_1 > 0$), such that: $k_1 < y(\tau) < k_2$ for all τ

$$\frac{dy}{d\tau} = \alpha(\tau)(y - k_1)(k_2 - y).$$

The solution of this equation is the function:

$$y(\tau) = k_1 + \frac{(k_2 - k_1) \cdot \Lambda(\tau)}{\Lambda(\tau) + \beta}, \tag{2.41}$$

Where for any $\beta > 0$

$$\Lambda(\tau) = exp\left[(k_2 - k_1)\int_{\tau_0}^{\tau} \alpha(\tau)d\tau\right].$$

In this model, time does not pass linearly but rather proportionally to $\alpha(\tau)$, making the shape of $y(\tau)$ highly dependent on $\alpha(\tau)$. The simplest case $\alpha(\tau) = const$ yields the Fisher-Pry model of technological shift. The less $\alpha(\tau)$ resembles a constant, the more nonlinear the resulting development becomes.

In some cases, $\alpha(\tau)$ should be considered a pulse-type function peaking at $\tau_1 > \tau^*$, for example:

$$\alpha(\tau) = \alpha/[(\tau - \tau^{*}) + \gamma]$$

with α, γ >0, which corresponds well with the hypothesis of a "double" wave of technological paradigm shifts.

In this model, the first wave is due to the endogenous logistic growth of the function (2.39), while the second is caused by a local "compression" of time at τ^{*}, resulting from exogenous factors [196].

A similar approach is applied to the thermal model of the two-sided meat frying process under the influence of electric current.

To carry out computer simulations, construct, and validate the proposed thermal model, it is necessary to study the temperature kinetics inside HCCT meat during two-sided frying under compression conditions.

2.7. Conclusions of the Chapter

1. A comprehensive methodology for analyzing the energy efficiency of thermal devices has been developed.

2. Technological requirements for the process of conductive meat frying, including meat with a high content of connective tissue (HCCT), have been formulated, taking into account the prevention of HA formation in finished products.

3. The factors contributing to the intensification of the conductive frying process have been analyzed and substantiated. These include:

– an increase in the heat exchange surface and the contact area between the meat and the frying surfaces during two-sided heat supply, which leads to an increase in the heat transfer coefficient from the frying surfaces to the meat surface;

– a change in the thermophysical properties of the meat, in particular, an increase in its thermal conductivity coefficient;

– a reduction of meat thickness to the effective thickness of the liquid layer through the application of pressure or electric current during the conductive frying process.

4. An analytical model of the two-sided frying process under the influence of physical and electrophysical methods has been substantiated based on intensification factors, including the reduction of meat thickness to an effective value, the increase in thermal conductivity, and the enhancement of heat transfer from the frying surfaces to the meat surface.

To calculate the theoretical duration of the process, it is necessary to study the patterns of mass transfer under the influence of electric current, heat flux from the heating surface, and their combined effect.

5. A classification of the two-sided frying process, including for HCCT meat in a functionally closed chamber (FCC) and under the influence of electric

current, into three main stages has been proposed. Among these, the second stage is the most energy-intensive, during which heat is transferred through the surface layer of meat via constant evaporation and condensation of water vapor. This vapor is generated due to moisture being drawn to the surface layers of the product in contact with the heating surfaces.

A method has been proposed to determine the heat transfer and heat conduction coefficients from the frying surfaces to the meat, the required specific surface power, and the capillary diameters in the surface layer of meat during the second stage. This is based on the construction of the thermodynamic process in a T-S diagram.

To calculate the theoretical process duration, it is necessary to study the duration of thermodynamic processes in the capillary menisci and the average integrated temperature difference (temperature head) during the second stage.

6. A thermal model of the two-sided frying process for HCCT meat in FCC conditions has been proposed by solving the unsteady heat conduction equation using a nonlinear generalized reduced gradient method, which is used for smooth nonlinear problems.

To perform computer simulations, construct and validate the adequacy of the proposed thermal model, it is necessary to investigate the temperature kinetics inside HCCT meat during two-sided frying under compression conditions.

CHAPTER 3. DEVELOPMENT AND STUDY OF MEAT CONDUCTIVE FRYING PROCESSES UNDER THE INFLUENCE OF ELECTRIC CURRENT

3.1. Mass Transfer in Meat Under Physical and Electrophysical Influence

The study of mass transfer in meat under physical and electrophysical influence required the creation of experimental setups and the development of research methodology.

The object of the study was the processes of mass release and mass transfer in pork longissimus muscle under the influence of electric current, heat flow, pressure, and their combined effects.

The subject of the study was samples made from the longissimus muscle of pork.

The aim of the research was to determine the influence of electric current, heat flow, and their combined effect, as well as applied excess pressure, on the quantitative parameters of substance transfer in meat.

The study required the development of an experimental setup that met the following requirements:

– the ability to regulate the voltage of the electric current applied to the samples;

– the ability to regulate the amount of heat flow supplied to the samples;
– the ability to vary the amount of excess pressure applied to the samples;
– the ability to study the combined influence of electric current and heat flow;
– the ability to visually record the quantitative parameters of substance transfer and mass release processes;
– the ability to study substance transfer and mass release in samples of varying thickness and area.

Substance Transfer in Meat Under the Influence of Electric Current

The objective of the study was to determine the quantitative parameters of substance transfer processes based on the applied electric voltage **U**, exposure duration, and the geometric parameters of the experimental samples.

The determination of quantitative parameters of substance transfer in meat under the influence of electric current was conducted using an experimental setup, the schematic and general appearance of which are shown in Figures 11 and 12.

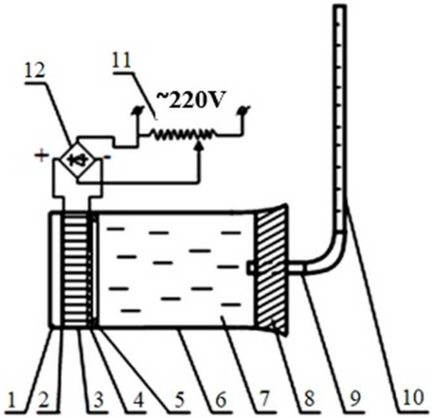


Fig. 11. Schematic diagram of the experimental setup for determining the quantitative parameters of substance transfer in meat under the influence of electric current:
1 – sealing gasket; 2, 4 – sealed and perforated electrodes; 3 – experimental meat sample; 5 – pressing ring; 6 – glass cylinder; 7 – distilled water; 8 – stopper; 9 – tube; 10 – measuring capillary; 11 – autotransformer (LATR); 12 – diode bridge

The setup consists of a glass cylinder (6), sealed on one side with a sealing gasket (1) and a sealed electrode (2). Inside the glass cylinder are a perforated electrode (4) and a pressing ring (5), which during the experiment are tightly pressed against the meat sample (3). The other side of the cylinder is closed with a stopper (8) connected to a measuring capillary (10). To supply rectified electric current (with pulsation) to the electrodes, the setup is equipped with a laboratory autotransformer (11) and a diode bridge (12).

Samples were prepared from the longissimus muscle of a single animal with surface areas of $(3{,}46\ldots12{,}62)\cdot10^{-4}$ m² and thicknesses of 0,005, 0,01, and 0,015 m. The longissimus muscle was sliced across the fibers using measuring attachments to obtain samples of specified thickness. Cylindrical samples of the specified area were then cut using the sharpened edge of the glass cylinder (6).

During the experiments, meat samples (3 in Fig. 11) with a temperature of 293 K were placed in the glass cylinder (6) between the sealed electrode (2) and the perforated electrode (4) and pressed with the ring (5) to prevent deformation during the test.

Fig. 12. Experimental setup for determining quantitative parameters of substance transfer in meat under the influence of electric current

After assembly, the system on the side of the perforated electrode was filled with distilled water (7) at 293 K and closed with stopper (8). A measuring capillary (10) was connected to the system via a tube (9) through the stopper. The volume of substance transferred through the sample was determined by measuring the volume of displaced water during electric current exposure. The water volume in the measuring capillary (10) was recorded using video footage from an LG P970 mobile phone at 25 frames per second. Still frames in JPG format were extracted using the demo version of *Free Video to JPG Converter* for further analysis.

To study the effect of sample thickness on substance transfer under electric current, the glass cylinder (6) was oriented vertically. The system was filled with the same volume of distilled water and closed with stoppers (8) of varying height. This maintained a constant excess pressure of 400 Pa from the water column for equivalent experimental conditions.

The electric current source was a 220 V power supply. The current was delivered through the LATR (11) and diode bridge (12) to convert AC into pulsating DC with a voltage range of 9 to 36 V.

The duration of electric current exposure was controlled using an *Elektronika IT-01* electronic stopwatch.

All experiments on substance transfer in pork meat were conducted within an exposure duration range of 0–5 seconds.

To quantitatively determine mass release parameters due to differences in substance concentration and electric current action, a sample with a thickness of 0.01 m and surface area of $8{,}04\cdot10^{-4}$ m² was placed in the glass cylinder (6), filled with $20\cdot10^{-6}$ m³ of distilled water at 293 K, and the amount of dry matter transferred into the water was determined using a laboratory refractometer *URL Model 1*.

Perforated electrodes (4) with a perforation ratio of 0,19…0,44 were used in the study.

Since the driving factors of substance flow in meat are electric voltage and concentration gradient of dry matter, the kinetics of mass release under these influences were studied separately. The results are shown in Fig. 13.

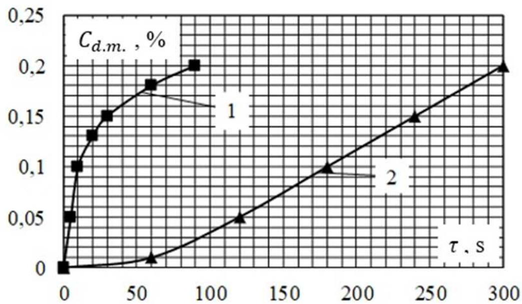


Fig. 13. Kinetics of the increase in the amount of dry matter transferred into distilled water under the

influence of:
1 – electric current;
2 – concentration gradient

The obtained data indicate that the influence of driving factors — voltage and concentration gradient – is significant, but the intensity of mass transfer under their action is different. In the interval from 0 to 20 seconds, the effect of the concentration gradient is not particularly significant, whereas the influence of the electric current potential difference is decisive. For this reason, in subsequent studies, the driving force in the form of concentration gradient was not taken into account.

The results of experimental studies on determining the volume of substance transferred in meat under horizontal and vertical mass transfer vectors depending on the applied electric voltage and exposure duration, at a constant surface area of $8{,}04 \cdot 10^{-4}$ m² and thickness of 0,01 m of the sample, are presented in Table 3.1.

Table 3.1

Results of the study of the volume of transferred substance in meat depending on electric voltage and exposure duration

Electric voltage, U, В	Volume of transferred substance $V_{liq} \cdot 10^6$, м^3, at $S_m = const = 8{,}04 \cdot 10^{-4}$, м^2, and

	$\delta_m = const = 0{,}01$ м, and exposure duration τ, с,					
	0,5	1	2	3	4	5
For horizontal mass transfer vector						
9	0,020	0,040	0,080	0,120	0,160	0,200
18	0,040	0,080	0,160	0,240	0,320	0,400
27	0,060	0,120	0,240	0,360	0,480	0,600
36	0,080	0,160	0,320	0,480	0,640	0,800
For vertical mass transfer vector						
9	0,018	0,036	0,072	0,108	0,144	0,180
18	0,036	0,072	0,144	0,216	0,288	0,360
27	0,054	0,108	0,216	0,324	0,432	0,540
36	0,072	0,144	0,288	0,432	0,576	0,720

Constructing the model of dependence V_{liq} on U and τ requires determining the correlation relationship between the resulting indicator $V_{\text{р}}$ and the factors U and τ that influence it. Analytically, such a relationship is expressed by the following equation:

$$V_{liq} = k_1 \cdot U \cdot \tau, \text{ m}^3; \quad (3.1)$$

where k_1 – proportionality coefficient depending on the geometric parameters and electrophysical properties of the meat sample, for this case: with horizontal mass transfer vector - $k_1 = 10{,}16 \cdot 10^{-9} m^3$/(W·s); with vertical mass transfer vector - $k_1 = 9{,}13 \cdot 10^{-9}$ m^3/(W·s).

The general form of dependence (3.1) is shown in Fig. 14.

During the experiment, visual dehydration of the meat sample layer in contact with the sealed electrode was observed. Moreover, as the exposure time increased to 5,0 s, the temperature of this layer slightly increased, which may indicate the occurrence of complex processes associated with dehydration under the influence of electric current, vapor formation in this layer, and the emergence of a pressure gradient that became the driving force for mass transfer.

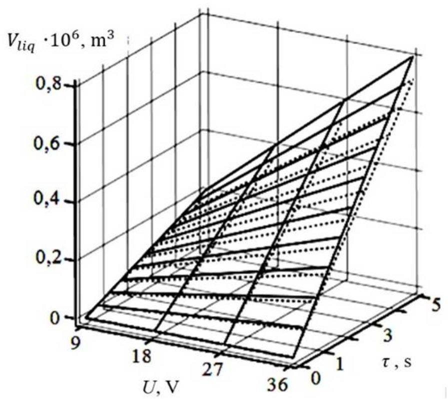


Fig. 14. Theoretical kinetics of the volume of substance transferred in meat under electric voltage U = 9…36 V during τ = 0.5…5.0 s, with constant area $S_m = const = 8{,}04 \cdot 10^{-4}$ m² and constant sample thickness $\delta_m = const = 0{,}01$ m, for mass transfer vector:- horizontal; vertical

The results of experimental studies on determining the volume of substance transferred in meat depending on the sample area and duration of exposure to a constant electric voltage of 27 V (at constant sample thickness of 0.01 m) are presented in Table 3.2.

Table 3.2

Results of the study on the volume of substance transferred in meat depending on sample area and exposure duration to electric current

Sample area,, $S_m \cdot 10^4$, м^2	Volume of transferred substance,, $V_{liq} \cdot 10^6$, м^3, at $U = const = 27$ В, $\delta_m = const = 0{,}01$ m, and duration τ, s,					
	0,5	1	2	3	4	5
Horizontal mass transfer vector						
3,46	0,026	0,052	0,104	0,156	0,208	0,260
8,04	0,060	0,120	0,240	0,360	0,480	0,600
12,62	0,094	0,188	0,376	0,564	0,752	0,940
Vertical mass transfer vector						
3,46	0,023	0,046	0,093	0,139	0,186	0,232
8,04	0,054	0,108	0,216	0,324	0,432	0,540
12,62	0,085	0,170	0,339	0,509	0,678	0,848

Constructing the model of V_{liq} dependence on S_m and τ requires determining the correlation between the resulting indicator V_{liq} and the factors S_m and τ.

Analytically, this relationship is expressed by the equation:

$$V_{liq} = k_2 \cdot S_m \cdot \tau \ \text{m}^3; \quad (3.2)$$

where k_2 – proportionality coefficient depending on the electric voltage and electrophysical properties of the meat sample, for this case: with horizontal mass transfer vector - $k_2 = 340{,}34 \cdot 10^{-6}$, m/s, with vertical mass transfer vector – $k_2 = 306.69 \cdot 10^{-6}$, m/s.

The general form of dependence (3.2) is shown in Fig. 15.

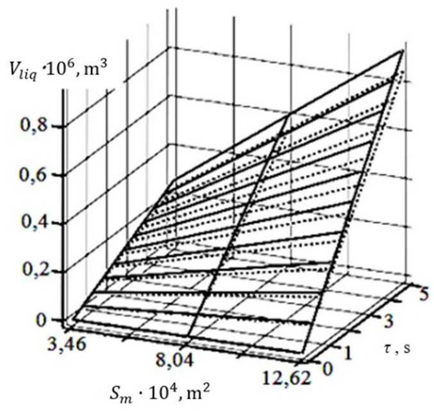


Fig. 15. Theoretical kinetics of the volume of substance transferred in meat under constant electric voltage U = const = 27 V, with constant sample thickness $\delta_m = const = 0{,}01$ m, during τ = 0.5…5.0 s, depending on sample area $S_m = (3{,}46 \ldots 12{,}64) \cdot$

10^{-4}, (3.46…12.64)·10^{-4} m², for mass transfer vector:
— horizontal;
···· vertical

The results of experimental studies on determining the volume of substance transferred in meat depending on sample thickness and duration of exposure to constant voltage U = 27V at constant sample area S_m = 8,04·10^{-4} m² are presented in Table 3.3.

Constructing the model of V_{liq} dependence on δ_m and τ requires identifying the correlation between the resulting indicator V_{liq} and the factors δ_m and τ. Analytically, this dependence is expressed by the equation:

$$V_{liq} = k_3 \cdot {\delta_m}^{-0,728} \cdot \tau, \text{ m}^3; \quad (3.3)$$

де k_3 – proportionality coefficient depending on electric voltage, surface area, and physical properties of the meat sample, for this case: horizontal vector - $k_3 = 9{,}59 \cdot 10^{-9}$, m^4/s, vertical vector – $k_3 = 8{,}63 \cdot 10^{-9}$, m^4/s.

Table 3.3

Results of the study on the volume of substance transferred in meat depending on sample thickness and duration of electric current exposure

Sample thickness, δ_m, m	Volume of transferred substance, V_{liq}·10^6, m^3, at $U = const = 27$, V, $S_m = const = 8{,}04 \cdot 10^{-4}$, $м^2$, and exposure time τ, c					
	0,5	1	2	3	4	5
Horizontal mass transfer vector						
0,005	0,100	0,200	0,400	0,600	0,800	1,000
0,010	0,060	0,120	0,240	0,360	0,480	0,600
0,015	0,045	0,090	0,180	0,270	0,360	0,450
Vertical mass transfer vector						
0,005	0,089	0,178	0,356	0,534	0,712	0,890
0,010	0,054	0,108	0,216	0,324	0,432	0,540
0,015	0,040	0,080	0,160	0,240	0,320	0,400

The general view of the dependence (3.3) is shown in Fig. 16.

Solving the system of dependencies (3.1–3.3) within the given parameter range (U, S_m, δ_m, τ), as defined by each of the mentioned relationships, allows for the determination of the volume of substance transferred in meat under the influence of electric current, which can be analytically expressed as:

$$V_{liq} = k_e \cdot U \cdot S_m \cdot \delta_m{}^{-0,728} \cdot \tau \text{ , m}^3; \quad (3.4)$$

where k_e – effective kinetic coefficient of the mass transfer process in meat under electric current, м^{1,728}/(s·W), for this case: horizontal vector - $k_e = 0{,}1935 \cdot 10^{-6}$ м^{1,728}/(s·W), vertical vector – $k_e = 0{,}1741 \cdot 10^{-6}\, m^{1,728}$/(s·W).

In the case of the vertical mass transfer vector, the weight of the distilled water additionally acts on the experimental sample in the direction opposite to the voltage drop and the direction of substance movement in meat under electric current. This explains the 6,5% decrease in the value of k_e in the vertical case. Thus, external applied pressure influences the magnitude of the effective kinetic coefficient of substance transfer in meat under the influence of electric current.

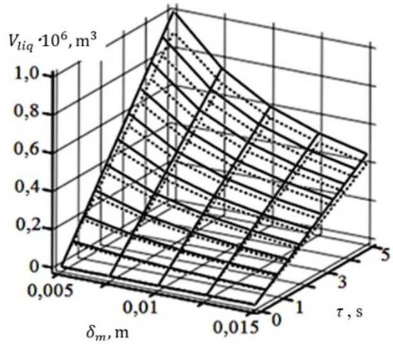


Fig. 16. Theoretical kinetics of the volume of substance transferred in meat under constant electric voltage U = 27 V, with constant sample area $S_m =$

$const = 8{,}04 \cdot 10^{-4}$ m², over τ = 0.5–5.0 s,
depending on sample thickness δ_m = 0,005…0,015 m,
for mass transfer vector:
— horizontal;
······· vertical

On one side, the meat sample is in contact with a perforated electrode (Fig. 11), which has a mesh structure. Changing the contact area of this electrode may affect the occurrence of mass conductivity under electric current.

The results of the study on the influence of electrode contact area with meat on the volume of transferred substance under electric current are presented in Table 3.4.

Table 3.4

Results of the study on the volume of substance transferred in meat under electric current depending on the contact area of the product with the perforated electrode and exposure time

Contact area, $S_k \cdot 10^4$, м^2	Volume of transferred substance, $V_{liq} \cdot 10^6$, м^3, at exposure time τ, c					
	0,5	1	2	3	4	5
$1{,}53 \cdot 10^{-4}$	0,049	0,098	0,196	0,294	0,392	0,490
$2{,}53 \cdot 10^{-4}$	0,055	0,109	0,218	0,327	0,436	0,545
$3{,}52 \cdot 10^{-4}$	0,060	0,120	0,240	0,360	0,480	0,600

The results of the study on the influence of excess pressure on the sample on the volume of transferred substance are presented in Table 3.5 and Fig. 17.

Table 3.5

Results of the study on the volume of substance transferred in meat under electric current depending on pressure applied to the sample and exposure time

Pressure, p, Па	Volume of transferred substance, $V_{liq}\cdot 10^6$, м³, at $U = const = 27$, V, $S_m = const = 8{,}04 \cdot 10^{-4}$, м², $\delta_m = const = 0{,}01$, м, and exposure time τ, с					
	0,5	1	2	3	4	5
580	0,067	0,134	0,268	0,402	0,536	0,670
1160	0,063	0,126	0,252	0,378	0,504	0,630
1740	0,059	0,118	0,236	0,354	0,472	0,590
2320	0,055	0,110	0,220	0,330	0,440	0,550

We analyze the results of the study on the volume of substance transferred in pork meat under electric current, depending on the contact area of the product with the perforated electrode S_k and exposure time τ (Table 3.4), and the results on volume transferred depending on excess pressure p and exposure time τ (Table 3.5).

A model describing the dependence of the volume of substance transferred in meat under electric current on the contact area of the perforated electrode with meat, pressure, and exposure time can be represented as:

$$V_{liq_e} = k_e \cdot k_s \cdot U \cdot S_m \cdot \delta_m{}^{-0,728} \cdot \frac{(p_{lim} - p)}{p_{lim}} \cdot \tau, m^3; \qquad (3.5)$$

where k_s – proportionality coefficient accounting for the ratio between the contact area of the perforated electrode and the sample area: $k_s = S_к / S_м$; $0 < k_s \leq 1$;

p – applied excess pressure, Pa;

p_{lim} – the maximum allowable pressure for the given meat sample at which structural destruction begins, Pa. This value depends on the animal's age, sex, muscle type, post-slaughter storage time, freezing and thawing conditions, and feeding and watering conditions. For the meat used in the experiment, p_{lim} = 10,4·10^3 Pa.

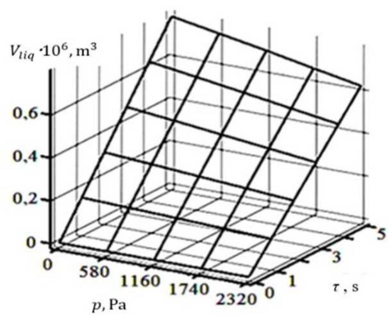


Fig. 17. Theoretical kinetics of the volume of substance transferred in meat under constant electric

voltage U = const = 27 V, at constant surface area $S_m = const = 8{,}04 \cdot 10^{-4}$ m² and constant sample thickness $\delta_m = const = 0{,}01$m, depending on the applied pressure p = 580…2321 Pa, over time τ = 0.5…5.0 s

According to equation (3.5), the volume of transferred substance (mass flux J_{liq}) through a unit surface area S_m of meat per unit time τ in this range of parameters depends on electric voltage *U*, meat thickness δ_m, and the value of applied pressure *p*:

$$J_{liq_e}^{V} = \frac{V_{liq_e}}{S_m \cdot \tau} = k_e \cdot k_S \cdot U \cdot {\delta_m}^{-0{,}728} \cdot \frac{(p_{lim} - p)}{p_{lim}}, \mathrm{m^3/(m^2 \cdot s)}; \ (3.6)$$

or in mass units:

$$J_{liq_e}^{G} = \frac{V_{liq_e} \cdot \rho_m}{S_m \cdot \tau} = k_e \cdot k_S \cdot U \cdot {\delta_m}^{-0{,}728} \cdot \frac{(p_{lim} - p)}{p_{lim}} \cdot \rho_{м}, \text{кг}/(\mathrm{m^2 \cdot s}); \ (3.7)$$

where ρ_m – meat density, kg/m³.

The proposed experimental setup based on the modified Perrin device (Fig. 11) can be used for the quantitative determination of the effective kinetic coefficient of substance transfer in meat under the influence of electric current in the specified parameter range [197]:

$$k_{\mathrm{e}} = \frac{J_{liq_e}^{V} \cdot p_{lim}}{k_S \cdot U \cdot \delta^{-0,728} \cdot (p_{lim} - p)} =$$

$$= \frac{V_{liq} \cdot p_{lim}}{k_S \cdot U \cdot \delta^{-0,728} \cdot (p_{lim} - p) \cdot \tau}, \mathrm{м}^{1,728}/(s \cdot V). \qquad (3.8)$$

Substance Transfer in Meat Under the Influence of Heat Flow from a Heater

The aim of the study is to determine the volume of substance transferred in the sample under the influence of heat flow *Q*, exposure time *τ*, and the geometric parameters of the experimental samples.

The determination of the quantitative parameters of substance transfer was carried out using the experimental setup, the schematic and general view of which are shown in Figs. 18 and 19.

The principle of the setup shown in Fig. 18 is essentially the same as in Fig. 11, with the only difference being the absence of a sealing gasket, whose function is performed by a copper plate (1) with a thickness of $0.35 \cdot 10^{-3}$ m, through which the heat flow from the electric heater is supplied.

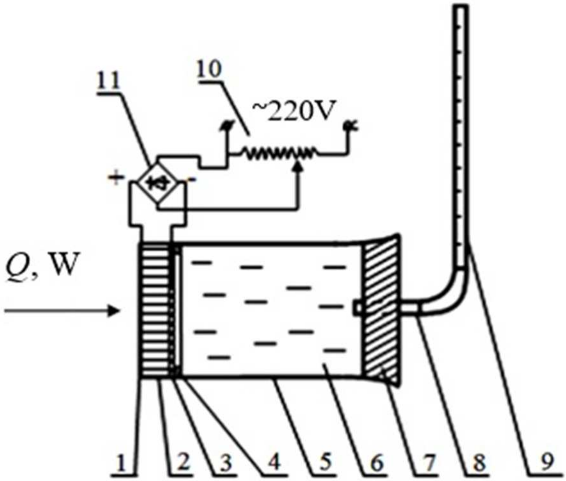


Fig. 18. Schematic diagram of the experimental setup for determining the quantitative parameters of substance transfer in meat under the influence of heat flow and electric current:
1, 3 – sealed (copper plate) and perforated electrodes; 2 – meat sample; 4 – pressing ring; 5 – glass cylinder; 6 – distilled water; 7 – stopper; 8 – tube; 9 – measuring capillary; 10 – autotransformer (LATR); 11 – diode bridge

Preparation and placement of the meat samples in the setup were performed using the same method.

For the experiments, a flat heating element with a surface temperature of 423 K was used, which was tightly pressed against the copper plate (1). All experiments were conducted with a constant heat flow of *Q*= 72 W, regulated using a phase voltage controller with a BTA16-600B triac.

During frying of natural meat products, the liquid at the contact point with the heating surface boils almost instantly. Therefore, the starting point for measuring substance transfer was the moment when complete boiling of moisture and intensive steam formation began near the copper plate (1), observed visually.

Fig. 19. Experimental setup for determining the quantitative parameters of substance transfer in meat under the influence of heat flow and electric current

It was established during the experiments that heating the copper plate (which also functions as the sealed electrode) to a temperature of 380…381 K, at which intensive boiling of moisture in adjacent product layers occurs (under heat flow Q = 72 W), took approximately 15 seconds. Increasing or decreasing the heat flow respectively shortened or prolonged the heating time.

The study on the effect of heat flow magnitude and duration of exposure on the volume of transferred substance in meat under horizontal and vertical mass transfer vectors (based on the orientation of the glass cylinder) was conducted using samples with surface area $S_m = const = 8{,}04 \cdot 10^{-4}$ m² and thickness $\delta_m = 0{,}01$ m. The results are shown in Table 3.6.

Table 3.6

Results of the study on the effect of heat flow from the heater and exposure time on the volume of substance transferred in meat

Heat flow, Q, W	Volume of transferred substance, $V_{liq} \cdot 10^6$, м^3, at $S_m = const = 8{,}04 \cdot 10^{-4}$, m^2, $\delta_m = const = 0{,}01$, м, and τ, s				
	1	2	3	4	5
Horizontal vector					
18	0,0074	0,0148	0,0221	0,0295	0,0369
36	0,0148	0,0295	0,0443	0,0590	0,0738
54	0,0221	0,0442	0,0664	0,0885	0,1106

72	0,0295	0,0590	0,0885	0,1180	0,1475
Vertical vector					
18	0,0059	0,0118	0,0177	0,0236	0,0295
36	0,0118	0,0236	0,0354	0,0472	0,0590
54	0,0177	0,0354	0,0531	0,0708	0,0885
72	0,0236	0,0472	0,0708	0,0944	0,1180

We consider the model of the dependence of the volume of substance transferred in meat V_{liq} on the heat flow Q from the heater and heating duration τ from the moment of complete heating of the copper plate and the onset of intense steam formation. Analytically, this model is expressed by the equation:

$$V_{liq} = k_5 \cdot Q \cdot \tau, m^3; \quad (3.9)$$

where k_5 – proportionality coefficient depending on the properties of the meat sample, for this case: horizontal vector - $k_5 = 40{,}7 \cdot 10^{-9}$, m^3/(W·s), vertical vector – $k_5 = 32{,}6 \cdot 10^{-9}$, m^3/(W·s).

The general form of dependence (3.9) is shown in Fig. 20.

The data in Table 3.6 show that the heat flow from the heater significantly affects substance transfer processes. Increasing the heat flow during sample heating and the exposure duration leads to a linear increase in the volume of transferred substance.

The results of the study on the effect of sample surface area (samples with thickness $\delta_m = 0{,}01$ m and surface areas $S_m = 3{,}46 \cdot 10^{-4}$, m^2, $8{,}04 \cdot 10^{-4}$, $м^2$, 12,62·10^{-4}, m² were used) and duration τ on substance transfer under constant heat flow Q = 72 W are presented in Table 3.7.

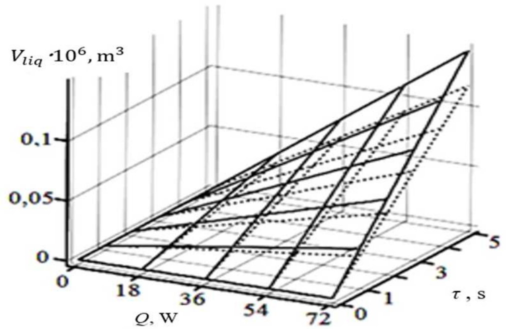


Fig. 20. Theoretical kinetics of the volume of substance transferred in meat under the influence of heat flow from a heater Q = 0…72 W, at constant surface area $S_m = const = 8{,}04 \cdot 10^{-4}$ $8.04{\cdot}10^{-4}$ m² and thickness $\delta_m = const = 0{,}01$, over time τ = 0…5 s, from the moment of full copper plate heating and intensive steam formation, for mass transfer vector:
— horizontal;
······· vertical

We now consider the model of dependence of V_{liq} on sample surface area S_m and exposure time τ under constant heat flow Q = 72 W, from the moment of complete heating of the copper plate and the start of steam formation (complete heating lasted 15 s). This relationship is analytically expressed as:

$$V_{liq} = k_6 \cdot S_m \cdot \tau, m^3, \qquad (3.10)$$

where k_6 – proportionality coefficient depending on the properties of the meat sample, for this case: horizontal vector - $k_6 = 36{,}692 \cdot 10^{-6}$, m/s, vertical vector – $k_6 = 29{,}353 \cdot 10^{-6}$, m/s.

Table 3.7

Results of the study on the influence of meat sample surface area and duration of heat flow from the heater on the volume of substance transferred in meat

Sample surface area, $S_m \cdot 10^{-4}$, м^2	Volume of transferred substance, $V_{liq} \cdot 10^6$, м^3, at $Q = const = 72$, W, $\delta_m = const = 0{,}01$, m, and exposure duration τ, s							
	5	10	15	16	17	18	19	20
Horizontal mass transfer vector								
3,46	0,015	0,030	0,045	0,058	0,071	0,083	0,096	0,109
8,04	0,035	0,070	0,105	0,135	0,164	0,194	0,223	0,253

12,62	0,055	0,110	0,165	0,211	0,257	0,304	0,350	0,396
Vertical mass transfer vector								
3,46	0,012	0,024	0,036	0,046	0,057	0,067	0,077	0,087
8,04	0,028	0,056	0,084	0,108	0,131	0,155	0,178	0,202
12,62	0,044	0,088	0,132	0,169	0,206	0,243	0,280	0,317

The general form of dependence (3.10) is shown in Fig. 21.

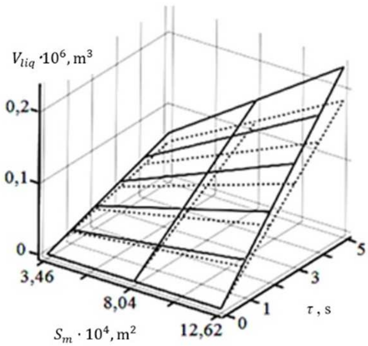


Fig. 21. Theoretical kinetics of substance volume transferred in meat under constant heat flow from the

heater $Q = const = 72$ W, with constant sample thickness $\delta_m = const = 0{,}01$ m, as a function of surface area $S_m = (3{,}46 \ldots 12{,}64) \cdot 10^{-4}$ m², over τ = 0.5…5.0 s, from the moment of full copper plate heating and intensive vapor formation, for mass transfer vector:

— horizontal;

······· vertical

The results of experimental studies on the volume of substance transferred in meat depending on sample thickness and duration of exposure to constant heat flow Q = 72 W at constant surface area $S_m = 8{,}04 \cdot 10^{-4}$, m^2 are shown in Table 3.8.

Table 3.8

Results of the study on the volume of substance transferred in meat under heat flow depending on sample thickness and heating duration

Sample thickness, δ_m, m	Volume of transferred substance, $V_{liq} \cdot 10^6$, m^3, at $Q = const = 72$, W, $S_m = const = 8{,}04 \cdot 10^{-4}$, m^2, and τ, s							
	5	10	15	16	17	18	19	20
Horizontal mass transfer vector								
0,005	0,045	0,090	0,135	0,169	0,203	0,237	0,271	0,305
0,010	0,035	0,070	0,105	0,135	0,164	0,194	0,223	0,253
0,015	0,025	0,050	0,075	0,100	0,125	0,150	0,175	0,200

Vertical mass transfer vector								
0,005	0,036	0,072	0,108	0,135	0,162	0,190	0,217	0,244
0,010	0,028	0,056	0,084	0,108	0,131	0,155	0,178	0,202
0,015	0,020	0,040	0,060	0,080	0,100	0,120	0,140	0,160

We consider the model of the dependence of substance volume V_{liq} transferred in meat on sample thickness δ_m and heating duration τ under constant heat flow Q = 72 W, starting from the moment of full heating of the copper plate and intense vapor formation (complete heating lasted 15 s). Analytically, this relationship is expressed by the equation:

$$V_{liq} = k_7 \cdot {\delta_m}^{-0,272} \cdot \tau, \text{ m}^3, \quad (3.11)$$

where k_7 – proportionality coefficient depending on the roperties of the meat sample, for this case: horizontal vector - $k_7 = 8{,}2 \cdot 10^{-9}$, м/s, vertical vector – $k_7 = 6{,}5 \cdot 10^{-9}$ м/s.

The general form of dependence (3.11) is shown in Fig. 22.

The influence of the mass transfer vector is explained by the fact that, under vertical orientation, the substance in the capillaries and pores of the meat is additionally affected by excess pressure up to 400 Pa generated by distilled water, as well as by gravitational force, both of which create additional resistance to substance transfer.

The results of the study on the effect of pressure p on substance transfer processes in meat under constant heat flow Q = 72 W, during 0…5 s, from the moment of complete copper plate heating, at constant surface area $S_m = const = 8{,}04 \cdot 10^{-4}$ m^2 and sample thickness $\delta_m = 0{,}01$ m, are presented in Table 3.9.

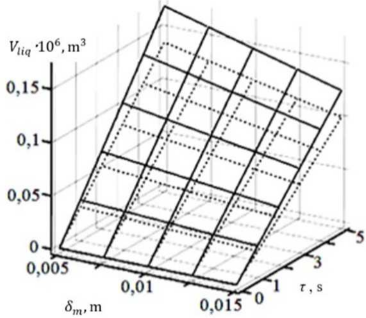


Fig. 22. Theoretical kinetics of the volume of substance transferred in meat under constant heat flow from the heater Q = const = 72 W, at constant surface area $S_m = const = 8{,}04 \cdot 10^{-4}$ m², as a function of sample thickness δ_m = 0,005…0,015 m, over τ = 0.5…5.0 s, from the moment of full copper plate heating and intense vapor formation, for mass transfer vector:
— horizontal;
······· vertical

Table 3.9

Results of the study on the dependence of the volume of substance transferred in pork meat under heat flow on excess pressure and heating duration

Excess pressure on sample, p, Pa	Volume of transferred substance, $V_{liq}\cdot 10^6$, m^3, at $S_m = const = 8{,}04 \cdot 10^{-4}$, m^2, $\delta_m = const = 0{,}01$, m, and τ, s					
	0,5	1	2	3	4	5
580	0,018	0,036	0,072	0,108	0,144	0,180
1160	0,017	0,034	0,068	0,102	0,136	0,170
1740	0,016	0,032	0,064	0,096	0,128	0,160
2320	0,015	0,030	0,060	0,090	0,120	0,150

For the meat used in the experiment, $p_{lim} = 10{,}4\cdot 10^3$ Pa.

We consider the model of the dependence of substance volume V_{liq} transferred in meat on pressure p and exposure time τ under constant heat flow from the heater Q = 72 W, from the moment of complete heating of the copper plate and intense vapor formation. Analytically, this relationship is expressed as:

$$V_p = k_8 \cdot \frac{(p_{lim} - p)}{p_{lim}} \cdot \tau, \text{ m}^3, \qquad (3.12)$$

де k_8 – proportionality coefficient depending on the geometric and physical properties of the meat sample, for this case: vertical mass transfer vector - $k_8 = 0{,}03 \cdot 10^{-6}$m^3/c.

The general form of dependence (3.12) is shown in Fig. 23.

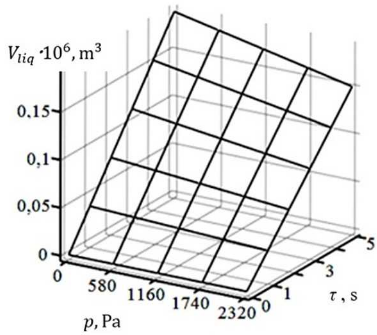


Fig. 23. Theoretical kinetics of substance volume transferred under constant heat flow Q = 72 W, at constant surface area $S_m = const = 8{,}04 \cdot 10^{-4}$ m² and sample thickness $\delta_m = const = 0{,}01$ m, as a function of applied pressure p = 580…2320 Pa, over τ = 0.5…5.0 s, from the moment of full copper plate heating

Solving the system of dependencies (3.9–3.12) within the given parameter range (Q, δ_m, S_m, p, τ) as defined by each of the respective relationships, allows us to determine the volume of substance transferred in meat under the influence of heat flow from a heater. This can be analytically expressed by the following equation:

$$V_{liq} = k_h \cdot Q \cdot S_m \cdot \delta_m{}^{-0,272} \cdot \frac{(p_{lim} - p)}{p_{lim}} \cdot \tau, \text{ м}^3, \quad (3.13)$$

where k_h – – effective kinetic coefficient of the substance transfer process in meat under the influence of heat flow, $m^{1,272}/(s\cdot W)$; for this case with vertical mass transfer vector $k_h = 0{,}11314 \cdot 10^{-6} m^{1,272}/(s\cdot W)$.

Equation (3.13), with a confidence level of 0.95, enables approximation of the experimental data obtained (Tables 3.6–3.9).

According to equation (3.13), the volume of transferred substance (mass flux J_{liq_h} through a unit surface area S_m per unit time τ within this parameter range depends on the heat flow Q from the heater, the sample thickness δ_m, and the applied excess pressure p:

$$J^V_{liq_h} = \frac{V_{liq_h}}{S_m \cdot \tau} = k_h \cdot Q \cdot \delta_m{}^{-0,272} \cdot \frac{(p_{lim} - p)}{p_{lim}}, \text{ m/s}, \quad (3.14)$$

or in mass units:

$$J^G_{liq_h} = \frac{V_{liq_h} \cdot \rho_m}{S_m \cdot \tau} = k_h \cdot Q \cdot \delta_m{}^{-0,272} \cdot \frac{(p_{lim} - p)}{p_{lim}} \cdot \rho_m, \text{ kg/(m}^2\text{·s)}. \quad (3.15)$$

The proposed experimental setup, based on the modified Perrin device (Fig. 18), can be used for quantitative determination of the effective kinetic coefficient of substance transfer in meat under the influence of heat flow from a heater in the given parameter range [198], $m^{1,272}/(s \cdot W)$

$$k_h = \frac{J_{liq_h}^V \cdot p_{lim}}{Q \cdot \delta^{-0,272} \cdot (p_{lim} - p)} = \frac{V_{liq_h} \cdot p_{lim}}{Q \cdot S_m \cdot \delta^{-0,272} \cdot (p_{lim} - p) \cdot \tau}. \quad (3.16)$$

The similarity between the laws of mass transfer and heat conduction makes it possible to evaluate the effect of applied excess pressure on the thermal conductivity coefficient of meat [199, 200]:

$$\lambda_m = \lambda_{m_0} + \left(\lambda_{liq} - \lambda_{m_0}\right) \cdot \frac{p}{p_{lim}}, \text{ W/(m} \cdot {}^{o}\text{C)}, \quad (3.17)$$

where λ_{m_0} – thermal conductivity of meat at atmospheric pressure,, W/(m·K);

λ_p – thermal conductivity of the liquid (meat juice), W/(m·K).

As a result of the conducted research, experimental data were obtained that revealed the regularity of substance flow formation in pork meat under the influence of heat flow from a heater, described by equations (3.14–3.15). Additionally, a method and formula (3.16) for determining the effective kinetic coefficient of the substance transfer process in meat under heat flow was proposed.

Combined Influence of Heat Flow from the Heater and Electric Current on Substance Transfer in Meat

The objective of this study was to determine the combined effect of heat flow, electric current, and excess pressure on substance transfer processes in meat.

The research was conducted under the following values of excess pressure on the sample: 580, 1160, 1740, and 2320 Pa, using the experimental setup, the schematic and general view of which are shown in Figs. 24 and 25.

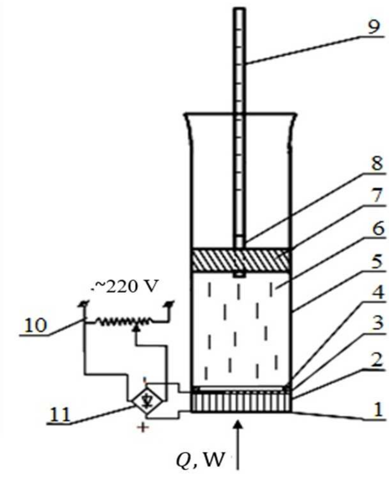


Fig. 24. Schematic diagram of the experimental setup for determining the combined influence of heat flow,

electric current, and excess pressure on the quantitative parameters of substance transfer in meat:
1, 3 – sealed (copper plate) and perforated electrodes;
2 – experimental meat sample;
4 – pressing ring; 5 – glass cylinder; 6 – distilled water; 7 – stopper; 8 – tube;
9 – measuring capillary; 10 – autotransformer (LATR); 11 – diode bridge

The design of the setup shown in Fig. 25 is similar to that in Fig. 18, except for the elongated glass cylinder (5). The required excess pressure on the samples was generated by a column of distilled water, whose height was precisely fixed by the stopper.

Fig. 25. Experimental setup for determining the combined influence of heat flow, electric current, and excess pressure on the quantitative parameters of substance transfer in meat

The experimental samples were prepared from the longissimus dorsi muscle of pork, which was sliced across the fibers using a special measuring adapter into segments of 0.01 m thickness. From these, using the sharpened edge of the glass cylinder (5), samples with a surface area of $10.17 \cdot 10^{-4}$ m² were cut out.

The study of pressure influence on the quantitative parameters of substance transfer in meat was conducted only under vertical orientation of the glass tube, with constant electric voltage of 27 V and constant heat flow of Q = 72 W.

The preparation of samples, their placement into the experimental setup, and the supply of electric current and heat flow were carried out using the same methodology as in previous experiments.

Considering that frying occurs only on horizontal heating surfaces in equipment, the investigation of substance transfer in natural meat under combined heat flow and electric current was conducted only for vertical mass transfer vector in the experimental setup shown in Fig. 24.

The results of the combined influence of heat flow from the heater and electric current on the volume of transferred substance in meat as a function of sample surface area, thickness (at U = 27 V, Q = 72 W, and excess pressure p = 400 Pa), and the applied excess pressure over τ = 0…5 s from the moment of full copper plate heating are presented in Table 3.10 and Fig. 26.

Table 3.10

Results of the study on the volume of substance transferred in pork meat under the combined action of electric current and heat flow

Parameter	Transferred substance volume, $V_{liq} \cdot 10^6$, m^3, over exposure time τ, s					
	0,5	1	2	3	4	5
Sample area, $S_m \cdot 10^4$, m^2						
3,46	0,033	0,065	0,130	0,174	0,218	0,252
8,04	0,075	0,150	0,300	0,405	0,505	0,585
12,62	0,117	0,234	0,468	0,636	0,792	0,918
Sample thickness, δ_m, m						
0,005	0,117	0,234	0,468	0,635	0,745	0,815
0,010	0,075	0,150	0,300	0,405	0,505	0,585
0,015	0,058	0,115	0,230	0,335	0,425	0,515
Excess pressure, p, Pa						
580	0,085	0,170	0,340	0,451	0,549	0,622
1160	0,080	0,160	0,320	0,425	0,517	0,586
1740	0,075	0,150	0,300	0,398	0,484	0,548
2320	0,070	0,140	0,280	0,372	0,453	0,513

The data in Table 3.10 indicate that during the first 2 seconds, the effects of heat flow and electric current on the volume of transferred substance in the test samples overlap, which is reflected in a linear relationship. After 2 seconds of combined exposure, the character of the relationship becomes nonlinear, which can likely be explained by the dehydration of the meat layer adjacent to the copper plate (sealed electrode). This relationship remains consistent for samples with thickness $\delta_m = 0{,}005 \ldots 0{,}015$ m, surface area $S_m = 3{,}46 \cdot 10^{-4} \ldots 12{,}56 \cdot 10^{-4}$, m², and under excess pressure in the range p = 400…2300 Pa**.**

Based on the obtained experimental data (Table 3.10), the volume of transferred substance under the combined action of heat flow from the heater and electric current within an exposure duration of 0…2 **s**, for the specified parameter range (U, Q, S_m, δ_m, p), can be determined using the following equation:

$$V_{liq} = V_{liq_h} + V_{liq_e} = k_h \cdot Q \cdot S_m \cdot {\delta_m}^{-0{,}272} \cdot \frac{(p_{lim} - p)}{p_{lim}} \cdot \tau + \\ + k_e \cdot k_s \cdot U \cdot S_m \cdot {\delta_m}^{-0{,}728} \cdot \frac{(p_{lim} - p)}{p_{lim}} \cdot \tau = \\ = \left(k_h \cdot Q \cdot {\delta_m}^{-0{,}272} + k_e \cdot k_s \cdot U \cdot {\delta_m}^{-0{,}728}\right) \cdot S_m \cdot \frac{(p_{lim} - p)}{p_{lim}} \cdot \tau, m^3. \quad (3.18)$$

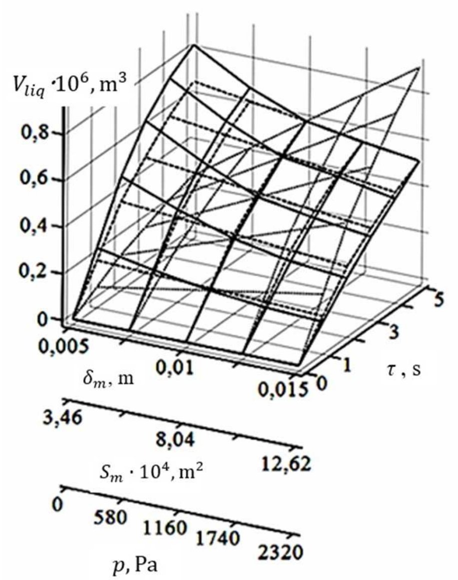


Fig. 26. Actual kinetics of the substance volume transferred in meat under the combined action of heat flow and electric current, depending on:
— sample thickness;
······· sample area;
------ applied pressure magnitude

Based on equation (3.18), the substance flux J_{liq}, that occurs under the combined influence of heat flow from the heater and electric current within the duration of 0…2 **s** can be determined by the equation [197]:

$$J_{liq}^{V} = \frac{V_{liq}}{S_m \cdot \tau} = \left(k_h \cdot Q \cdot \delta_m{}^{-0,272} + k_e \cdot k_s \cdot U \cdot \delta_m{}^{-0,728}\right) \cdot \frac{(p_{lim} - p)}{p_{lim}}, \text{ m/s}, \quad (3.19)$$

or in mass terms:

$$J_{liq}^{G} = \frac{V_{liq} \cdot \rho_m}{S_m \cdot \tau} = \left(k_h \cdot Q \cdot \delta_m{}^{-0,272} + k_e \cdot k_s \cdot U \cdot \delta_m{}^{-0,728}\right) \times \frac{(p_{lim} - p)}{p_{lim}} \cdot \rho_m, \text{ kg/(m}^2\text{·s)}. \quad (3.20)$$

Analysis of the dependencies for substance flux J_{liq} under the combined influence of heat flow from the heater and electric current (equations 3.19 and 3.20) allows the following conclusions:

- the substance flux J_{liq} in meat is directly proportional to the heat flow *Q* and the voltage *U* only during the first 2 seconds;
- an increase in meat thickness δ_m significantly and nonlinearly reduces the value of the flux J_{liq} ;
- an increase in pressure (due to greater compression force) leads to a linear decrease in the value of J_{liq};

the flux J_{liq} is directly proportional to the ratio of the electrode contact area to the surface area of the meat sample k_s;

There is a significant correlation between the applied excess pressure p and the ratio k_s of electrode contact area to meat surface area.

These conclusions indicate that during the combined action of heat flow and electric current in two-sided meat frying, the maximum flux J_{liq} is achieved through the superposition of substance flows generated by the heat and the electric current for a duration of 2 seconds. In the case of two-sided frying with electric current, maximum mass transfer is also achieved within 2 seconds, after which the polarity of the electrodes (cooking surfaces) must be reversed for another 2 seconds. This suggests that the optimal frequency of the electric current during two-sided frying under its influence is 0.5 Hz.

To develop optimal parameters for the meat frying process under the influence of electric current, it is necessary to conduct studies on the effects of heater heat flow Q, electric voltage U, current frequency, and pressure p during frying on the process duration and final product yield.

3.2. Research Results of the Conductive Frying Process of Meat under the Influence of Electric Current

Results of Studies on the Effect of Electric Current Voltage on the Duration of Double-Sided Frying and the Yield of the Finished Product

To investigate the effect of electric current during the double-sided frying of meat, an experimental setup was developed (Figures 26, 27). This setup included: an experimental prototype of a device for double-sided frying of meat under the influence of electric current; two digital TPC 02 "Universal Plus" devices with four XC-0.5 thermocouples for regulating the temperature of the frying surfaces and measuring the internal temperature of the samples; a variable autotransformer (LATRA) with a set of measuring instruments (voltmeter and ammeter) and the "Energia-9" electricity meter, through which the device was connected; and another LATRA with a set of measuring instruments (voltmeter and ammeter) and a frequency converter for regulating the parameters of the electric current.

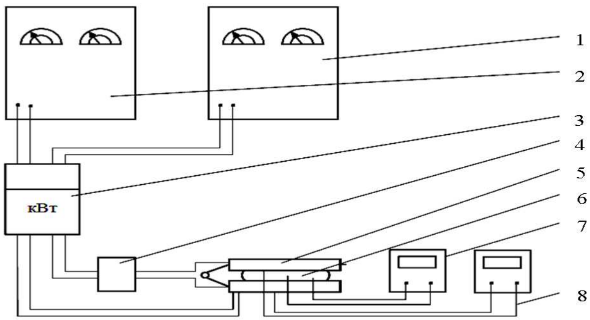


Fig. 26. Diagram of the Experimental Setup for Studying the Duration of the Double-Sided Frying Process under the Influence of Electric Current:

1 – LATRA for supplying electric current to the meat with a set of measuring instruments (voltmeter,

ammeter); 2 – LATRA for supplying power to the heating elements with a set of measuring instruments (voltmeter, ammeter); 3 – current frequency converter;
4 – "Energia-9" electricity meter; 5 – device for double-sided frying under the influence of electric current; 6 – test sample; 7 – digital device TPC 02 "Universal Plus";
8 – XC-0.5 thermocouples.

The experimental device consists of upper and lower platforms connected via a hinge. Each platform includes a frame, a heating element NEF-HK-0.5/110 [201], a heating plate, and a thermocouple embedded into the plate for regulating the frying surface temperature.

The study used meat samples with dimensions of 0.08 m in length, 0.06 m in width, and 0.01 m in height, without prior tenderization. The initial mass of the test sample $G_{s.f.}$ and the mass of the finished hot products $G_{f.p.}$ were determined using an "AXIS AD-600" analytical balance with an accuracy of up to 10^{-3} kg.

Fig. 27. Experimental Setup for Studying the Duration of the Double-Sided Frying Process under the Influence of Electric Current

The duration of the frying process was measured from the temperature at the center of the test samples $T_{поч} = 288$ K to $T_{ц} = 345$ K [56]. The temperature was recorded using three thermocouples inserted into the sample and connected to the TPC device. The frying time was recorded using the "Elektronika IT-01" stopwatch.

The yield of the finished product z was calculated using the formula [17]:

$$z = \frac{G_{s.f.}}{G_{f.p.}}. \tag{3.21}$$

The power consumed during double-sided frying under the influence of electric current was determined using the “Energia-9” electricity meter and a set of measuring instruments (voltmeter and ammeter).

Since the TPC 02 "Universal Plus" temperature controller allows for pulsed voltage supply to the heating elements, and the device was connected through the electricity meter, the total energy consumption $A_{tot.}$ during the frying process was determined as the difference between the final and initial readings using the formula:

$$A_{tot.} = A_{fin.} - A_{in.}, W \cdot s, \qquad (3.22)$$

where $A_{in.}, A_{fin..}$ – are the readings of the electricity meter at the beginning and end of the frying process, respectively, in W·s.

The specific energy consumption for the double-sided frying process under the influence of electric current was calculated using the formula:

$$b_e = \frac{3{,}6 \cdot 10^6 \cdot A_{tot.}}{G_{f.p.}}, kW \cdot h/kg, \qquad (3.23)$$

The quality of the finished products was assessed organoleptically in accordance with [202].

For the sensory evaluation of product quality, the most common 5-point system was used. The main quality indicators included: appearance, color, aroma, taste, texture, and juiciness, with weight coefficients considered (Appendix 2).

To ensure the reliability of the results, all experiments were conducted in triplicate.

The aim of the study was to determine the effect of the voltage of the electric current applied to the test sample on the duration of the double-sided frying process and the yield of the finished product.

Voltages of 0, 6, 9, 18, 27, and 36 V were applied to the frying surfaces, regulated using a laboratory transformer. Voltages above 36 V were not used due to safety concerns for human life [210].

The frequency of the electric current during the experiments was 50 Hz, and the excess pressure applied to the product was maintained at 800…1000 Pa.

The study used samples made from the longissimus dorsi muscle of pork, without prior tenderization, with dimensions of 0.08 m in length, 0.06 m in width, and 0.01 m in height, seasoned with salt and pepper according to the recipe [203].

The results of experimental studies on the influence of voltage U=9…36U = 9…36U=9…36 V (at a constant current frequency of 50 Hz and excess product pressure of 800…1100 Pa) on the duration of double-sided frying under electric current and on the yield of finished products made from the longissimus dorsi muscle of pork ($\delta_м = 0{,}01$ m) are presented in Fig. 28.

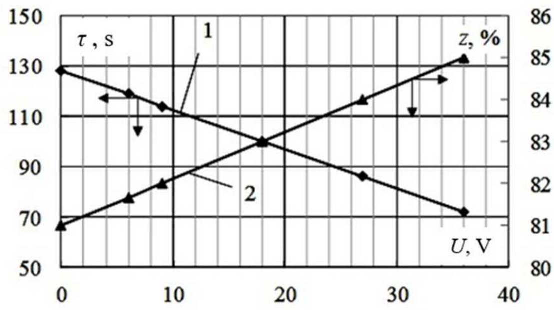


Fig. 28. Duration of Double-Sided Meat Frying τ (1) and Yield of Finished Product z (2) Depending on Voltage U at Constant Electric Current Frequency f = 50 Hz

As seen in Fig. 28, increasing the electric current voltage *U* during double-sided frying leads to a reduction in the duration of the thermal processing *τ* and an increase in the yield of the finished product zzz, following a linear relationship. For instance, at an electric current voltage of 36 V, the frying time is reduced nearly 1.8 times, from 128 to 72 seconds, and the yield of the finished product increases from 81% to 85% compared to conventional double-sided frying.

This effect can be explained by the fact that, in addition to the equalization of the temperature field throughout the product volume due to the oscillatory motion of substances under alternating electric current, the heating of the product is additionally carried out due to its electrical resistance as the voltage increases.

During the experiment, it was established that the application of electric current affects the organoleptic properties of the finished product. When the electric current voltage exceeds 30 V, unpleasant odor and taste due to electrolysis, as well as gray coloration of the product's surface, are observed. At voltages in the range of 6…27 V, these effects were not observed.

Since meat acts as a conductor through which electric current passes during double-sided frying, it additionally receives heat due to its own electrical conductivity in the amount of (0.5…4.0) × 10^3 J, which constitutes from 1% to 10% of the useful heat used for the frying process, depending on the applied voltage [204].

Thus, considering the deterioration of organoleptic characteristics at a voltage of 36 V, the rational electric current voltage for double-sided frying is 20–30 V. Further studies of the double-sided frying process under the influence of electric current were conducted at 27 V [205].

Results of Studies on the Effect of Electric Current Frequency on the Duration of Double-Sided Frying and the Yield of the Finished Product

The studies were conducted using the experimental setup (Figs. 26, 27). The objective was to determine the influence of electric current frequency applied to the test sample on the duration of the double-sided frying process and the yield of the finished product.

Electric current was supplied to the frying surfaces at frequencies of 0.5, 1.0, 2.0, 10.0, 20.0, and 50.0 Hz. The frequency was regulated and set using a current frequency converter.

The electric current voltage of 27 V was maintained using a LATRA, and excess pressure on the product was kept at 800–1000 Pa.

The results of the experimental studies on the duration of double-sided frying under electric current and the yield of finished products made from pork longissimus dorsi muscle samples (thickness 0.01 m) depending on electric current frequency f = 0,5…50, Hz, at constant voltage of 27 V and excess pressure of 800–1000 Pa, are shown in Fig. 29.

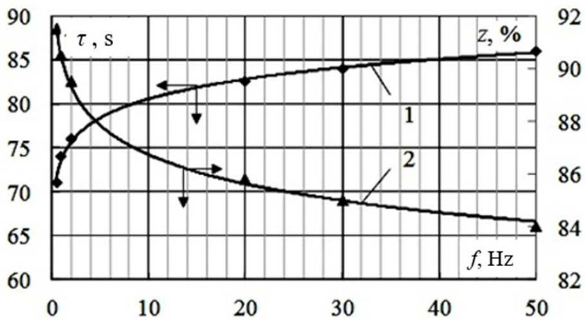


Fig. 29. Duration of Double-Sided Meat Frying τ (1) and Yield of Finished Product z (2) Depending on Electric Current Frequency f U = 27V

From Fig. 29, it is evident that increasing the frequency of electric current during double-sided frying leads to a longer thermal processing time τ and a lower finished product yield z, following a nonlinear trend. At a current frequency of 0.5 Hz, the frying duration and product yield were 71 seconds and 91.5%, respectively, while at 50 Hz they were 86 seconds and 84%. It should be noted that in the range from 0.5 to 2.0 Hz and from 2.0 to 20 Hz, a relatively sharp increase in frying duration is observed—up to 7–8.5%. When the frequency increases further from 20 to 30 Hz and from 30 to 50 Hz, the increase in frying duration becomes more gradual, with an increase of only about 1.8–2.4%.

An electric current frequency of 0.5 Hz, corresponding to a change in polarity on the frying surfaces every 2 seconds, promotes the most effective heat and mass transfer within the meat. This frequency ensures the formation of an effective liquid layer δ_{ef} in the meat with a high thermal conductivity coefficient, and enables thermodynamic processes of water vapor in capillary menisci as the liquid moves toward the frying surface. The heat transfer under these conditions is described in section 2.5.

Additionally, the change in fluid flow direction due to polarity switching leads to the formation of cavities with increased heat exchange surface area near the frying surfaces.

Due to the action of electric current causing the liquid to change direction every 2 seconds and remain inside the meat, the yield of the finished product increases.

Thus, the use of low-frequency electric current (0.5 Hz) compared to industrial frequency current (50 Hz) allows for a reduction in the duration of double-sided frying by nearly 18% and a reduction in mass loss of the finished product by 7.5% [206].

Results of Studies on the Effect of Excess Pressure on the Duration of Double-Sided Frying under Electric Current and the Yield of the Finished Product

The studies were conducted using the experimental setup (Figs. 26, 27).

The aim of the study was to determine the influence of the magnitude of excess pressure applied to the samples on the duration of the double-sided frying process and the yield of the finished product.

The experiments were based on the results of previous studies, which had established the optimal parameters: voltage of 27 V and electric current frequency of 0.5 Hz.

Excess pressure on the product was created by placing weights of 0.2, 0.5, 1.0, and 2.0 kg on the upper panel of the frying device.

The experiments were conducted under the following excess pressure values: 0, 0.4×10^3, 0.8×10^3,

1.0×10^3, 1.2×10^3, 1.6×10^3, 2.0×10^3, 2.4×10^3, 3.2×10^3, 4.0×10^3, and 4.8×10^3 Pa.

The results of experimental studies on the duration of double-sided frying under the influence of electric current and the yield of finished products made from pork longissimus dorsi muscle samples (thickness 0.01 m), depending on the applied excess pressure p=0…4800p = 0…4800p=0…4800 Pa, at constant voltage of 27 V and current frequency of 0.5 Hz, are shown in Fig. 30.

As seen in Fig. 30, increasing the excess pressure ppp applied to the samples has a nonlinear effect on the frying duration τ and the yield of the finished product z. The minimum frying duration (73 seconds) and maximum product yield (91.3%) are achieved in the excess pressure range of 800–1100 Pa. Increasing the excess pressure from 1100 to 4800 Pa leads to an increase in frying time by 1.3 times, up to 95 seconds, and a decrease in yield by 8.3%.

It is evident that increasing the excess pressure from 0 to 800 Pa improves the contact between the product and the frying surfaces, which enhances heat transfer conditions. However, increasing the pressure above 1100 Pa reduces the volume of capillaries and pores in the meat that are free from liquid, thus reducing the surface area available for heat exchange. Further increases in excess pressure cause mass transfer under electric current to cease, as the pressure forces liquid in the meat toward the frying surfaces, halting its movement under electric current.

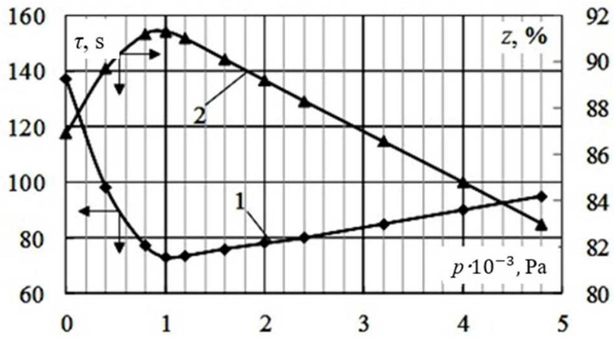


Fig. 30. Duration of Double-Sided Meat Frying τ (1) and Yield of Finished Product z (2) Depending on Excess Pressure p at Constant Voltage U = 27 V and Electric Current Frequency f = 50 Hz

Therefore, the optimal excess pressure during double-sided frying under electric current is in the range of 800–1100 Pa. This ensures firm contact between the product and the frying surfaces without excessively reducing the internal volume of capillaries in the meat or altering its thermophysical properties [203].

Results of Studies on the Effect of Heat Flux Intensity from Frying Surfaces on the Duration of Double-Sided Frying under Electric Current and the Yield of the Finished Product

The studies were conducted using the experimental setup (Figs. 26, 27).

The aim of the study was to determine the effect of heat flux intensity from the heater on the duration of the double-sided frying process under the influence of electric current and the yield of the finished product.

The experiments were carried out at the following heat flux values: 20, 40, 60, 80, 100, and 120 W.

The corresponding heat flux supplied to the product was maintained by adjusting the power of the heating elements using a LATRA.

The electric current voltage of 27 V, frequency of 0.5 Hz, and excess pressure of 800...1100 Pa were kept constant throughout the experiment.

The test samples used for the study were made from pork longissimus dorsi muscle without prior tenderization, measuring 0.05 m in length, 0.04 m in width, and 0.01 m in thickness, seasoned with salt and pepper according to the recipe [201].

The results of the experimental studies on the duration of double-sided frying under electric current and the yield of finished products made from pork longissimus dorsi muscle samples (0.05 m × 0.04 m × 0.01 m), depending on the heat flux from one frying surface Q = 20…120 W, and the corresponding specific heat flux per unit area of the sample q = $10…60 \cdot 10^3$ W/m², at constant electric current voltage of 27 V, frequency of 0.5 Hz, and excess pressure of 800…1100 Pa, are presented in Figs. 31 and 32.

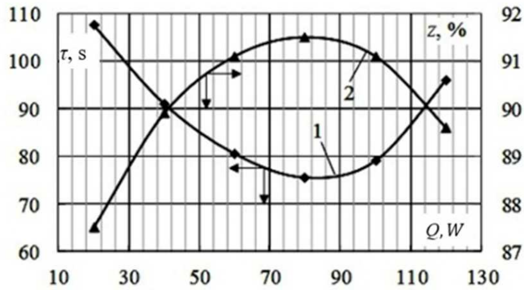


Fig. 31. Duration of Double-Sided Meat Frying τ (1) and Yield of Finished Product z (2) Depending on Heat Flux from the Heater Q at Constant Voltage U = 27 V and Electric Current Frequency f = 50 Hz

As shown in Figs. 31 and 32, an increase in the heat flux Q from the frying surfaces and, consequently, the specific heat flux q during double-sided frying under the influence of electric current nonlinearly affects the frying duration τ and the yield of the finished product z.

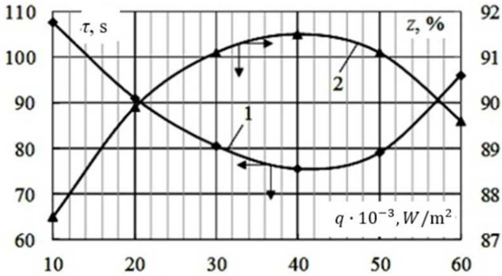


Fig. 32. Duration of Double-Sided Meat Frying τ (1) and Yield of Finished Product *z* (2) Depending on Specific Heat Flux *q* at Constant Voltage *U* = 27 V and Electric Current Frequency *f* = 50 Hz

The minimum frying duration of 75 seconds for samples with a surface area of 0.002 m^2 and the maximum yield of 91.5% were observed at a heat flux from one frying surface in the range of 77…83 W, corresponding to a specific heat flux of 38.5…41.5 × 10^3 W/m^2.

When the heat flux exceeds 41.5 × 10^3 W/m^2, the frying duration increases significantly. This can be explained by overheating of steam in the surface layers of the product in contact with the frying surfaces and the formation of a continuous layer of superheated steam in the contact zone, which significantly impairs heat transfer from the frying surfaces to the meat [204].

Results of Experimental Determination of the Duration of Thermodynamic Processes in Capillary

Menisci during Double-Sided Meat Frying under Electric Current

It is practically impossible to directly determine the duration of the thermodynamic process τ in each individual capillary. However, it can be indirectly estimated from the frequency spectrum of the sound emitted during frying.

To determine the duration of thermodynamic processes in the capillary menisci during double-sided meat frying under the influence of electric current, an experimental setup was used, as shown in Figs. 26 and 27.

A thermocouple XC-0.5 was placed in the center of the prepared meat sample (semi-finished product) with a thickness of 0.01 m and a mass of 0.05 kg. The signal from the thermocouple was recorded by the TPC 0.2 “Universal Plus” device, which transmitted temperature data to a computer for display.

To record sound, a digital LG voice recorder was used in accordance with [207]. It was placed on a tripod at the height of the sample and at a distance of 0.2 m in front of the experimental double-sided frying device operating under pressure.

The process of double-sided frying under optimal parameters (U = 27 V, f = 0.5 Hz, excess pressure p=1100 Pa, frying surface temperature 423 K) and the corresponding sound recording were carried out at night.

The recorded sound file was analyzed using the *Spectrum Player* program.

The duration of the thermodynamic processes τ during double-sided frying was determined based on the sound frequency spectrum *f*, Hz, using the formula:

$$\tau = \frac{1}{f}, s. \tag{3.24}$$

We recorded the sound during double-sided meat frying under optimal conditions (*U* = 27 V, current frequency 0.5 Hz, steam overpressure p=1100 Pa, specific surface power of each frying surface 38,500 W/m^2), and analyzed the resulting *wav* file using *Spectrum Player*. *Spectrum Player* allows frequency analysis of sound not only at a specific moment but also over a selected time interval.

A screenshot of the frequency spectrum of sound during the double-sided frying process under electric current in *Spectrum Player* is shown in Fig. 33.

As shown in Fig. 33, the sound spectrum during double-sided frying is divided into four main sub-ranges: (2.5–4), (4.5–6), (6.5–7.5), and (8–9) kHz. These ranges correspond to four groups of capillaries by diameter: (122–195)×10^{-6} m, (81–108)×10^{-6} m, (65–75)×10^{-6} m, and (54–60)×10^{-6} m.

According to formula (3.11), the duration of thermodynamic processes in the capillaries ranges from 111×10^{-61} to 400×10^{-6} s.

The heat transfer coefficient under the given conditions, with a mean temperature difference (temperature head) $\Delta\overline{T}_c = 8$ K [17], using the ratio $d_\kappa/\tau = 0{,}488$ m/s and the difference in specific volumes at points 3 and 1 (Fig. 6) on the *T-S* diagram for water and steam at normal atmospheric pressure Δv=1,653 m³/kg, is: k=4813 W/(m²K). The heat transfer coefficient from vapor to liquid in the menisci of each of the two surface layers is: $\alpha_2 = 2 \cdot k =$ 9626 W/(m²K). Thus, the total heat transfer coefficient from steam to liquid in the menisci, considering heat supply from both sides, is: α=19252 W/(m²K).

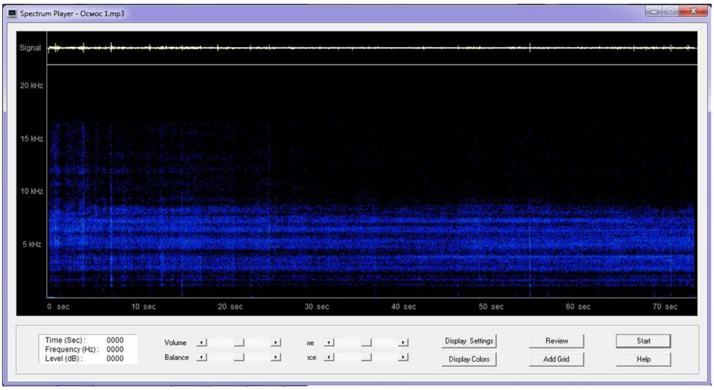


Fig. 33. Screenshot of Sound Frequency Spectrum during Double-Sided Meat Frying under Electric Current in the Spectrum Player Program

The thermal conductivity of lean pork longissimus dorsi at 293 K and atmospheric pressure is: $\lambda_{м0} =$ 0,54 W/(m·K) [208]; For meat juice under the same conditions:, – $\lambda_{р} = 0{,}645$ W/(m·K) [209]. Under the influence of electric current and due to the formation of an effective liquid layer (meat juice), the thermal conductivity of the meat approaches: $\lambda_{м} = 0{,}645$ W/(m·K). The density of the meat under compression is: $\rho = 960$ kg/m^3; The specific heat capacity of the liquid: $c = 4000$ J/(kg·K). The thermal diffusivity of the meat during heating to 345 K: $a = \frac{0{,}645}{4000 \cdot 960} = 16{,}8 \cdot 10^{-8} m^2$/s. The Biot number for the first stage of the frying process is: $Bi = \frac{19252 \cdot 0{,}000093}{0{,}645} = 2{,}8$, where 0,000093 m – is the radius of the largest capillary in the surface layer of the meat ($d_{к_{max}} = 195 \cdot 10^{-6}$ m). For the second stage of frying, the half-thickness of the effective meat layer is: $\delta_{еф}/2$ based on the total thickness $\delta_{м} = 0{,}01$ m, and calculated $\delta_{еф} = 0{,}0072$ m, using formulas (2.28) and (2.29) from Appendix 3. The Biot number for the second stage of frying: $Bi = \frac{19252 \cdot 0{,}0036}{0{,}645} = 107{,}5$.

The duration of the first frying stage—from the initial meat temperature of 288 K to the surface layer temperature of 393 K—for a thickness equivalent to the radius of the largest surface capillary at $\rho = 0$, is determined using the formula [172]:

$$Fo^{(0)} = \frac{1}{12} + \frac{1}{3 \cdot Bi} - \frac{2}{3 \cdot Bi^2} ln\left[1 + \frac{1}{2} \cdot Bi\right], \qquad (3.25)$$

$$Fo^{(0)} = \frac{1}{12} + \frac{1}{3 \cdot 2{,}8} - \frac{2}{3 \cdot 2{,}8^2} ln\left[1 + \frac{1}{2} \cdot 2{,}8\right] = 0{,}128.$$

Then, according to formula (2.25):

$$Fo^{I} = \frac{2{,}8 + 3}{32{,}8} ln\left(\frac{2 \cdot (423 - 288)}{(2{,}8 + 2) \cdot (383 - 373)}\right) + 0{,}128 = 1{,}33,$$

from which, using formula (2.27), the duration of the first frying stage is:

$$\tau_I = \frac{1.33 \cdot 0{,}000093^2}{16{,}8 \cdot 10^{-8}} = 0{,}068\ s.$$

The Fourier number according to formula (4.21) for the second stage is:

$$Fo^{(0)} = \frac{1}{12} + \frac{1}{3 \cdot 107,5} - \frac{2}{3 \cdot 107,5^2} ln\left[1 + \frac{1}{2} \cdot 107,5\right] = 0,087.$$

and according to formula (2.26):

$$Fo^{II} = \frac{1}{3} ln\left(\frac{107,5 \cdot (383 - 374)}{2 \cdot (373 - 345)}\right) + 0,087 = 0,95.$$

From which, using formula (2.27), the duration of the second frying stage is:

$$\tau_{II} = \frac{0,95 \cdot 0,0036^2}{16,8 \cdot 10^{-8}} = 73,29\ s.$$

Therefore, the theoretical duration of the double-sided frying process of meat under the influence of electric current, until the temperature at the center of the product reaches 345 K, is:

$$\tau_0 = 0,068 + 73,29 = 73,4\ s.$$

The calculated data fully correspond to the process data presented in Figs. 32 and 33 [190].

Results of Studies on the Double-Sided Frying Process of Frozen Semi-Finished Products

The study of the double-sided frying process of frozen semi-finished products under the influence of electric current was conducted using the experimental setup (Figs. 26, 27) and the following methodology.

The aim of the study was to determine the efficiency of the process of double-sided frying of frozen meat under pressure and the influence of electric current, as well as to evaluate the duration, yield, and quality of the finished product and energy indicators.

The research was conducted using samples made from chilled pork longissimus dorsi muscle (hereinafter referred to as the control), after preliminary freezing in a freezer and subsequent thawing in air at a temperature of 293 K (hereinafter referred to as meat 1), and frozen meat (hereinafter referred to as meat 2) with the addition of salt and pepper according to the recipe.

The samples of meat 1 were frozen to a central temperature of 255 K in a SAMSUNG COOLTECH BIO freezer and then thawed in air to a central temperature of 288 K. The samples of meat 2 were frozen to a central temperature of 255 K.

To study the process of double-sided frying under the influence of electric current, the above-mentioned experimental setup and methodology were used. The study of double-sided frying under pressure was conducted in accordance with the methodology presented in [90].

Double-sided frying under the influence of electric current was carried out with the following parameters: voltage of 27 V, current frequency of 0.5 Hz, applied excess pressure of 1000 Pa, and heat flux from each frying surface of $39 \cdot 10^3$ W.

Product readiness was determined by reaching a central temperature of 345 K.

The results of the study of the frying process of samples after preliminary freezing to 255 K (meat 2) and thawing in air to 288 K (meat 1) (Figure 34) indicate that the duration of the double-sided frying process under compression for meat 1 was almost the same as for the control and amounted to 61 and 60 s, respectively. The frozen semi-finished products (meat 2) required 2.3 times longer frying time compared to the products made from chilled meat (control), namely 140 and 60 s, respectively.

A similar trend was observed during double-sided frying under the influence of electric current. Thus, the products after preliminary freezing and thawing (meat 1) reached culinary readiness in approximately the same time as the control samples – 76 and 75 s, respectively. Products made from frozen meat (meat 2) required twice as much time as the control samples – 150 and 75 s, respectively.

The study of the yield of the finished product was conducted taking into account losses during freezing and thawing for meat 1, and during freezing for meat 2. According to the results, it was established that mass losses of semi-finished products due to freezing and thawing processes amounted to 0.6% and 4.6% of the initial mass, respectively.

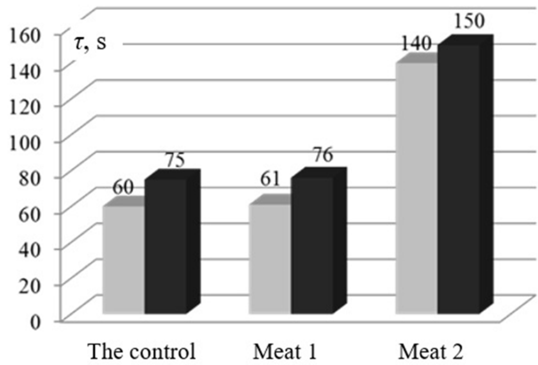


Fig. 34. Duration of double-sided frying of frozen pork semi-finished products:
▯ – under excess pressure at the critical level (p_{crit} = 12,400 Pa);
▮ – under the influence of electric current (U = 27 V, f = 0.5 Hz).

The yield of finished products (Fig. 35) relative to the initial mass of the semi-finished products during double-sided frying under excess pressure at the critical level is 81.9% for meat 1 and 90% for meat 2, compared to 89% for the control.

During frying under the influence of electric current, the yield of finished products for meat 1 and meat 2 is 87.3% and 93%, respectively, compared to 91% for the control sample.

The significant mass loss in finished products made from meat 1 by both frying methods is explained by technological losses during thawing and an increase in the amount of free moisture.

The high yield of finished products from meat 2 can be attributed to minimal losses during thawing in the frying process, as it occurs intensively and lasts about 40–60 seconds.

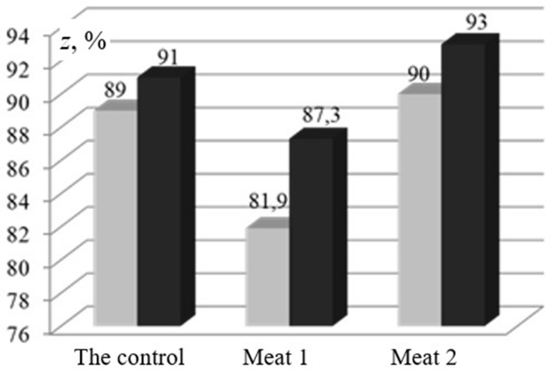


Fig. 35. Yield of finished products from frozen semi-finished meat products after double-sided frying:
▫– under excess pressure at the critical level (p_{crit} = 12400 = 12,400 Pa);
▪– under the influence of electric current (U = 27 V, f = 0.5 Hz).

The total specific electricity consumption for the processes of freezing to a temperature of 255 K and frying (both under pressure and under the influence of electric current) amounts to 0.380–0.420 kWh/kg, of which 0.320–0.335 kWh/kg is the specific energy consumption directly for the frying process [210, 211].

Thus, double-sided frying of frozen portioned semi-finished meat products under the influence of electric current is a promising direction for the industrialization of fried natural meat product manufacturing. It ensures a finished product yield of 93% within 145–155 seconds, helps minimize specific energy consumption for producing fried products, and reduces non-technological losses during transportation, thawing, and thermal processing.

3.3. Research Results on the Quality of Finished Products after Double-Sided Frying under the Influence of Electric Current

Results of quality assessment of finished products based on physicochemical indicators

Among the most important physicochemical indicators of finished products are pH, tenderness, and the content of substances hazardous to human health.

The active acidity (pH) of finished products reflects the acid content and the associated activity of enzymes and bacteria, which affects the shelf life of the product.

The study was conducted using samples made from pork longissimus dorsi muscle with dimensions of 0.08 m in length, 0.06 m in width, and 0.01 m in thickness. Acidity was measured for raw meat, for finished products fried by the conventional method in a frying pan until reaching a center temperature of 345 K at a surface temperature of 453 K, and for finished products after double-sided frying under the influence of electric current until reaching a center temperature of 345 K at a frying surface temperature of 423 K. The current frequencies were 0.5, 1.0, 2.0, 10, 20, and 50 Hz, at a voltage of 27 V and an excess pressure on the product of 1000 Pa.

The active acidity of the samples was measured using a pH meter HI 9321 in accordance with [212].

Meat tenderness was determined using the Warner–Bratzler method, modified by Maksakov [213].

During frying under the influence of electric current, there is a possibility that material from the frying surfaces—aluminum—may transfer into the finished product. Approaching or exceeding its maximum allowable concentration (MAC) in the product may result in a ban on human consumption. The recommended daily intake of aluminum for an adult is 49–50 mg [214], according to other data—1 mg per 1 kg of body weight per day [215], while the maximum allowable intake is 90 mg [216].

The determination of aluminum content (concentration) was conducted in an accredited research and testing center for food products of the state enterprise "Poltava Regional Scientific and Technical Center for Standardization, Metrology, and Certification," in accordance with DSTU ISO/IEC 17025-2006 (accreditation certificate No. 2H289 dated 30.11.2009).

The aluminum content was studied in samples made from pork longissimus dorsi muscle with dimensions of 0.08 m in length, 0.06 m in width, and 0.01 m in thickness after frying by the conventional method in an aluminum pan to a center temperature of 345 K at a frying surface temperature of 453 K; after double-sided frying under the influence of electric current at a current frequency of 0.5 Hz, voltage of 27 V, and excess pressure on the product of 1000 Pa until a center temperature of 345 K at a frying surface temperature of 423 K; and in raw meat as a control.

The aluminum content was determined in accordance with [217].

The initial total moisture content of the test meat samples was determined in accordance with [218].

The results of experimental studies on the effect of electric current frequency on the active acidity of finished products after double-sided frying are presented in Table 3.11 and Figure 36.

Table 3.11

Results of active acidity determination in experimental samples

Treatment Method	Active Acidity of Products (pH)					
After double-sided frying under electric current with frequency:	0,5 Hz	1 Hz	2 Hz	10 Hz	20 Hz	50 Hz
	5,90	5,75	5,58	5,42	5,30	5,19
After conventional frying	5,30					
Raw meat (control)	5,10					

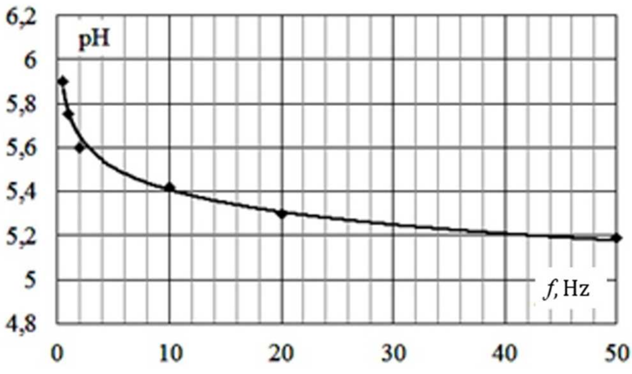


Fig. 36. Kinetics of changes in active acidity (pH) of finished products
after double-sided frying under electric current of different frequencies, $U = 27$ V

The obtained results show that with an increase in electric current frequency from 0.5 to 50 Hz, the active acidity (pH) of the finished products decreases non-linearly from 5.90 to 5.19. The best results were obtained from the samples with acidity closest to neutral—after double-sided frying under the influence of electric current at a frequency of 0.5 Hz.

The results of the study on the effect of electric current frequency during double-sided frying on the tenderness of pork products, according to the Warner–Bratzler method in the Maksakov modification, are presented in Table 3.12 and Figure 37.

Table 3.12

Results of tenderness determination of finished products

Treatment Method	Tenderness of Finished Products (cm^3/s)					
After double-sided frying under electric current with frequency:	0,5 Hz	1 Hz	2 Hz	10 Hz	20 Hz	50 Hz
	17,40	17,37	17,34	17,22	17,14	17,00
After conventional frying	17,10					
Raw meat	12,40					

The analysis of the obtained results shows that an increase in the electric current frequency during double-sided frying from 0.5 to 50 Hz leads to a non-linear decrease in the tenderness of the finished products, from 17.40 to 17.00 cm³/s.

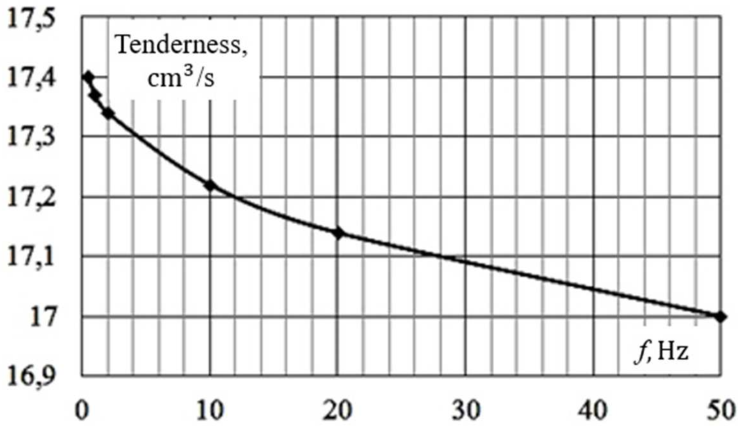


Fig. 37. Kinetics of changes in tenderness of finished products after double-sided frying under the influence of electric current of different frequencies, U = 27 V

The results of aluminum content studies in raw meat and finished products after conventional frying and double-sided frying under the influence of electric current (Table 3.13) indicate that as a result of exposure to electric current, aluminum from the frying surfaces migrates into the product.

Table 3.13

Results of the safety assessment of raw pork and finished products after conventional frying in a pan and double-sided frying under electric current, based on aluminum content

Treatment Method	Actual Aluminum Concentration, mg/kg
Raw meat	less than 0,05*
After conventional frying in an aluminum pan	less than 0.07*
After double-sided frying under electric current	3,02

The concentration of aluminum in products after double-sided frying under the influence of electric current is 3.02 mg/kg, after conventional frying – 0.07 mg/kg, and in raw meat – 0.03 mg/kg. Since aluminum content in food products is not regulated in Ukraine [214], and the recommended daily intake for an adult is 49–50 mg [213], or 1 mg per 1 kg of body weight [215], the aluminum content in the finished products at the level of 3.02 mg/kg can be considered acceptable for human consumption.

The test protocols for determining aluminum content in finished products from the frying surfaces are provided in Appendix 4.

These data indicate that the aluminum concentration in finished products after double-sided frying under the influence of electric current does not exceed the recommended limit for human consumption and is entirely safe [219, 220].

Results of the Quality Assessment of Finished Products Based on Microbiological Indicators

The aim of the study was to determine the level of microbiological safety of finished products made from pork longissimus dorsi muscle after double-sided frying under electric current with a frequency of 0.5 Hz, voltage of 27 V, and an excess pressure on the product of 1000 Pa, until the core temperature reached 345 K, at a frying surface temperature of 423 K. Microbiological quality indicators were determined for raw meat, meat fried by the conventional method in a pan to a core temperature of 345 K at a surface temperature of 453 K, and meat fried using the double-sided method under the specified electric parameters.

Microbiological indicators for raw meat and finished products were determined at the research and testing center for food products of the State Enterprise "Poltava Regional Scientific and Technical Center for

Standardization, Metrology, and Certification," accredited in accordance with the requirements of DSTU ISO/IEC 17025-2006 (Accreditation Certificate No. 2H289 dated 30.11.2009).

The list of indicators for assessing the microbiological safety of raw meat was established in accordance with DSTU 7158:2010 [221], and for finished products – in accordance with sanitary regulations DSP 4.4.5.078-2001 [222].

The number of mesophilic aerobic and facultative anaerobic microorganisms (MAFAM CFU) was determined according to GOST 10444.15-94 [223].

Bacteria of the coliform group were determined in accordance with GOST 7702.2.2-93 [224].

Detection of *Proteus* spp. was conducted in accordance with GOST 28560-90 [225].

The presence of *Staphylococcus aureus* was determined according to GOST 10444.2-94 [226].

The presence of pathogenic organisms, including *Salmonella*, was determined in accordance with GOST 30519-97 [227].

The results of the study on the quality of semi-finished products, finished products after conventional frying, and those after double-sided frying under the influence of electric current at the following parameters: frying surface temperature not exceeding 423 K, specific heat flux from each frying surface $39 \cdot 10^3$ W/m², electric current voltage 27 V, current frequency 0.5 Hz – based on microbiological indicators, are presented in Table 3.14.

The data in Table 3.14 indicate the complete absence of pathogenic and harmful microorganisms, whose presence is not allowed in either raw or cooked meat [218, 219].

It was found that the MAFAM count in 1 g of the semi-finished product was 1.5×10^5, which is 150 times higher than the permissible limit of 1×10^3 CFU/g [218]. Frying by both the conventional method and double-sided frying under electric current reduces this figure to levels acceptable for human consumption—not more than 1×10^4 CFU/g [222, 228], amounting to 1.5×10^2 and 4.5×10^2 CFU/g, respectively.

The proposed frying method achieves these results at significantly lower temperatures and in a shorter time [218, 219, 229].

Table 3.14

Results of the quality assessment of fried products and raw meat based on microbiological indicators

Sanitary-bacteriological characteristics	Sample name		
	Raw meat	After conventional frying in a pan	After double-sided frying

					under the influence of electric current
	standard	actual	standard	actual	actual
Coliform bacteria in 1 g	not permitted	not detected	not allowed	not detected	not detected
Proteus bacteria in 0.1 g	not allowed.	not detected	not allowed	not detected	not detected
MAFAM (CFU/g)	not more than $1{\cdot}10^3$	$1{,}5{\cdot}10^5$	not more than $1{\cdot}10^4$	$1{,}5{\cdot}10^2$	$4{,}5{\cdot}10^2$
Pathogenic microorganisms incl. *Salmonella* in 25 g	not allowed	not detected	not allowed	not detected	not allowed
Staphylococcus aureus in 1.0 g	not allowed	not detected	not allowed	not detected	not allowed

Results of Quality Assessment of Finished Products Based on Organoleptic Indicators

To evaluate consumer preferences for food products, the organoleptic method is widely used, relying on the human senses: sight, smell, taste, touch, and hearing.

The advantages of organoleptic analysis include accessibility and speed in determining quality indicators, and the absence of a need for costly equipment.

Disadvantages include subjectivity, the relative and non-dimensional nature of the results, incompatibility, and insufficient reproducibility [230].

Organoleptic methods provide a rapid, objective, and reliable general characterization of product quality based on properties such as appearance, color, aroma, taste, and texture.

Using vision, one evaluates the appearance – general visual impression; shape – geometric properties of the product; color – an impression caused by a light stimulus.

Touch is used to evaluate texture – product's structural characteristics and rheological properties; density – resistance felt when pressing the product; elasticity – ability to return to original shape after compression; and firmness-related to the speed and degree of shape recovery after deformation ends.

Smell assesses the product's aroma - a sensation triggered by olfactory receptors; and the fragrance – a pleasant, harmonious smell typical of the product.

In the mouth, one evaluates juiciness – the sensation created by the juice released during chewing; uniformity – the texture impression from product particles; consistency - the perception of thickness and pressure during tongue manipulation; fibrousness – resistance due to fibers while chewing; tenderness – a conditional term assessed by resistance to chewing; taste—sensations from taste receptors, both qualitative and quantitative; and flavor – a complex sensation of taste, smell, and texture during oral distribution [231].

For assessing food quality, two main organoleptic methods are used:

- consumer evaluation methods, aimed at checking consumer reactions to changes in formulation or processing, comparing a new product with a traditionally prepared one.
- analytical methods, based on quantitative assessments of quality indicators and enabling correlation analysis between specific attributes.

The point-rating system, part of analytical methods, best meets modern requirements. It allows determining both individual (by criterion) and overall product quality levels and includes a five-level scale for quality attributes [230].

Organoleptic evaluation of the finished products' quality was performed using the 5-point rating system described in Appendix 2, assessing the following indicators: appearance, color, aroma, texture, juiciness, and taste, taking into account the weighting coefficient of each parameter.

The results of the quality evaluation of finished products made from pork longissimus dorsi after conventional frying, double-sided frying, double-sided frying under electric current, and double-sided frying under electric current of frozen semi-finished products are presented in Table 3.15

As shown in Table 3.15, the lowest score of 3.60 was received by the products fried in a pan using the conventional method. This can be explained by significant deformation of the products and uneven crust formation, reduced juiciness and a dense texture, as well as the development of an unpleasant burnt taste and smell due to the long duration and high-temperature mode of the frying process.

Table 3.15

Results of the organoleptic evaluation of the quality of finished products

Organoleptic indicators	Weight coefficient	Frying method			
		Conventional frying	Double-sided frying	Double-sided frying under the influence of electric	Double-sided frying under the influence of electric current

				current	of frozen semi-finished products
Appearance	0,1	3,56	4,89	4,78	4,78
Color	0,1	3,78	4,89	4,67	4,67
Smell, aroma	0,1	3,89	4,78	4,78	4,89
Texture	0,2	3,44	4,56	4,78	4,89
Taste	0,3	3,89	4,89	4,78	4,78
Juiciness	0,2	3,11	4,11	5,00	5,00
Average score considering weight coefficient	1	3,60	4,66	4,81	4,85

Products subjected to double-sided frying, regardless of the method, received significantly higher scores for appearance, color, smell, aroma, and taste, with no substantial differences among them. In terms of texture and juiciness, the products prepared by double-sided frying under electric current scored much higher. This is explained by the better moisture retention inside the product due to continuous internal circulation of water during the process.

However, the finished products made from frozen semi-finished goods exhibited the most tender texture, which is attributed to the softening of muscle tissue during freezing.

The average scores for products after double-sided frying and double-sided frying under electric current, including from frozen semi-finished products, were 4.66, 4.81, and 4.85, respectively [228, 232].

3.4. Conclusions for the Chapter

1. Based on the analysis of calculated indicators of energy efficiency in the processes of conductive meat frying in devices designed for their implementation, using the comprehensive methodology developed in Section 2.1, directions have been formulated for improving energy efficiency and resource conservation in the process of conductive frying.

2. As a result of studying mass transfer under physical and electrophysical influences:

– regularities of substance flow formation in meat under the influence of electric current within a duration of 1–5 seconds were established in the form of dependencies (3.6) or (3.7), according to which the substance flow J_{liq_e} is directly proportional to the electric voltage U, the ratio of the electrode area to the meat area k_S ($0 \leq k_S \leq 1$), the ratio of the difference between the meat's limiting pressure p_{lim} and the applied excess pressure p to the limiting pressure $(p_{lim} - p)/p_{lim}$, and nonlinearly depends on the meat thickness δ_m;

– regularities of substance flow formation in meat under the influence of heat flux from a heater within 1–5 seconds were established in the form of dependencies (3.14) or (3.15), according to which the substance flow J_{liq_h} is directly proportional to the heat flux Q from the heater, the same pressure ratio $(p_{lim} - p)/p_{lim}$ and nonlinearly depends on the meat thickness δ_m;

– regularities of substance flow formation in meat under combined action of electric current, heat flux, and applied excess pressure within 1–2 seconds were established in the form of dependencies (3.19) or (3.20), according to which the total substance flow J_{liq} is directly proportional to the superimposed substance flows J_{liq_e} and J_{liq_h}, generated by electric current and heat flux from the heater;

–It was established that the maximum substance flow J_{liq} under combined thermal and electrical influences, with direct superposition of flows J_{liq_e} and J_{liq_h}, is achieved after 2 seconds of exposure.

3. These regularities confirm the hypothesis about the formation of an effective liquid layer (meat juice) δ_{ef}, thinner than the meat thickness δ_m, during double-sided frying under electric current, with the thermophysical properties of meat juice as presented in Section 2.3.

4. As a result of studying the double-sided meat frying process under electric current:

– it was established that increasing the voltage above 27 V leads to a sharp deterioration in product quality due to the unpleasant taste and smell of electrolysis and the gray coloration of the crust;

– it was determined that the minimum process duration is $\tau = 75$ s for chilled and $\tau = 150$ s for frozen semi-finished products. The maximum product yield is $z = 91.5\%$ for chilled and $z = 93\%$ for frozen semi-finished products, achieved at a current frequency of 0.5 Hz, applied excess pressure of 800–1100 Pa, and heat flux of 77–83 W, or specific heat flux of 38.5–41.5×10^3 W/m². This formed the basis for the development and patenting of the invention "Method of meat frying" in Ukraine [233];

– it was established that the quality of the products fried under these parameters – based on physicochemical, microbiological, and organoleptic indicators – is no lower than that of products fried traditionally in a pan or via double-sided frying under compression.

Based on the analysis of sound recordings during double-sided frying under the above parameters, and using the methodology developed in Section 3.5.5:

– the duration of evaporation and condensation processes in capillary menisci of various diameters was determined, ranging from 111×10^{-6} to 400×10^{-6} s;

– the diameter range of capillaries in the surface layer of the meat during double-sided frying under electric current was determined to be 54×10^{-6} to 195×10^{-6} m;

- the heat transfer coefficient from one and two frying surfaces to the product was calculated;
- the dependence of the heat transfer coefficient on the specific surface power of the frying surfaces was established;
- theoretically calculated durations of the first and second stages of the process coincided with actual values, confirming the adequacy of the analytical model (2.27).

CHAPTER 4. DEVELOPMENT AND STUDY OF ENERGY- AND RESOURCE-EFFICIENT PROCESSES OF CONDUCTIVE FRYING OF MEAT WITH HIGH CONNECTIVE TISSUE CONTENT UNDER EXCESS PRESSURE IN A FUNCTIONALLY CLOSED VOLUME

4.1. Results of the Study of the Double-Sided Frying Process of Meat with High Connective Tissue Content in a Functionally Closed Volume

According to the technological requirements for the conductive frying process of meat with high connective tissue content (HCCT), the preservation of native moisture and the supply of the required amount of heat without deformation of the product surface are essential conditions for ensuring a sufficient degree of collagen-to-gelatin conversion.

The technological requirements for the conductive frying process of HCCT meat, as well as the influence of excess pressure at the level of p_{lim}, at which mass transfer does not occur (see equations (3.14) or (3.15)), allow for the justification of rational parameters of the double-sided frying process of HCCT meat in a functionally closed chamber (FCC):

–the surface temperature of the heating plates must not exceed 423 K;

–the compression force must ensure the steam pressure p at the limit level for HCCT meat p_{lim}, i.e., $p = p_{lim}$, at which there are no conditions for substance (liquid) flow in the meat. According to equation (3.17), the thermal conductivity of meat at this point approaches that of a liquid;

–the temperature at the center of the product, to ensure the highest yield of the finished product, should not exceed 358 K.

To study the process of double-sided frying of HCCT meat under compression in the FCC, a pilot experimental apparatus was designed and built (Figures 38 and 39). In this apparatus, mica-based electric heaters NEF-HK-0.5/110 [199] were used as heat-generating devices to convert electrical energy into heat, providing a specific heat flux of 38500 W/m^2.

The temperature of each heating surface is maintained at the set level using the TRC-02 "Universal Plus" dual-channel temperature measurement and control device, which supplies pulsed voltage to the electric heaters near the regulation temperature, and two XK-0.5 thermocouples embedded in the heating surfaces at a distance of 0.0005 m from the surface.

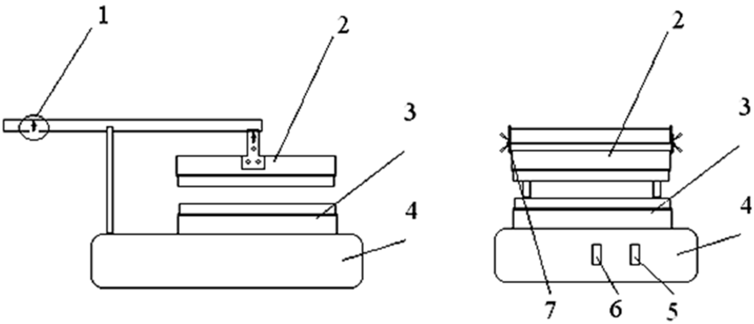


Fig. 38. Diagram of the pilot experimental apparatus for double-sided frying under pressure:
1 – counterweight; 2, 3 – upper and lower heating surfaces made of aluminum with a thickness of 6×10^{-4} m; 4 – frame; 5, 6 – switches for the lower and upper heating surfaces; 7 – upper surface locking mechanism

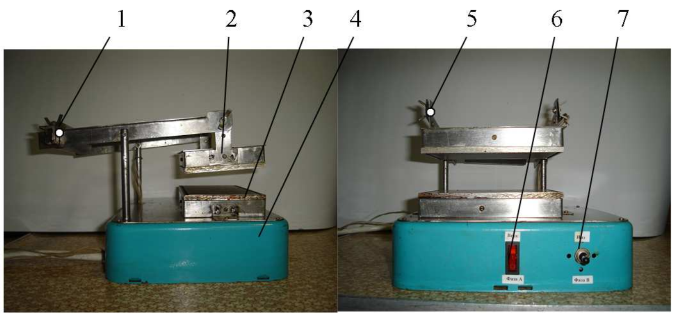


Fig. 39. General view of the pilot experimental apparatus for double-sided frying under pressure:
1 – counterweight; 2, 3 – upper and lower heating surfaces; 4 – frame; 5 – upper surface locking

mechanism; 6, 7 – switches for the upper and lower heating surfaces

To investigate the process parameters, an experimental test bench was also developed (Figures 40 and 41).

The experimental test bench included the following components: Block I – a set of measuring devices (a multifunctional electricity meter of the "Energia 9" type, version STK-3 with accuracy class 1.0; a dual-channel device for measuring and regulating the temperatures of the frying surfaces – TRC-02 "Universal Plus");

Block II – PC; Block III – the developed apparatus for double-sided frying under pressure.

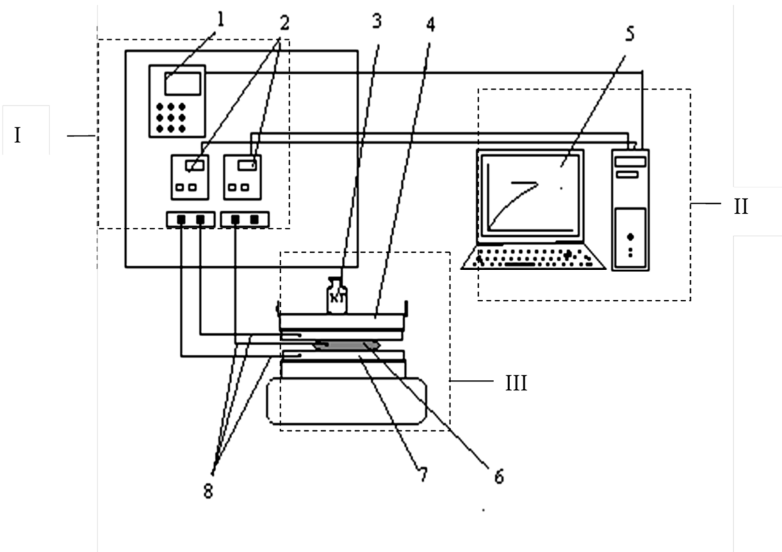


Fig. 40. Diagram of the experimental test bench for studying the process of double-sided frying of HCCT meat under pressure:
1 – electronic electricity meter; 2 – TRC-02 temperature controllers;
3 – weight; 4, 7 – upper and lower heating surfaces;
5 – PC; 6 – meat sample under study; 8 – XK-0.5 thermocouples

To create the required pressure, a set of weights weighing 0.2, 0.5, 1.0, 2.0, and 5.0 kg was used.

As experimental samples for double-sided frying under pressure, pieces of beef (shoulder part) weighing 0.050 kg and 0.01 m thick were used.

Functionally closed containers (Fig. 42) were developed for the study. These consist of two trays (upper and lower). The meat semi-finished product is placed on the lower tray and covered with the upper tray, which is smaller in perimeter and depth. This assembly is then placed between the upper and lower surfaces of the apparatus. The FCC loaded with the product undergoing thermal processing is placed on the lower heating surface of the apparatus, and the upper surface of the apparatus is lowered. Weights are placed on the upper surface.

Fig. 41. General view of the experimental test bench for the study of the double-sided frying process under pressure:
1 – PC; 2, 3 – lower and upper heating surfaces;
4 – TRC 0.2 "Universal Plus" temperature controller;
5 – electronic energy meter

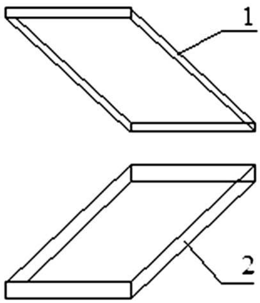


Fig. 42. Functionally closed containers:
1 – upper tray; 2 – lower tray

After the thermal treatment, the FCC with the cooked product was removed from the apparatus and weighed. Then the finished product was removed from the FCC and weighed separately [234].

The aim of the study is to confirm the justification of rational parameters for the double-sided frying process of HCCT meat in an FCC.

Results of Studies on the Temperature Kinetics in Meat and Heating Surfaces During Double-Sided Frying Under Excess Pressure

The experimental test bench for the study of the double-sided frying process under pressure was used during the research.

The aim of the study was to determine the temperature kinetics in the meat and on the frying surfaces during the double-sided frying process.

The bench setup (Figs. 40, 41) was supplemented with 9 XK-0.5 thermocouples, with signals recorded by MASTECH M890G multimeters every 4 seconds.

In the central part of a pork semi-finished sample weighing 0.05 kg and 0.01 m thick, 11 XK-0.5 thermocouples were installed at a horizontal distance of 0.002 m and a vertical distance of 0.001 m from each other. The signals from 9 thermocouples inside the meat were recorded using MASTECH M890G multimeters every 4 seconds, and the signals from 2 thermocouples located in the surface layers of the meat were recorded using the TRC 02 “Universal Plus” device. The layout of the thermocouples in the meat is shown in Fig. 43.

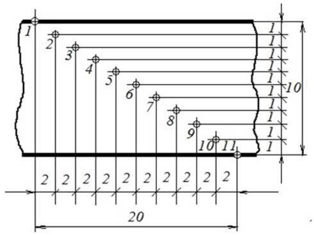


Fig. 43. Layout of thermocouples in HCCT meat during the experiment

The duration of the frying process was measured from the initial temperature in the center of the samples $T_{initial}$ = 288 K to the target temperature T_c = 345 K using the “Elektronika IT-01” stopwatch.

The temperature kinetics of the frying surfaces were recorded using the TRC-0.2 “Universal Plus” device with computer output of the temperature data to a display.

For greater reliability, the experiment was conducted with five repetitions.

The limiting excess pressure for the meat was p_lim = 10.4×10^3 Pa.

The results of the experimental studies are presented in Table 4.1 and in Fig. 44.

The temperature kinetics of the frying surfaces were recorded using the TRC-0.2 "Universal Plus" device with computer output of temperature data to a display.

For greater reliability, the experiment was repeated five times.

The limiting excess pressure for the meat was $p_{lim} = 10{,}4 \cdot 10^3$ Pa.

The results of the experimental studies are presented in Table 4.1 and in Fig. 44.

Table 4.1

Actual Temperature Kinetics Inside the Meat During Double-Sided Frying Under Compression Conditions

Frying duration, s	Temperature, K, within the meat at a distance from the upper and lower surface, 10^{-3} m										
	0	0,7	1,4	2,1	2,8	3,5	2,8	2,1	1,4	0,7	0
0	288	288	288	288	288	288	288	288	288	288	288
4	379	321	297	290	288	288	288	290	297	321	379
8	379	332	308	296	291	288	291	296	308	332	379

40	36	32	28	24	20	16	12
380	380	379	379	379	379	379	379
366	364	362	358	354	350	345	339
355	353	349	345	340	334	327	317
347	343	338	332	325	318	309	302
341	337	333	325	319	313	305	297
335	331	326	320	314	307	300	294
341	337	333	325	319	313	305	297
347	343	338	332	325	318	309	302
355	353	349	345	340	334	327	317
367	365	362	358	354	350	345	339
383	382	379	379	379	379	379	379

44	48	52	56	60
382	384	386	388	391
368	369	370	371	372
358	360	362	363	363
350	352	354	355	356
345	347	348	350	350
339	342	344	344	345
345	347	348	350	350
350	352	354	356	357
358	360	362	363	364
369	370	371	372	373
384	386	389	391	394

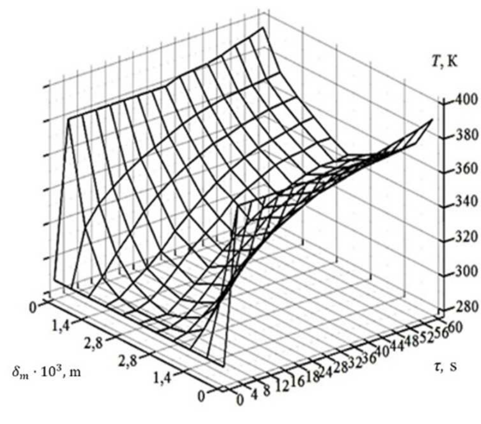


Fig. 44. Actual temperature kinetics inside the meat during double-sided frying under compression conditions

The actual temperature kinetics observed during the double-sided frying of meat under limiting pressure closely match the theoretical kinetics shown in Fig. 5 [194].

The results of experimental determination of the temperature kinetics of the frying surfaces and surface layers of the product during double-sided frying under limiting excess pressure are shown in Fig. 45.

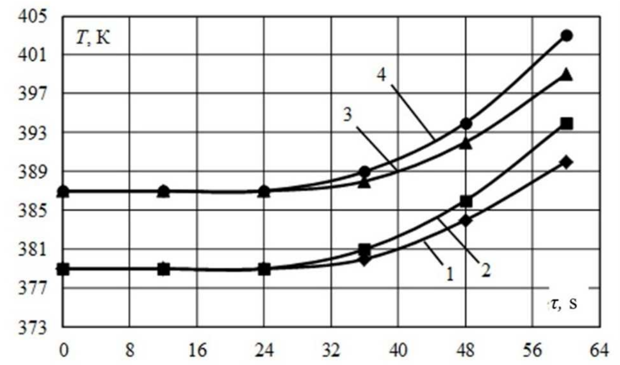


Fig. 45. Temperature kinetics of the frying surfaces and surface layers of the product during double-sided frying under limiting pressure:
1 – lower surface layer of the product; 2 – upper surface layer of the product; 3 – lower frying surface; 4 – upper frying surface

As seen in Fig. 45, the temperature gradient $\Delta\overline{T}$ (the difference between the temperature of the frying surface and the surface layer of the product) remains practically unchanged during the frying process for both the upper and lower surfaces.

Based on the above, to ensure uniform heat transfer conditions, it is necessary to regulate the upper and lower heating surfaces of the apparatus independently.

Results of Experimental Determination of the Duration of Thermodynamic Processes in Capillary Menisci During Double-Sided Frying of Meat with High Connective Tissue Content

It is practically impossible to directly determine the duration of the thermodynamic process τ in each individual capillary. However, it can be indirectly estimated from the spectrogram of sound frequencies during frying. We recorded the sound during the double-sided frying of HCCT meat under an excess pressure of 32×10^3 Pa and a specific surface power of each frying surface of 38500 W/m^2 using the method described in section 3.2. The resulting *wav* file was analyzed using the programs Fabfilter Pro·Q^2 and Spectrum Player**.**

The Fabfilter Pro·Q^2 software allows analysis of the frequency and volume of sound from digital audio tracks. The Spectrum Player software allows the decomposition of sound into frequencies not only at a given moment but also over a time interval.

A screenshot of the sound frequency spectrogram for 10 seconds of the double-sided frying process of HCCT meat under an excess pressure of 32×10^3 Pa in Fabfilter Pro·Q^2 is shown in Fig. 46.

As seen in Fig. 46, the sound frequency range during double-sided frying of HCCT meat is 3–20 kHz (the yellow line indicates the natural background). Accordingly, the duration of the thermodynamic processes in the surface layers of the meat, according to formula (3.24), is $(50 \ldots 333) \times 10^{-6}$ s. According to formula (2.31), the diameter of the capillaries in HCCT meat during double-sided frying under compression conditions is $(24 \ldots 160) \times 10^{-6}$ m. The ratio d_c/τ equals 0.482 m/s.

Screenshots of the sound frequency spectrum distribution during double-sided frying of HCCT meat under excess pressure of 32×10^3 Pa in Spectrum Player are shown in Fig. 47.

Fig. 46. Screenshot of the sound spectrogram during double-sided frying of HCCT meat under limiting pressure at 10 seconds into the process

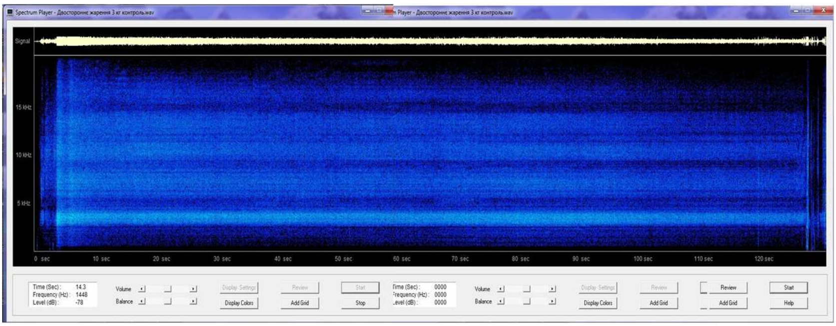


Fig. 47. Screenshots of the sound frequency spectrum distribution during double-sided frying of HCCT meat under limiting pressure in Spectrum Player

As shown in Fig. 47, the sound frequency spectrum during double-sided frying is divided into five main groups: (3–4), (6–8), (9–12), (13–14), and (16–19) kHz. These evidently correspond to five groups of capillary diameters: (120–160)×10^{-6} m, (60–80)×10^{-6} m, (40–54)×10^{-6} m, (34–37)×10^{-6} m, and (24–30)×10^{-6} m. The most pronounced and abundant range is (3–4) kHz, corresponding to capillaries with diameters of (120–160)×10^{-6} m, which likely belong to the peripheral capillaries of the interfiber space filled with free moisture. The most interesting is the fifth group, which begins to disappear after 90–100 seconds of frying. This may indicate the cessation of the steam collapse phenomenon in the capillary menisci, i.e., the completion of the second stage of the frying process.

The heat transfer coefficient under the given conditions, with a mean integral temperature difference (temperature gradient) of $\Delta\bar{T}^{m} = 8$ K, a ratio $d_c/\tau = 0{,}482$ m/s, and Δv = 1.653 m³/kg, is: $k = 4750$ W/(m²·K).

The heat transfer coefficient from steam to the liquid in the menisci of each of the two surface layers is: $\alpha_2 = 2 \cdot k = 9500$ W/(m^2·K). The total heat transfer coefficient from steam to the liquid in the menisci, considering double-sided heat supply from the frying surfaces, is: $\alpha_2 = 2 \cdot k = 19000$ Вт/(m^2·K) [189].

Results of the Study on the Influence of Pressure During Double-Sided Frying of Meat with High Connective Tissue Content on Process Duration and Final Product Yield

The pressure level during double-sided frying of HCCT meat in a functionally closed chamber (FCC) is justified by the relationships (3.14) or (3.15). To avoid conditions for mass transfer within HCCT meat during frying—which promotes an increase in the meat's thermal conductivity according to (3.17), and thus reduces process duration—compression force must be applied to generate steam pressure at the limiting level p_{lim}.

This justification required experimental confirmation. Therefore, an experimental determination of the influence of pressure during double-sided frying of HCCT meat in an FCC on process duration and final product yield was conducted using the above-described methodology and the experimental test bench (Figs. 40 and 41).

The tested range of excess pressure was within (12–40)×10^3 Pa.

The limiting excess pressure for meat was 32×10^3 Pa. The results of the study are shown in Fig. 48.

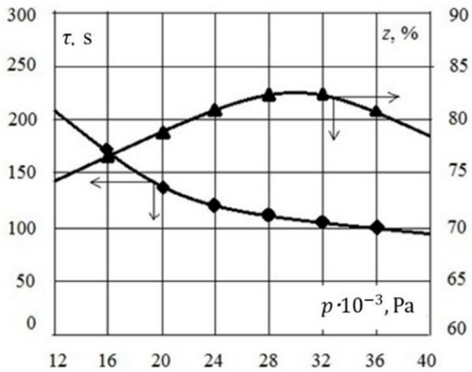


Fig. 48. Duration of the process τ and yield of the final product z depending on excess pressure p during double-sided frying of beef with HCCT ($T_{f.s.} = 423$ K; $\delta_m = 0{,}01$ м)

As shown in Fig. 48, during double-sided frying under excess pressure, there is a directly proportional decrease in frying time in the range of (12–28)×10^3 Pa – by a factor of 1.75, from 210 to 120 seconds. In the range of (28–40)×10^3 Pa, the duration remains almost unchanged. As pressure increases from 12×10^3 to 32×10^3 Pa, the yield of the final product increases by 7% to 82%. However, further increasing the pressure to 40×10^3 Pa results in a 6% decrease in yield.

The highest average sensory evaluation scores were obtained for the samples fried under excess pressure of 32×10^3 Pa. These products exhibited greater juiciness, a more pronounced crust color, and a tender texture. The lowest scores were observed for products cooked under 24×10^3 and 36×10^3 Pa, which were less juicy and tougher – likely due to higher moisture loss during frying.

Thus, the results of the experimental determination of the pressure's influence on the duration and yield of the double-sided frying process confirm the necessity of conducting the process at an optimal excess pressure near the limiting value p_{lim}. Under the limiting pressure for meat in the experiment— $p_{lim} = 32 \cdot 10^3$ Pa - the process duration was shortest at 120 seconds, and the yield reached 82% [233, 253].

To determine the degree of influence of pressure on the double-sided frying process of HCCT meat, an analysis of variance (ANOVA) was conducted. The influence of compression force on heat treatment duration and final product yield was evaluated. Based on the obtained experimental data, the coefficient of determination R^2 was 0.99 (or 99%). Since R^2 is close to 1, the compression force, in comparison to other factors, fully determines the variation in the resulting parameters—that is, the process duration and the final product yield.

Verification of the Adequacy of the Thermal Model of the Double-Sided Frying Process of Meat

Normalization of the output data matrix (Table 4.1), i.e., if x_{ij} are the elements of the initial matrix XXX, was performed using the formula:

$$y_j = \frac{x_{ij} - x_{j,min}}{x_{j,max} - x_{j,min}}$$

for each j (column-wise normalization of the matrix).

The results of the normalization of the input data matrix obtained from the experimental study of temperature kinetics in meat during double-sided frying under compression are presented in Table 4.2.

A graphical visualization of the normalized input data matrix, i.e., the temperature kinetics in meat during double-sided frying under compression in normalized form, is shown in Fig. 49.

Modeling of the thermal conductivity function was carried out in two steps: selection of the structure and parameter estimation. A nonlinear least squares method with root mean square deviation (RMSD) evaluation was used.

Subsequently, the functions $y(\tau)$ y – trends of the heat transfer (or heat and mass transfer) process – were constructed (Table 4.3). Analysis of computer visualizations (Fig. 49) shows that the logistic curve (2.38) can be proposed to describe this function.

Table 4.2

Normalized temperature within the meat thickness

12	8	4	0	δ_m,мм τ, с	Max,К	Min, К
0,883	0,883	0,883	0,000	0,00	391	288
0,607	0,524	0,393	0,000	0,7	372	288
0,387	0,267	0,120	0,000	1,4	363	288
0,206	0,118	0,029	0,000	2,1	356	288
0,145	0,048	0,000	0,000	2,8	350	288
0,105	0,000	0,000	0,000	3,5	345	288
0,145	0,048	0,000	0,000	2,8	350	288
0,203	0,116	0,029	0,000	2,1	357	288
0,382	0,263	0,118	0,000	1,4	364	288
0,600	0,518	0,388	0,000	0,7	373	288
0,858	0,858	0,858	0,000	0	394	288

44	40	36	32	28	24	20	16
0,913	0,893	0,893	0,883	0,883	0,883	0,883	0,883
0,952	0,929	0,905	0,881	0,833	0,786	0,738	0,679
0,933	0,893	0,867	0,813	0,760	0,693	0,613	0,520
0,912	0,868	0,809	0,735	0,647	0,544	0,441	0,309
0,919	0,855	0,790	0,726	0,597	0,500	0,403	0,274
0,895	0,825	0,754	0,667	0,561	0,456	0,333	0,211
0,919	0,855	0,790	0,726	0,597	0,500	0,403	0,274
0,899	0,855	0,797	0,725	0,638	0,536	0,435	0,304
0,921	0,882	0,855	0,803	0,750	0,684	0,605	0,513
0,953	0,929	0,906	0,871	0,824	0,776	0,729	0,671
0,906	0,896	0,887	0,858	0,858	0,858	0,858	0,858

60	56	52	48
1,000	0,971	0,951	0,932
1,000	0,988	0,976	0,964
1,000	1,000	0,987	0,960
1,000	0,985	0,971	0,941
1,000	1,000	0,968	0,952
1,000	0,982	0,982	0,947
1,000	1,000	0,968	0,952
1,000	0,986	0,957	0,928
1,000	0,987	0,974	0,947
1,000	0,988	0,976	0,965
1,000	0,972	0,953	0,925

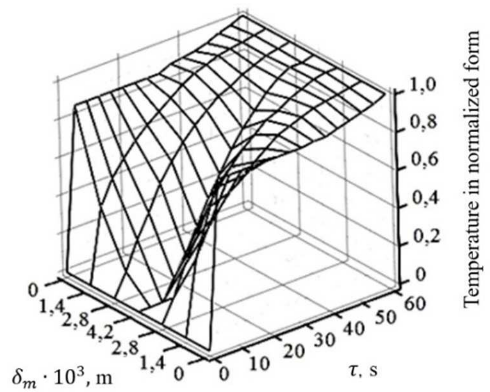


Fig. 49. Normalized temperature kinetics across meat thickness during double-sided frying under compression conditions

Table 4.3

Determination of the functions $y(\tau)$ – trends of the heat conductivity process

Frying duration, s	*b*	*b*	*b*	*b*	*b*	*b*	*b*
	158 0,3	2,7	7,4	33,2	7,4	2,7	158 0,3
	c	*c*	*c*	*c*	*c*	*c*	*c*
	5,3	0,1	0,1	0,1	0,1	0,1	5,3
	Normalized temperature within the meat thickness at a distance from the upper and lower surface, 10^{-3} m						
	0,0	0,7	1,4	3,5	1,4	0,7	0,0
0	0,001	0,271	0,120	0,029	0,120	0,271	0,001
4	1,000	0,360	0,177	0,049	0,177	0,360	1,000
8	1,000	0,459	0,255	0,080	0,255	0,459	1,000
12	1,000	0,561	0,352	0,129	0,352	0,561	1,000

44	40	36	32	28	24	20	16
1,000	1,000	1,000	1,000	1,000	1,000	1,000	1,000
0,972	0,958	0,938	0,909	0,869	0,814	0,744	0,658
0,956	0,932	0,897	0,845	0,775	0,685	0,578	0,463
0,912	0,859	0,781	0,678	0,553	0,421	0,300	0,201
0,956	0,932	0,897	0,845	0,775	0,685	0,578	0,463
0,972	0,958	0,938	0,909	0,869	0,814	0,744	0,658
1,000	1,000	1,000	1,000	1,000	1,000	1,000	1,000

СКВ	60	56	52	48
0,150	1,000	1,000	1,000	1,000
0,087	0,994	0,992	0,987	0,981
0,028	0,993	0,989	0,982	0,972
0,015	0,989	0,981	0,968	0,946
0,028	0,993	0,989	0,982	0,972
0,087	0,994	0,992	0,987	0,981
0,150	1,000	1,000	1,000	1,000

Next, functions $z(\delta_{ef})$ – components of thermal conductivity depending only on sample thickness – were constructed. To describe this function, a second-order polynomial (2.34) can be used. The graphical visualization of the function $z(\delta_{ef})$ is shown in Fig. 50, and its analytical definition is provided in Table 4.4.

A three-dimensional graphical representation of the temperature function from two variables $T(\tau, \delta_{ef})$ is shown in Fig. 51.

Table 4.4

Definition of the function $z(\delta_м)$

Frying duration, s	Point from the surface to the center across the thickness, 10^3 м										
	0	0,7	1,4	2,1	2,8	3,5	4,2	4,9	5,6	6,3	7
8	Row										
	a_2 = 0,067				a_1 = -0,474				a_0 = 0,841		
	0,841	0,542	0,309	0,142	0,042	0,007	0,039	0,137	0,301	0,530	0,826
20	Row										
	a_2 = 0,043				a_1 = -0,303				a_0 = 0,913		
	0,913	0,722	0,573	0,466	0,401	0,378	0,398	0,459	0,563	0,709	0,897
32	Row										
	a_2 = 0,020				a_1 = -0,143				a_0 = 0,935		
	0,935	0,844	0,773	0,722	0,691	0,679	0,688	0,716	0,763	0,831	0,918

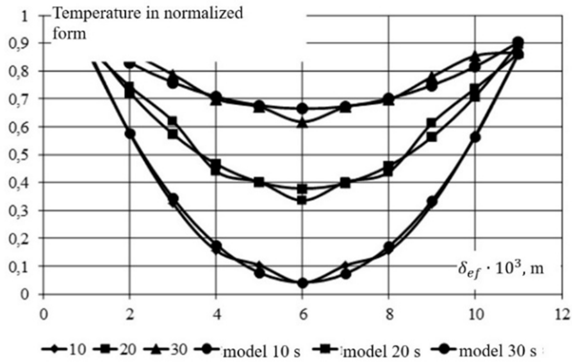


Fig. 50. Theoretical and actual normalized temperature kinetics across meat thickness during double-sided frying under pressure

Comparison of the results of experimental determination of temperature kinetics in meat during double-sided frying under compression (Table 4.2, Fig. 49) and the proposed thermal model in the form of function (2.40) (Tables 4.3, 4.4; Fig. 51) shows that the relative error of the thermal model does not exceed 10%, which is fully acceptable for engineering calculations [194].

A similar structure is observed in the thermal models of the double-sided frying process of HCCT meat in an FCC under compression and in the double-sided frying process under the influence of electric current.

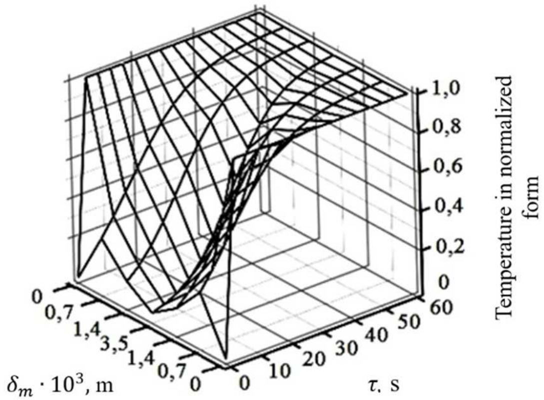


Fig. 51. Theoretical normalized temperature kinetics according to the proposed thermal model during double-sided frying of meat at limiting pressure

The thermal conductivity coefficient of the shoulder muscle of beef (grade III, low fat content) at 293 K and atmospheric pressure is $\lambda_{m0} = 0{,}5$ W/(m·K) [206]; and for meat juice under the same conditions $\lambda_{liq} = 0{,}54$ W/(m·K) [207]. Under compression to excess pressure $p_{lim} = 35 \cdot 10^3$ Pa, the thermal conductivity coefficient of meat approaches $\lambda_m = 0{,}54$, W/(m·K). The density of meat under compression is$\rho = 1100$ kg/m^3, and the specific heat capacity is $c = 3620$ J/(kg·K) [206]. The thermal diffusivity of meat during heating up to 358 K is: $a = \frac{0{,}54}{3620 \cdot 1100} = 13{,}56 \cdot 10^{-8} m^2$/s. The Biot number for the first stage of the frying process is: $Bi = \frac{19000 \cdot 0{,}00008}{0{,}54} = 2{,}84$, where 0,00008 m – the radius of the largest capillary in the surface layer of meat. For the second stage of frying: $Bi = \frac{19000 \cdot 0{,}0035}{0{,}54} = 124{,}44$, where 0,0035 m – the half-thickness of the meat during frying [236].

The duration of the first stage of frying, from the initial meat temperature of 293 K to a surface layer temperature of 374 K, for a thickness equal to the radius of the largest capillary at ρ=0, is determined from equation (2.21).

$$Fo^{(0)} = \frac{1}{12} + \frac{1}{3 \cdot 2{,}84} - \frac{2}{3 \cdot 2{,}84^2} \cdot ln\left[1 + \frac{1}{2} \cdot 2{,}84\right] = 0{,}128.$$

Then, from formula (2.26):

$$Fo^{I} = \frac{2{,}84 + 3}{3 \cdot 2{,}84} ln\left[\frac{2 \cdot (423 - 293)}{(2{,}84 + 2) \cdot (382 - 274)}\right] + 0{,}128 = 1{,}43,$$

from which the duration of the first stage of frying is:

$$\tau_I = \frac{1{,}43 \cdot 0{,}00008^2}{13{,}56 \cdot 10^{-8}} = 0{,}067\ s.$$

The Fourier number for the second stage, from formula (2.21), is:

$$Fo^{(0)} = \frac{1}{12} + \frac{1}{3 \cdot 124{,}44} - \frac{2}{3 \cdot 124{,}44^2} ln\left[1 + \frac{1}{2} 124{,}44\right] = 0{,}11;$$

$$Fo^{II} = \frac{1}{3} ln\left[\frac{124{,}44 \cdot (382 - 374)}{2 \cdot (374 - 358)}\right] + 0{,}11 = 1{,}14;$$

from which the duration of the second stage of frying is:

$$\tau_{II} = \frac{1{,}14 \cdot 0{,}0035^2}{13{,}56 \cdot 10^{-8}} = 103\ s.$$

Thus, the theoretical total duration of the first and second stages of the double-sided frying process of beef with HCCT, up to a center temperature of 358 K, is:

$$\tau_0 = 0{,}067 + 103 = 103{,}067\ s.$$

The calculated data fully coincide with the process data presented in Figs. 4.1 and 4.4 [234].

4.2. Results of the Study on the Quality of Cooked Products After Double-Sided Frying Under Excess Pressure in Functionally Closed Containers

Results of the Study on the Degree of Collagen-to-Gelatin Transformation in Meat with High Connective

Tissue Content After Double-Sided Frying Under Excess Pressure in Functionally Closed Containers, Assessed via Hydroxyproline

Methods for determining connective tissue content in meat can be divided into two groups. The first group of methods is based on the extraction of connective tissue proteins by treating the meat with acids and alkalis or through enzymatic digestion of the tissue, followed by determination of the dry residue by weighing [227]. According to [28], these methods have drawbacks because some connective tissue proteins may be lost during the extraction process. One of the methods suitable for routine analysis is the hydroxyproline-based evaluation of connective tissue, determined in hydrolysates of meat samples. This method is based on the exceptionally high hydroxyproline content in collagen—the primary connective tissue protein in meat—while hydroxyproline is not found in other muscle proteins.

The hydroxyproline method for determining connective tissue has gained widespread use in the modified version developed by Verbytskyi and Deteridge, who adapted the Neuman and Logan method for determining hydroxyproline in muscle tissues [237, 238].

The hydroxyproline determination method was performed according to [239, 240].

The collagen content in tissues was determined by quantifying the amino acid hydroxyproline. The method involves preliminary hydrolysis of collagen polypeptides followed by a colorimetric reaction for hydroxyproline and photometric analysis. It includes the following steps: hydrolysis of tissue with hydrochloric acid, acid neutralization, oxidation of hydroxyproline, a color reaction using p-(dimethylamino)-benzaldehyde, and measurement of color intensity by photometry.

The experiments were conducted in duplicate. A custom-designed hydrolysis unit was used (Figs. 52, 53).

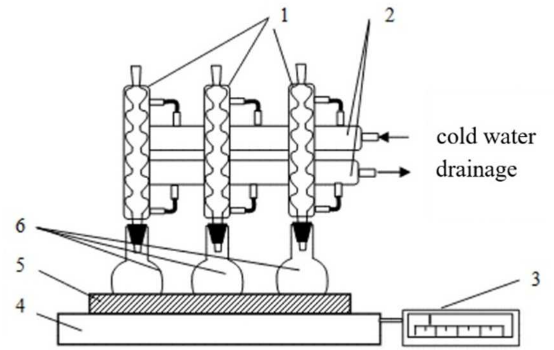


Fig. 52. Diagram of the hydrolysis unit:
1 – water condenser; 2 – manifold; 3 – temperature controller; 4 – heating surface; 5 – sand bath; 6 – flask with hydrolysate

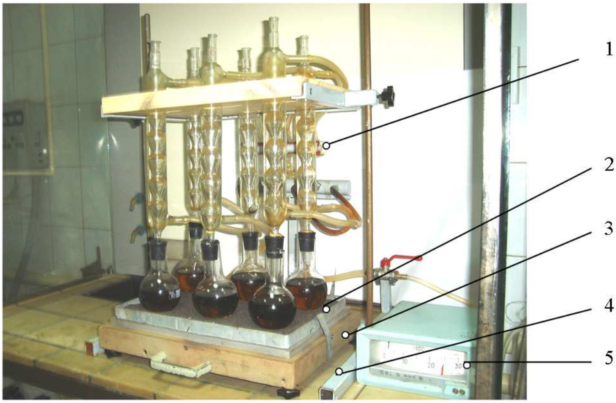


Fig. 53. General view of the hydrolysis unit:
1 – water condenser; 2 – flask with hydrolysate; 3 – sand bath; 4 – heating surface; 5 – MP-64-02 temperature controller

The hydrolysate flasks (6), connected to the condensers (1), were placed in the sand bath (5). Through the manifolds (2), cold tap water was supplied and discharged into the drain. The sand bath was placed on the heating surface (4), which contained flat heating elements. The hydrolysis temperature was maintained using the temperature controller (3).

Total moisture content was determined using the formula:

$$x = \frac{(A - B) \cdot 100}{A}, \qquad (4.1)$$

where x – total moisture, %; A – weight of the sample before drying, g; B – weight of the sample after drying, g.

Conversion to dry matter was performed using the formula [241]:

$$R = \frac{100}{100 - x}. \tag{4.2}$$

Total moisture in the product was determined by drying the sample to constant weight. To stop enzymatic processes, the meat was subjected to short-term holding (1800...3600 s) at elevated temperature (353...378 K), then dried to constant weight in a drying cabinet at 333...338 K. After reaching constant weight, the sample was kept for 3...4 hours at room temperature in a desiccator, then weighed again to determine air-dry mass [241].

The amount of hydrolyzed collagen was determined as the difference between the collagen content in raw meat and in the sample after heat treatment.

The determination of hydrolyzed collagen content was conducted on samples of natural portion-sized products made from the shoulder part of beef that underwent double-sided frying under pressure—both without and with FCC.

The results of the hydroxyproline-based analysis of collagen-to-gelatin transformation (Table 4.5) confirm the feasibility of performing double-sided frying of HCCT meat under compression.

Data in Table 4.5 show that in HCCT meat samples after double-sided frying under compression and under compression in FCC, the amount of hydrolyzed collagen was 30.4% and 33.2%, respectively. The amount of hydrolyzed collagen in samples cooked in the FCC was 2.8% higher. This can be explained by the fact that steam generated during frying remains within the working volume of the FCC and contributes more significantly to collagen hydrolysis.

Table 4.5

Results of the Study on Collagen Hydrolysis in Meat Based on Hydroxyproline Content

Sample Description	Total Moisture, %	Hydroxyproline Content, mg% (dry basis)	Connective Tissue Content, % (dry basis)	Hydrolyzed Collagen, %
Raw beef (shoulder part)	75,26	0,927	7,484	-
Beef (shoulder part) after double-	65,07	0,645	5,208	30,4

sided frying under pressure				
Beef (shoulder part) after double-sided frying under pressure in FCC	66,45	0,619	4,999	33,2

The amount of hydrolyzed collagen ranges from 25 to 40%, which corresponds to the data from [27, 57]. Meat samples cooked without FCC had a tougher texture compared to those cooked in FCC.

Additionally, Table 4.5 shows that the moisture content retained in the meat during thermal processing affects the rate of collagen hydrolysis.

Thus, during double-sided frying under pressure in FCC of portion-sized natural products made from beef with HCCT, a sufficient amount of collagen is hydrolyzed to achieve culinary readiness [242].

Results of the Study on the Degree of Collagen-to-Gelatin Transformation in Meat with High Connective Tissue Content After Double-Sided Frying Under Excess Pressure in Functionally Closed Containers, Based on Shear Force Resistance

One of the key characteristics of meat quality is its tenderness. The tenderness of HCCT meat is significantly influenced by the degree of collagen-to-gelatin transformation. An objective method for assessing meat tenderness involves mechanical devices—consistometers—that measure shear force resistance. The determination of shear force resistance in both raw and heat-treated meat samples was carried out using the Warner-Bratzler method in the Maksakov modification [212, 243].

Cubic meat samples were cut from raw and heat-treated beef (shoulder cut), each with a cross-sectional area of 10^{-4} m^2. The sample was placed into the device, and shear force resistance was measured. The method is based on applying a force via a rectangular blade (0.0005 m thick) to a meat sample with a 10^{-4} m^2 cross-section. The force is generated by shot (metal granules) poured into a container connected to the knife, creating stress in the meat proportional to the force. When the applied force exceeds the sample's shear resistance, the blade cuts through it. The mass of the shot and the time taken until the sample is cut were recorded.

Shear force resistance was calculated using the formula:

$$H = \frac{P}{S}, \qquad (4.3)$$

where P – applied force, kg; S – cross-sectional area of the sample, m².

The applied force was determined using:

$$P = v \cdot \tau \cdot \frac{l_1}{l_2}, \qquad (4.4)$$

where v – shot drop rate, kg/s;
τ – drop time, s;
l_1 – distance from the center of the collection container to the axis, m;
$l_1 = 0{,}44$ m; l_2 – distance from the knife to the axis, $l_2 = 0{,}11$ m.

Shear force resistance was measured across the fibers for raw and cooked meat samples using various heat treatment methods (Table 4.6).

Table 4.6

Shear Force Resistance of Beef (Shoulder Cut) Before and After Heat Treatment

Heat Treatment Method	Shear Resistance × 10^4, Pa
Before heat treatment	88
Boiling for 1 hour	32
Traditional pan frying	62
Double-sided frying under pressure	48
Double-sided frying under pressure in FCC	36

As shown in Table 4.6, shear resistance after double-sided frying under pressure in FCC decreased by 2.43 times compared to raw meat, by 1.7 times compared to traditional pan-frying, and by 1.3 times compared to double-sided frying under pressure without FCC. The difference in shear resistance between boiling and double-sided frying under pressure in FCC for shoulder meat samples was minimal (an increase of only 3.7×10^4 Pa). This is important since the softening of connective tissue plays a key role in achieving culinary readiness for this cut.

Thus, based on the results of shear resistance – an objective measure of meat toughness—the feasibility of using FCC during double-sided frying of HCCT beef under pressure has been confirmed [244, 245].

Microbiological Quality Evaluation of Cooked Products

The aim of the study was to determine the impact of double-sided frying under compression in FCC on the microbiological indicators of cooked natural portion-sized meat products made from the shoulder cut of beef.

Beef samples weighing 0.050 kg and 0.001 m thick were used. Double-sided frying under pressure with FCC was carried out at FCC surface temperatures of 423 K, ensured by heating surfaces at 453 K, and under excess steam pressure of 32×10^3 Pa.

Bacteriological tests were conducted on raw and fried samples processed to a core temperature of 358 K.

The study was carried out at the microbiological laboratory of the Research and Testing Center for Food Products of SE "PoltavaStandartMetrologiya" according to the methods in section 3.3.

Fresh chilled beef (shoulder cut) was used. Microbiological indicators were determined for fresh meat samples and for meat samples processed by the developed double-sided frying method under pressure in FCC. Results are presented in Table 4.7.

As shown in Table 4.7, the MAFAM CFU per 1 g in fresh meat was 350,000. After double-sided frying under pressure in FCC, the CFU count in cooked portion-sized meat products ranged from 10 to 15, well within permissible limits [247].

Table 4.7

Microbiological Quality of Beef (Shoulder Cut) After Heat Treatment

Sample	Sanitary and Bacteriological Characteristics					
	MAFAM CFU/g	Coliforms/g	*S. aureus*/g	Proteus в 0,001g	*Proteus*/0.001	Pathogens incl. *Salmonella*/25 g
Raw meat	350000	-	-	-	-	-
Cooked under pressure in FCC	10…15	-	-	-	-	-
Standard limit	10000 0	Not allowed	Not allowed	Not allowed	Not allowed.	Not allowed

Based on the results of the study on the microbiological indicators of portion-sized fried meat products made from the shoulder cut of beef after double-sided frying under compression in an FCC, it was established that this method – while significantly reducing the duration of thermal processing – ensures a bactericidal effect on microorganisms and compliance with sanitary standards.

The positive effect can be attributed to the combined influence on microorganisms not only of temperature and pressure but also of steam present in the working environment of the FCC, which maintains a temperature of approximately 373 K on the lateral surfaces [247].

Results of the Quality Assessment of Cooked Products Based on Organoleptic Indicators

During the evaluation of finished product quality, the primary method is organoleptic assessment [248]. The sensory qualities of meat depend on parameters such as color, aroma, odor, appearance, texture, juiciness, and taste. Organoleptic analysis is carried out by tasting, i.e., sensory evaluation without measuring instruments. Various scoring systems are used to assess the organoleptic properties of meat products [69, 202].

Organoleptic evaluation was conducted accordingly.

For the assessment of beef product quality after double-sided frying under pressure in an FCC, the widely used 5-point scale was applied. The main quality indicators considered were: appearance, color, odor, taste, texture, and juiciness, each weighted with a corresponding coefficient.

The results of the organoleptic evaluation are presented in Table 4.8.

According to Table 4.8, the quality of cooked beef products after frying at an excess pressure of $32×10^3$ Pa was sufficiently high. The sample processed under this pressure had a more well-colored crust and a pleasant roasted meat aroma. The lowest score was given to the sample processed at $24×10^3$ Pa; tasters noted an aroma typical of stewed rather than roasted meat

Table 4.8

Organoleptic Evaluation of Products Made from HCCT Meat After Double-Sided Frying Under Pressure in FCC

Organoleptic Indicator	Weight Coefficient	Excess Pressure, $p·10^{-3}$ Pa			
		24	28	32	36
		Number of points on a 5-point scale			
Appearance	0,1	3	4	4	4
Color	0,1	4	4	4	4
Aroma/Odor	0,1	3	4	4	3
Texture	0,3	3	4	5	3
Taste	0,2	4	4	5	4

Juiciness	0,2	3	4	5	4
Average Score	1	3,3	4,0	4,7	3,6

Because more moisture is lost during frying at an excess pressure of 36×10^3 Pa, the resulting texture was found to be less juicy and firmer.

Based on the results of the organoleptic quality assessment, it was established that portion-sized natural fried meat products made from the shoulder cut of beef and cooked using double-sided frying under the limiting pressure of 32×10^3 Pa in an FCC demonstrated the best quality indicators.

4.3. Conclusions of the Chapter

As a result of this chapter:

1) The actual temperature kinetics in meat during double-sided frying under compression were determined;

2) It was established that the approach of excess pressure to p_{lim} has a directly proportional effect on the duration of the double-sided frying process of HCCT meat and the yield of the final product, confirming the validity of equation (3.20);

3) It was found that the minimum process duration τ = 120, s for HCCT meat and the maximum product yield z = 82% are achieved at frying surface or FCC surface temperature of 423 K and an excess steam

pressure p_{lim}, generated by compression [249]. The specific heat flux should be within the range of (38.5...41,5)×10^3 W/m^2. This formed the basis for applications and issuance of Ukrainian utility model patents: "Method of Double-Sided Frying of Meat and Meat Products" [250] and "Method of Frying Meat with High Connective Tissue Content" [251];

4) Based on the analysis of sound recordings during double-sided frying under the above parameters:

- the duration of evaporation and condensation cycles in capillary menisci of various diameters was determined to be from 50×10^{-6} to 333.3×10^{-6} s;
- the range of capillary diameters in the surface layer of HCCT meat during frying was determined to be 24×10^{-6} to 160×10^{-6} m;
- the heat transfer coefficients from one and two frying surfaces to the product were calculated;
- dependence was established between the heat transfer coefficient and the specific surface power of the frying surfaces;
- the theoretical duration of the first and second stages of the process was calculated and found to coincide with the experimental results;

5) The verification confirmed that the theoretical thermal model proposed in section 2.5 adequately describes the actual process of double-sided frying of HCCT meat under compression in FCC, with a reliability of 90%;

6) It was found that double-sided frying of HCCT meat in FCC under the proposed process parameters ensures a sufficient degree of collagen-to-gelatin transformation for human consumption (25…40%);

7) The quality of HCCT meat products fried under the proposed parameters, based on physicochemical, microbiological, and organoleptic indicators, is not inferior to that of products fried by traditional pan-frying or double-sided frying under compression.

CHAPTER 5. DEVELOPMENT OF ENERGY- AND RESOURCE-EFFICIENT EQUIPMENT FOR CONDUCTIVE MEAT FRYING

Technical requirements and design specifications for equipment for conductive meat frying

The implementation of the developed conductive meat frying processes is possible through the design of energy-efficient and resource-saving new equipment, which must meet the following requirements: technological, operational, energy efficiency, structural, economic, safety and sanitation, technical aesthetics, and reliability.

Technological requirements refer to the capability of the equipment to implement the optimal parameters of the developed conductive frying processes, including those with HCCT, without exceeding the necessary temperature level to prevent the formation of HA.

Operational requirements mean that the equipment design must meet modern conditions and have the specified productivity. For conductive frying equipment, this includes:

- simple operation and maintenance with minimal manual labor;
- prevention of product adhesion to the frying or FCC surfaces;

– accessibility for inspection, sanitation (cleaning, washing, disinfection), and repair;
– corrosion resistance to environmental exposure, contact with food products, cleaning, disinfecting solutions, and water;
– automated control and regulation of key frying parameters.

Energy efficiency requirements include the equipment's ability to ensure:
– maximum thermal, exergy, and energy efficiency coefficients and overall process efficiency;
– minimal specific energy carrier consumption.

Structural requirements include:
– simplicity of construction;
– low weight of the apparatus;
– sufficient strength;
– use of standard, easily replaceable parts;
– convenient and easy installation;
– user-friendly and low-maintenance design.

Economic requirements involve ensuring minimal costs for design, manufacturing, installation, and operation of the equipment, along with minimal energy consumption and specific energy carrier usage.

Safety and sanitation requirements include:
– structural strength with a safety margin;
– ensuring the surface temperature does not exceed 333 K;
– integration of automatic shut-off devices;

– safe and convenient loading of semi-finished products and unloading of ready items for operators;

– prevention of bacterial and chemical contamination and spoilage of the product;

– minimal environmental emissions and pollutants.

Technical aesthetics requirements aim for a simple form, convenient control element arrangement, proper appearance with rational color schemes, lighting, and workshop microclimate, reducing operator fatigue, easing labor, improving productivity, and contributing to high product quality [17].

Reliability requirements involve ensuring the equipment can consistently perform the required functions over time, maintaining optimal conductive frying parameters within specified limits under various operating conditions, usage, repair, maintenance, storage, and transportation.

During the design of a double-sided meat frying apparatus using electric current, the above requirements were incorporated into the technical specification. To fulfill these requirements, the apparatus should have:

– two separate frying surfaces (lower and upper) made of high thermal conductivity metal (food-grade aluminum alloys such as AK7, AK5M2, AK9, or AK12) [232, 252], chemically inert to the environment, food products, and cleaning/disinfecting agents; frying surfaces must have anti-adhesive properties (coated with a non-stick, electrically conductive layer);

- electric heaters ensuring a specific heat flux from each surface of (38,5…41,5)·10^3 W/m^2 and a temperature field non-uniformity not exceeding 20 K;
- independent temperature maintenance of both surfaces at 423 K to prevent HA formation and accumulation in the product;
- a voltage reducer from 220 V to 27 V with a nominal current of 1 A, maximum 2 A, and minimum 0.5 A, along with a frequency converter from 50 to 0.5 Hz [253];
- a switch to turn the electric current to the surfaces on/off;
- a top surface weight sufficient to create steam overpressure in the surface layers of 800–1100 Pa;
- thermal insulation to maintain outer surface temperature not exceeding 333 K;
- ease of operation and sanitary maintenance.

Based on these requirements, a patent application was submitted and a Ukrainian utility model patent was granted for the double-sided conductive meat frying apparatus [254].

When designing a double-sided frying apparatus for meat with HCCT in FCC under compression, the same requirements were included in the technical specification. To fulfill them, the apparatus must include:

- two heating surfaces (upper and lower);

– flexible mounting of heating surfaces to maintain steady steam overpressure in the product's surface layers during frying;

– electric heaters providing a specific heat flux of (38,5…41,5)·10^3 W/m^2 and temperature field non-uniformity not exceeding 20 K;

– independent regulation of heating surface temperatures in the range of 453–473 K, maintaining FCC surface temperature at 423 K to prevent HA formation;

– a clamping mechanism to compress the product between the heating surfaces with a preset force;

– a compression force indicator;

– a strain gauge transmitting signals to the indicator to monitor compression force;

– functionally sealed containers;

– a table for convenient FCC loading and unloading;

– the ability to monitor the internal temperature of meat products via a thermal probe (thermocouple);

– thermal insulation to maintain casing surface temperature below 333 K;

– user-friendly and easy operation and sanitation [255].

Based on these requirements, a patent application was submitted and a Ukrainian utility model patent was granted for the double-sided frying apparatus with HCCT in FCC under compression [256].

5.1. Design and Operating Principle of the Apparatus for Double-Sided Meat Frying under the Action of Electric Current

The technical documentation for the production of the pilot-industrial prototype of the double-sided meat frying apparatus operating under electric current was developed based on the specified requirements and thermal calculations.

The manufacturing of the pilot-industrial prototype of the double-sided meat frying apparatus was carried out in accordance with the developed technical documentation using the material and technical base and personnel of the Sectoral Research Laboratory of Food Production at the Poltava University of Economics and Trade (Ukoopspilka University), in cooperation with PJSC "Poltava Machine-Building Plant."

The apparatus for double-sided meat frying under electric current (Figures 54, 55) consists of a body (10), on which the upper (13) and lower (12) lids are mounted. These lids hold the upper (1) and lower (2) frying surfaces, respectively. The frying surfaces are made of aluminum with a surface roughness of 0.63 µm. A groove is located along the perimeter of the surfaces for collecting and draining meat juice and fat released during frying. Heating of the frying surfaces is performed by electric foil heaters (EFHs) (23) [199] with a total power of 2.2 kW, which are fixed on a shielding plate and ensure a maximum temperature field non-uniformity of no more than 5 K [90]. The working temperature of the upper and lower frying surfaces is regulated and maintained independently using a bimetallic thermostat (24).

The lower lid (12) is placed directly on the apparatus body (10), while the upper lid (13) is connected via two pairs of fixed (5, 6) and movable (7, 8) brackets. These allow the lid to be rotated by up to 180° using handle (11), enabling product loading and sanitary maintenance.

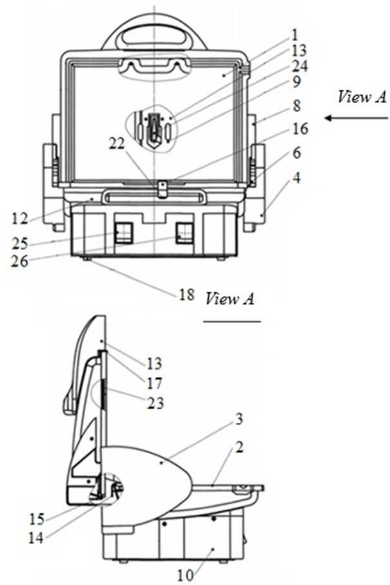


Figure 54. Schematic of the pilot-industrial prototype of the double-sided meat frying apparatus under electric current:

1, 2 – upper and lower frying surfaces; 3, 4 – right and left bracket body; 6 – right bracket; 8 – movable right bracket; 9 – shielding plate; 10 – body; 11 – handle; 12, 13 – lower and upper lids; 14, 15 – left and right clamp; 16, 17 – frying surface locks; 18 – support leg; 22 – lock nut; 23 – electric heating element; 24 – bimetallic thermostat; 25 – power switch for heating elements; 26 – power switch for frying surface current supply.

Compression of the meat during frying is achieved by the weight of the upper platform, which ensures excess steam pressure in the product’s surface layers in the range of 800–1100 Pa when three semi-finished products are loaded simultaneously. Electrical current is supplied to the product via a voltage reducer and a frequency converter, whose electrical circuit is detailed in the technical documentation [253].

Figure 55. Pilot-industrial prototype of the double-sided meat frying apparatus under electric current

The front panel of the apparatus body features two push-button switches: – 25: to supply voltage to the heating elements, – 26: to supply electric current to the frying surfaces.

The apparatus stands on four support legs (18). It is powered by a two-core cable with a grounding wire. All current-carrying parts are grounded, and the apparatus is equipped with a fuse in case of a short circuit.

The construction of the developed apparatus meets all specified requirements.

Operating principle of the pilot-industrial prototype of the double-sided meat frying apparatus under electric current is as follows: Before operation, all components must be checked for serviceability, and the secure fastening of the upper (1) and lower (2) frying surfaces to the upper (13) and lower (12) lids, respectively, should be verified. Then, the device is connected to a power supply (~220 V) using the power cable. Switch 25 is used to apply voltage to the heating elements (23), activating the preheating mode for 3–4 minutes.

Once the set temperature on the frying surfaces is reached (indicated by the green LED turning off on switch 25), the upper lid is lifted, the surfaces are greased with edible fat, and the prepared semi-finished meat products are placed on the lower surface. The upper lid is then lowered. Using switch 26, electric current is supplied to both frying surfaces.

During frying, direct contact between the upper and lower surfaces must be avoided to prevent short circuits.

After the frying cycle is complete, switch 26 is used to turn off the power supply to frying surfaces 1 and 2. The upper lid (13) is lifted and fixed in the vertical position. The ready products are removed using a wooden fork or spatula. The frying surfaces are re-greased, and the frying cycle is repeated.

At the end of the work, switch 26 is used to cut off the power to the heating elements, and the power cable is disconnected from the power supply. Sanitary cleaning of the frying surfaces and apparatus body is then carried out.

An instruction manual for operation and maintenance of the pilot-industrial prototype of the double-sided meat frying apparatus under electric current is provided in Appendix 7.

5.2. Design and Operating Principle of the Apparatus for Double-Sided Frying of Meat with High Connective Tissue Content in Functionally Closed Chambers

The technical documentation for the production of the pilot-industrial prototype of the apparatus for double-sided frying of meat with high connective tissue content (HCCT) in functionally closed chambers (FCC) under compression was developed based on the specified requirements and the calculation of the electric heaters' power.

The pilot-industrial prototype was manufactured according to the developed technical documentation using the material and technical base and staff of the Sectoral Research Laboratory of Food Production at the Poltava University of Economics and Trade (Ukoopspilka University), in cooperation with PJSC "Poltava Machine-Building Plant."

The apparatus can be used in foodservice enterprises and small meat processing facilities.

The schematic diagrams and general view of the apparatus for double-sided frying of meat with HCCT in FCC under compression are shown in Figures 56–58.

The apparatus consists of upper (3) and lower (4) heating surfaces, each heated by two flat foil heaters – NEF GK-1.1 [199]. The upper heating surface (3) is mounted on a working table (10) made of polished food-grade stainless steel with a hinge, which allows it to be rotated up to 110° relative to the lower heating surface (4) using a handle. It is rigidly fixed in a horizontal position during frying using a lock (11).

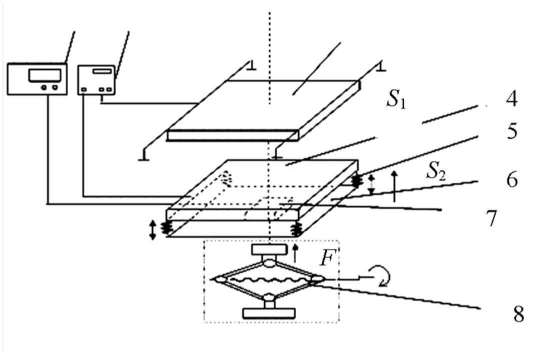


Figure 56. Basic schematic of the double-sided pressure frying apparatus:
1 – compression force indicator; 2 – temperature controller; 3, 4 – upper and lower heating surfaces; 5 – springs; 6 – platform supporting the springs; 7 – strain gauge; 8 – clamping mechanism.

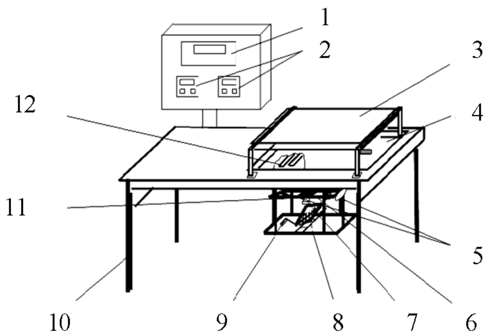


Figure 57. Schematic of the apparatus for double-sided frying of meat with HCCT in FCC under compression:
1 – KODA 2 weight terminal; 2 – TRC 0.2 temperature controller; 3, 4 – upper and lower heating

surfaces; 5 – springs; 6 – platform supporting the springs; 7 – MNC membrane strain gauge; 8 – clamping mechanism; 9 – handle; 10 – frame; 11 – lock; 12 – electric heating element (NEF).

The working table (10) is mounted on a welded frame. The lower heating surface (4) is connected to a platform (6) via four springs (5), which rests on an MNC membrane strain gauge (7) located on the clamping mechanism (8). This mechanism allows the vertical movement of the lower heating surface.

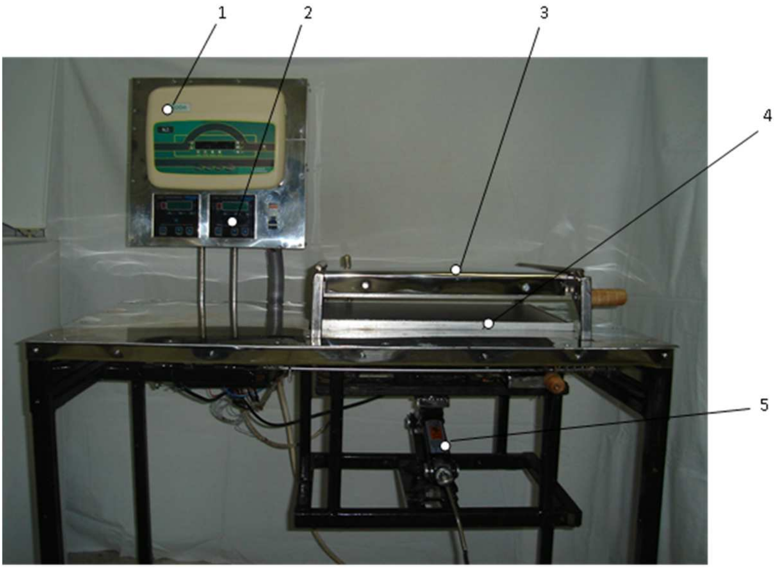


Figure 58. General view of the apparatus for double-sided frying of meat with HCCT in FCC under compression:

1 – KODA weight terminal; 2 – TRC 0.2 "Universal Plus" temperature controller; 3, 4 – upper and lower heating surfaces; 5 – compression mechanism.

The use of springs (5) ensures a constant excess steam pressure in the surface layers of the product during frying. The strain gauge (7) measures the compression force in real time, which is displayed on indicator (1) – the KODA weight terminal.

The required temperatures of heating surfaces (3) and (4) are maintained using a two-position temperature controller (2) – TRC 0.2 "Universal Plus," which receives signals from two XK-0.5 thermocouples embedded 0.00025 m deep into each heating surface. A second TRC 0.2 "Universal Plus" controller registers and displays the signal from a thermometric probe (an embedded XK-0.5 thermocouple) inserted into the center of a meat semi-finished product before the frying process.

Frying can be performed directly on the heating surfaces or within FCCs, which consist of two trays – upper and lower.

The apparatus is powered by a two-wire cable with a grounding wire. All current-carrying parts are grounded, and the apparatus is equipped with a fuse for short-circuit protection.

Operating Principle:

Meat semi-finished products are placed on the lower tray so that they are in close contact with the tray's surface, ensuring the larger side of each product is positioned down and that the distance between adjacent pieces is minimal. A thermometric probe is inserted into the center of one product. The lower tray is then covered with the upper tray, which is smaller in area and depth. The FCC is positioned between the upper (3) and lower (4) heating surfaces of the preheated apparatus (453–473 K). The required compression force is achieved using the clamping mechanism (8), which ensures the steam pressure in the surface layers of the meat reaches the required excess pressure level.

The frying process should not exceed 120 seconds. After completion, the lower heating surface (4) is lowered to table level using the clamping mechanism (8), the upper surface lock (11) is released, and the upper surface (3) is tilted back at an angle of 110° using the handle. The FCC with the finished product is then removed.

An excerpt from the technical documentation for the apparatus for double-sided frying of meat with HCCT in FCC under compression is provided in Appendix 9, and its safety operation guidelines are in Appendix 10.

5.3. Technical and Economic Indicators of the Developed Equipment

The technical and economic indicators of the developed equipment were determined during production testing under real operating conditions according to the following methodology.

The purpose of the production tests was to determine the technical characteristics of the developed equipment (the pilot-industrial prototype of the double-sided meat frying apparatus operating under electric current and the prototype of the apparatus for double-sided frying of meat with HCCT in FCC under compression) and the quality of the finished products after thermal processing.

The subject of the tests was the pilot-industrial prototypes of the developed equipment.

The production test program included the methods and procedures for testing both the double-sided electric current frying apparatus and the apparatus for double-sided frying of meat with HCCT in FCC under compression, through the following stages:

- Stage 1: Determination of thermal and operational performance indicators of the apparatus;
- Stage 2: Evaluation of the quality of the finished natural fried products after processing in the apparatus.

In the first stage, the following technical and operational indicators were determined: weight of the apparatus; power consumption; time required to reach steady-state mode; temperature of heating surfaces; yield of the finished product; productivity during the production of portioned natural fried products; and specific electricity consumption for the frying process.

For testing the prototype of the electric current-based double-sided frying apparatus, escalope semi-finished products were prepared from the chilled longissimus dorsi muscle of pork.

For testing the prototype of the apparatus for frying meat with HCCT in FCC under compression, entrecôte semi-finished products were prepared from the beef shoulder.

The apparatus weight was measured using VNSh-100 scales as the arithmetic average of three measurements.

Power consumption was determined using the "Energia 9" multifunctional electricity meter, STK-3 model (accuracy class 1.0), by integrating it into the power circuit of the apparatus. The readings were taken as the arithmetic average of three measurements while the apparatus was in the preheating mode.

Since the heating surface temperatures are regulated separately, the time to reach operating mode was measured from the moment the apparatus was connected to the power supply until the thermostat stopped power supply to both heating surfaces. This was timed using a stopwatch and averaged over three trials, with the apparatus cooled to the initial temperature between trials.

The frying surface temperature in the electric current-based double-sided frying apparatus was measured using a XK-0.5 thermocouple connected to a MASTECH M890G multimeter, placed between the surfaces during heating.

In the HCCT-FCC apparatus, the surface temperatures were measured using the built-in TRC 0.2 "Universal Plus" temperature controller with chromel-copel thermocouples (XK-0.5) embedded at the center of the upper and lower heating surfaces. The temperature was calculated as the average of the readings at the moment of power-off and power-on controlled by the thermostat, across three repetitions.

The yield of the finished product was determined using the formula:

$$z = \frac{G_{f.p.}}{G_{s.f.}}. \tag{5.1}$$

Readiness of the HCCT meat products was verified using a XK-0.5 thermocouple inserted into the semi-finished product and monitored with the MASTECH M890G multimeter, with doneness achieved at a core temperature of 358 K.

Productivity of the apparatus was calculated using the formulas:

$$Prod = \frac{n}{\tau}, psc./\ h, \tag{5.2}$$

$$Prod = \frac{G_{f.p.}}{\tau}, kg\ /\ h, \tag{5.3}$$

where:

- n – number of items, pcs.;
- τ – duration of thermal processing, including loading, unloading, and sanitary treatment time, h.

The duration of the frying process was measured using a stopwatch in triplicate, taking into account loading, unloading, and surface cleaning time.

Specific electricity consumption (kWh/kg) was calculated separately for the frying process and for hourly productivity.

Electricity consumption for frying was determined using the formula:

$$b_e = \frac{A}{G_{f.p.}}, \tag{5.4}$$

where:

- A – energy used during frying, kWh;
- *G_{f.p.}* – mass of finished product, kg.

Calculations were based on the average of three measurements. Data was obtained from previously determined indicators.

The results of Stage 1 were formalized in an official test report.

During Stage 2: “Evaluation of the quality of natural fried products based on organoleptic characteristics”, a tasting panel evaluated the finished products according to the methodology developed in section 3.3, using a point-based scoring system and weighting coefficients for each parameter.

In the organoleptic assessment of products fried in the electric current-based double-sided frying apparatus, each panelist received:

–Sample No. 1: traditionally fried (main method);

–Sample No. 2: fried in the double-sided apparatus;

–Sample No. 3: fried in the double-sided electric current-based apparatus;

–Sample No. 4: fried from a frozen semi-finished product in the electric current-based apparatus.

–For the HCCT meat fried in the FCC under compression, panelists evaluated:

–Sample No. 1: traditional heat-treated product (main frying method);

–Sample No. 2: beef product fried in the double-sided apparatus;

–Sample No. 3: beef product fried under compression in FCC.

The results of the sensory evaluation were recorded by each panelist on a scoring card using a five-point scale with weight coefficients. The overall score for each product was calculated as the weighted average across all indicators.

The results of the tasting evaluation were formalized in an official report.

The tests of the electric current-based double-sided meat frying apparatus were conducted at the training and production center of food technologies at the Poltava University of Economics and Trade.

Based on the results of Stage 1, documented in the official report, the key technical characteristics of the pilot-industrial prototype of the electric current-based double-sided frying apparatus were established and are presented in Table 5.1.

Table 5.1

Technical Characteristics of the Pilot-Industrial Prototype of the Double-Sided Meat Frying Apparatus under Electric Current

Characteristic	Unit of Measurement	Value
Productivity	kg/h	8,21
Power consumption	W	2600
Yield of finished product	%	91,2
Specific electricity consumption (numerator – for frying process, denominator –	(kW·h)/kg	0,132/0,200

by hourly productivity)		
Temperature of heating surfaces	K	423
Time to reach operating mode	s	200
Surface area of frying plates	m^2	0,048
Overall dimensions: – length – width – height	 m m m	 0,337 0,304 0,375
Weight	kg	6,87

As a result of Stage 1, the commission recommended the electric current-based double-sided frying apparatus for implementation in foodservice establishments and for mass production by food machinery enterprises.

The main identified drawback of the apparatus is the absence of a non-stick conductive coating on the frying surfaces. The commission recommended applying an electrically conductive non-stick coating to the frying surfaces.

During the second stage of production testing, the tasting commission confirmed the high quality of the finished products fried in the pilot-industrial prototype of the electric current-based double-sided frying apparatus.

The results of the quality assessment of products after thermal processing by traditional frying, double-sided frying, double-sided frying under electric current, and double-sided frying of frozen semi-finished products under electric current, using a 5-point scale, are presented in Table 5.2 and were formalized in an official report.

Table 5.2

Results of Quality Evaluation of Finished Products

Method of Thermal Processing	Quality Score (points)
Traditional frying	3,61
Double-sided frying	4,68
Double-sided frying under electric current	4,8
Double-sided frying under electric current from frozen semi-finished products	4,83

The data in Table 5.2 show that the quality of products after double-sided frying, both from chilled and frozen semi-finished products, is not inferior to that of traditional frying.

The testing of the apparatus for double-sided frying of meat with HCCT in FCC under compression was conducted at LLC “G.S.N. Group” (Yunist Café).

Based on the results of the first stage of production tests, as documented in the official report, the main technical characteristics of the pilot-industrial prototype of the apparatus for double-sided frying of meat with HCCT in FCC under compression were established and are presented in Table 5.3.

Table 5.3

Technical Characteristics of the Pilot-Industrial Prototype of the Apparatus for Double-Sided Frying of Meat with HCCT under Pressure in FCC under Compression

Characteristic	Unit of Measurement	Value
Productivity (based on finished product mass of 0.0645 kg)	psc./h kg/h	242 15,61
Time to reach operating mode	S	352
Yield of finished product	%	82
Specific electricity consumption	(kW·h)/kg	0,260
Temperature of heating surfaces	K	473
Temperature of FCC surfaces	K	423
Power consumption	W	4052

Overall dimensions: – length – width – height	 m m m	 0,915 0,56 1,21
Weight	kg	61,03

Based on the production test results, the commission recommended the apparatus for double-sided frying of meat with HCCT in FCC under compression for implementation in foodservice establishments and for mass production by food machinery enterprises.

The commission also formulated recommendations for improving the prototype apparatus: to include a collection tray for meat juices and to mechanize the pressure generation process.

During the second stage of production testing, the tasting commission confirmed the high quality of finished products processed in the pilot-industrial prototype of the apparatus for double-sided frying of meat with HCCT in FCC under compression.

The results of the quality evaluation of HCCT meat products processed by traditional frying, double-sided frying, and double-sided frying in FCC under compression, using a 5-point scale, are presented in Table 5.4 and were formalized in an official report.

Table 5.4

Results of Quality Evaluation of Finished HCCT Meat Products

Method of Thermal Processing of HCCT Meat	Quality Score (points)
Traditional frying	3,08
Double-sided frying	3,17
Double-sided frying in FCC under compression	4,02

The data in Table 5.4 demonstrate that the highest quality of HCCT meat products was achieved after double-sided frying in FCC under compression.

5.4. Conclusions for the Chapter

1. Technical requirements (technological, operational, energy efficiency, structural, economic, safety and sanitation, technical aesthetics, and reliability) and design specifications were developed for the creation of new energy-efficient and resource-saving equipment for conductive meat frying. The use of such equipment ensures the implementation of conductive frying processes under optimal process parameters.

2. A double-sided meat frying apparatus operating under electric current was developed. It is intended for the implementation of the double-sided conductive frying process using electric current. Its distinctive

features include an automated voltage supply system delivering 27 V electric current at a frequency of 0.5 Hz to meat products during the double-sided frying process, and the absence of a compression system. This significantly simplified the construction and improved operational convenience. Although the thermal processing duration is 20–25% longer compared to the declared characteristics of the pilot prototype PUCCU-1 (for double-sided frying under compression), the actual processing time at full load (Table 2.3) is twice as short (75 vs. 150 s); the yield of the finished product is 1.2% higher (91.2% vs. 90%). Compared to the closest structural analogue—the Elio L double-sided food frying apparatus—the thermal processing time is 3.38 times shorter (75 vs. 254 s), and the product yield is 10.2% higher (91.2% vs. 81%).

3. A double-sided frying apparatus for meat with high connective tissue content (HCCT) in functionally closed chambers (FCC) under compression was developed. It is designed to implement the double-sided frying process for HCCT meat in FCC under compression. Its distinguishing features include the use of FCC during frying and the presence of a compression mechanism. For the first time, the use of this apparatus enables conductive frying of meat products that are not typically suitable for frying due to their technological properties. The yield of the finished product is 82%, which is comparable to the 81% yield achieved with the Elio L apparatus, while the frying time is reduced by half (120 s vs. 254 s).

CHAPTER 6. ENERGY, SOCIO-ECONOMIC EFFICIENCY AND RESULTS OF IMPLEMENTATION OF SCIENTIFIC AND TECHNICAL DEVELOPMENTS IN PRODUCTION

6.1. Energy Efficiency of Scientific and Technical Developments

In the context of the energy crisis in Ukraine and the continuous rise in the cost of energy resources, the development and implementation of new highly energy - and resource-efficient equipment in the operations of food industry enterprises, including the restaurant sector, is gaining special importance.

The energy efficiency of the proposed processes and devices is suggested to be evaluated using a set of indicators: specific electricity consumption b_e, thermal efficiency η_h, exergy efficiency η_{ex}, energy efficiency η_{en}, and process efficiency η_{ef}. The developed methodology was used to analyze the energy efficiency of conductive meat frying processes using dedicated apparatus.

Based on a comprehensive study, new energy- and resource-efficient processes for conductive meat frying were developed, including those using HCCT (High-Current Conductive Treatment), as well as new devices for their implementation, which require evaluation of their energy efficiency according to the proposed methodology.

The calculation of energy efficiency indicators for the dual-sided meat frying apparatus operating under electric current based on production test data is presented in Appendix 11.

The results of energy efficiency calculations for the dual-sided meat frying device using HCCT in FCC (Forced Contact Compression) conditions based on production tests are shown in Table 6.1.

As shown in Table 6.1, the conductive frying process in the dual-sided frying device using electric current demonstrates high energy efficiency indicators. The specific energy consumption for frying b_e is 0.132 kWh/kg, which is 0.0291 kWh/kg lower than that of the PUCCU-1 device (Table 4.4). The thermal efficiency η_h of the device is higher than that of the PUCCU-1. The exergy efficiency η_{ex}, process efficiency η_{ef} , and energy efficiency η_{en} in the dual-sided frying device with electric current are also higher than those of the PUCCU-1 (Tables 2.6, 2.7). The increase in energy efficiency indicators is attributed to the higher yield of the final product and correspondingly lower heat and exergy losses during heating and moisture evaporation during the frying process [257].

Table 6.1

Energy Efficiency Indicators of the Developed Equipment

No.	Indicator Name	Dual-Sided Electric Frying Device	Dual-Sided Frying Device with HCCT in FCC Under Compression
1	Specific electricity consumption, b_e, kWh/kg	0,132	0,260
2	Thermal efficiency, η_h	0,9436	0,8744
3	Exergy efficiency, η_{ex}	0,7255	0,6193
4	Process efficiency, η_{ef}	0,8290	0,7540
5	Energy efficiency, η_{en}	0,7822	0,6593

The dual-sided frying device with HCCT in FCC under compression shows energy efficiency indicators comparable to the Elio L device (Tables 2.4, 2.6, 2.7). This is due to the specific technological purpose of the device—frying beef products with HCCT that require a higher core temperature—and the use of FCC in the frying process, which necessitates higher surface temperatures to ensure FCC surface temperatures do not exceed 423 K to prevent HA formation.

6.2. Socio-Economic Efficiency of Scientific and Technical Developments

There is a close interrelation between social and economic efficiency when implementing new energy- and resource-saving equipment and technologies in production. Economic efficiency forms the material basis for solving social problems faced by both product consumers and enterprise employees. In turn, social development of consumers and producers (improved well-being, educational and cultural levels, conscientious labor attitude, etc.) significantly influences the production efficiency at enterprises. The economic efficiency of implementing the developed dual-sided electric meat frying apparatus lies in substantial savings of electricity and raw materials. The calculation of economic efficiency was conducted relative to the PUCCU-1, Elio L, and SESC-0.2 frying devices.

As of June 1, 2015, the average cost of boneless pork loin is 245.00 UAH per kg [258].

According to the Law of Ukraine "On the Electricity Market," the Retail Electricity Market Rules approved by the National Commission for State Regulation of Energy and Utilities (Resolution No. 312 of March 14, 2018, with amendments), the Civil and Commercial Codes of Ukraine, effective from January 1, 2025, and the commercial offer of Poltavaenergozbut LLC No. 1A, the minimum tariff for electricity, including distribution, is 6.2223 UAH/kWh [259].

The economic efficiency calculation for the dual-sided electric meat frying device (ADSFMEC) is shown in Table 6.2.

Table 6.2

Economic Efficiency Calculation for the Dual-Sided Electric Meat Frying Device

No.	Indicator Name	SESC-0.2	Elio L	PUCCU-1	ADSFMEC
1	2	3	4	5	6
1	Specific electricity consumption, b_e, kWh/kg	0,5446	0,2678	0,1611	0,1320
2	Yield of finished product z	0,689	0,810	0,900	0,912
3	Electricity consumption per 1000 kg of finished product,	544,6	267,8	161,1	132

	kW·h				
4	Cost of electricity per 1 kg of finished product, UAN	3,39	1,67	1,01	0,82
5	Cost of electricity per 1000 kg of finished product, UAH	3388,66	1666,33	1002,41	821,34
6	Savings due to increased yield of finished product, Δz: – compared to SESC-0.2 – compared to Elio L – compared	– – –	– – –	– – –	0,223 0,102 0,012

	to PUCCU-1				
7	Economic effect per 1 kg of finished product due to increased yield, UAH: – compared to SESC-0.2 – compared to Elio L – compared to PUCCU-1	– – –	– – –	– – –	54,64 24,99 2,94
8	Economic effect per 1000 kg of finished product due to increased yield, UAH:	– – –	– – –	– – –	54640,00 24990,00 2940,00

	– compared to SESC-0.2 – compared to Elio L – compared to PUCCU-1				
9	Economic effect per 1 kg of finished product due to electricity cost, UAH: – compared to SESC-0.2 – compared to Elio L – compared to PUCCU-	– – –	– – –	– – –	2,57 0,85 0,19

	1				
10	Economic effect per 1000 kg of finished product due to electricity cost, UAH: – compared to SESC-0.2 – compared to Elio L – compared to PUCCU-1	– – –	– – –	– – –	2567,32 844,99 181,07
11	Total economic effect per 1 kg of finished product, UAH: – compared	– – –	– – –	– – –	57,21 25,84 3,13

	to SESC-0.2 – compared to Elio L – compared to PUCCU-1				
12	Total economic effect per 1000 kg of finished product, UAH: – compared to SESC-0.2 – compared to Elio L – compared to PUCCU-1	– – –	– – –	– – –	57207,32 25834,99 3121,07

As shown in Table 6.2, the total economic benefit of introducing the dual-sided electric meat frying device in the operations of restaurant enterprises per 1 kg of ready fried pork products compared to the SESC-0,2 frying pan is 57,21 UAH, which equals 1,12 EUR at the exchange rate of the National Bank of Ukraine as of 07.04.2025 (45,5524 UAH/EUR). Compared to the Elio L device, it is 25,84 UAH or 0,57 EUR, and compared to the PUCCU-1 device under compression – 3,13 UAH or 0,07 EUR.

The total economic benefit for 1000 kg (1 ton) of product is:

- compared to SESC-0,2 – 57207,32 UAH or 1255,86 EUR;
- compared to Elio L – 25834,99 UAH or 567,15 EUR;
- compared to PUCCU-1 – 3121,07 UAH or 68,52 EUR.

The payback period of capital investments depends on the production program, type of equipment being replaced, and the enterprises' financial capacity.

The social effectiveness of implementing the dual-sided electric frying device in restaurant enterprises includes:

- ensuring high quality and safety of finished products by preventing HA formation;
- reducing labor intensity in operating the device;

– improving working conditions for staff due to lower surface temperatures and reduced heat emissions.

Restaurant enterprises are the final link in delivering fried meat products to consumers. Thus, the socio-economic efficiency of implementing the dual-sided electric frying device concerns both the enterprises and consumers.
Meat raw materials are supplied to restaurant enterprises either as large piece semi-finished products or in half-carcasses, in chilled or frozen form.
Frozen products lead to additional material and energy costs due to thawing, during which up to 8% of raw material can be lost, along with 0.06–0.085 kWh/kg of electricity (for freezing and thawing), depending on the thawing method [260].

To reduce these costs, a technological production chain is proposed for portioned natural fried meat products, starting from primary meat processing enterprises [209, 261]. The chain is shown in Figure 59.

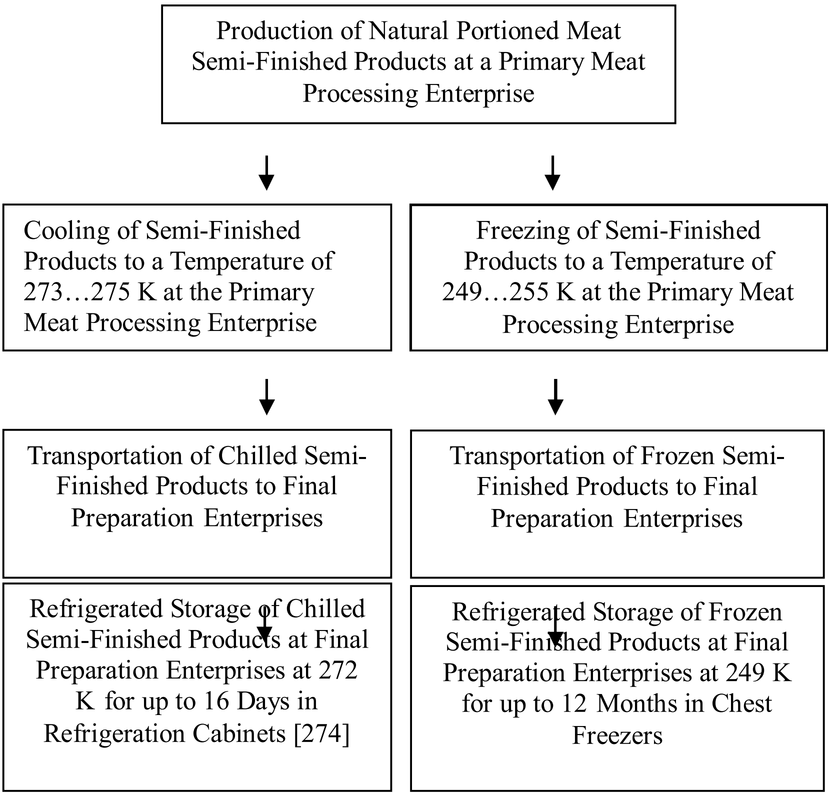
For chilled semi-finished products, the specific electricity consumption for the entire production process is 0,190–0,210 kWh/kg (excluding refrigeration and transport).

For frozen semi-finished products, the total consumption is 0,380–0,420 kWh/kg, of which 0,320–

0,335 kWh/kg is used directly for frying (excluding refrigeration and transport) [209, 261].

The yield of finished product from frozen semi-finished goods can reach 93% [210].

Implementation of the proposed technological chain (Fig. 59) in meat processing and restaurant enterprises allows minimization of electricity consumption, reduction of manual labor through mechanization and automation, optimization of product yield and quality, and overall fulfillment of consumer demands.



↓ ↓

Frying of Chilled or Frozen Semi-Finished Products in a Dual-Sided Electric Frying Device at the Point of Sale

Fig. 59. Technological Chain Diagram for the Production of Fried Portioned Natural Meat Products with Minimal Energy Consumption and Raw Material Losses

The production of fried portioned natural meat products from frozen semi-finished products is particularly relevant in terms of microbiological safety in the southern regions of Ukraine along the Black Sea and Sea of Azov coasts during the summer tourist season.

To minimize the specific electricity consumption in the production of semi-finished high-readiness fried portioned natural meat products at meat processing enterprises and to extend their shelf life, we have developed a technological sequence shown in Fig. 60.

Production of Natural Portioned Semi-Finished Products at a Primary Meat Processing Enterprise

↓

Thermal Processing of Semi-Finished Products in Dual-Sided Electric Frying Devices

↓

Cooling of Products to a Temperature of 273…275 K

↓

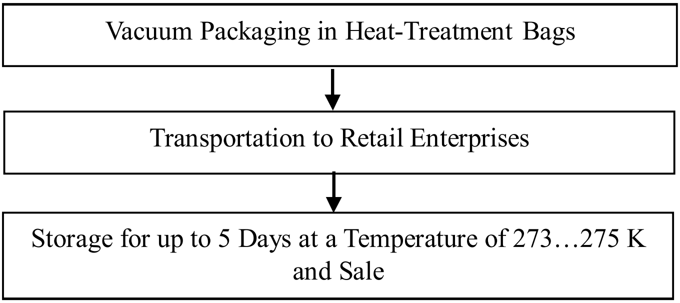


Fig. 60. Technological Sequence for the Production and Sale of Semi-Finished High-Readiness Fried Portioned Natural Meat Products

According to the technological sequence shown in Fig. 60, the total specific electricity consumption at the primary meat processing enterprise consists of the specific consumption for the frying process of semi-finished products, cooling to a temperature of 273…275 K, and vacuum packaging in heat-treatment bags using chamber-type vacuum packaging machines such as the HENKELMAN Mini Jumbo [262], and does not exceed 0,210 kWh/kg. The costs of refrigeration storage during transportation and sale are borne by the retail enterprise or the supplier and the retail enterprise.

After purchasing the semi-finished high-readiness fried portioned natural meat products in heat-treatment bags, the consumer can perform thermal regeneration (reheating) of the finished products at home to a serving temperature of 338 K directly in the heat-treatment bags either by microwave treatment at a power of 850 W for 30 seconds, or by heating in a water bath at 373 K for 120 seconds [263].

The implementation of this technological sequence (Fig. 60) at primary meat processing enterprises allows the minimization of specific electricity consumption for the production of fried portioned natural meat products, reduction of manual labor through mechanization and automation of the main stages of semi-finished product production and transportation, and ensures the highest quality and yield of finished products, thus fully meeting consumer demands.

The economic efficiency of implementing the dual-sided meat frying device with HCCT in FCC under compression (ADSFMCC) in the activities of restaurant enterprises lies in the substantial savings of financial and material resources due to the substitution of raw materials [264]. According to data [265], as of November 30, 2023, the cost of 1 kg of beef ribeye or sirloin in Ukraine is 359,00 UAH, while the cost of 1 kg of the beef shoulder part is 264,00 UAH. The economic effect per 1 kg of finished product due to the implementation of the device is not less than 35.00 UAH, and for 1000 kg (1 ton) — not less than 35000,00 UAH or 768,35 EUR.

The specific electricity consumption for the frying process in the dual-sided frying device with HCCT in FCC under compression – 0.26 kWh/kg – is at the same level as the Elio L device.

The social efficiency of implementing the dual-sided meat frying device with HCCT in FCC under compression in restaurant enterprises lies in reducing the cost price of finished meat products from HCCT-treated meat and ensuring their safety by preventing the formation of HA [266].

6.3. Results of Implementation of Scientific and Technical Developments

Based on the recommendations obtained from the results of production tests, a technical assignment was developed for the manufacturing of an industrial prototype of the dual-sided electric meat frying apparatus at the facilities of PJSC "Poltava Machine-Building Plant." The act of acceptance for development and manufacturing of the industrial prototype of the dual-sided electric meat frying apparatus was approved on February 25, 2014.

Also based on the recommendations from production tests, a technical assignment was developed for the manufacturing of an industrial prototype of the dual-sided meat frying apparatus with HCCT in FCC under compression at the facilities of PJSC "Poltava Machine-Building Plant." The act of acceptance for the development and manufacturing of this industrial prototype was approved on March 29, 2010.

The main provisions of this work have been implemented in the educational process at the higher educational institution of the Ukrainian Consumer Cooperative Union — Poltava University of Economics and Trade, and are used in the teaching of the disciplines "Technological Equipment of the Industry" and "Processes and Apparatus of Food Production" for students majoring in 6.051701 "Food Technologies and Engineering."

In addition, the main provisions of this work have been introduced into the curriculum at Kharkiv State University of Food Technology and Trade and are used in the teaching of the disciplines "Technological Equipment of Industry Enterprises," "Processes and Apparatus of Food Production," and "Calculation and Design of Equipment for Small-Scale Processing and Food Production" for students of the specialty 8.05050313 "Equipment for Processing and Food Production."

6.4. Conclusions for the Chapter

1. The calculation of thermal processing indicators for meat in the dual-sided electric frying apparatus ($b_e = 0{,}132$ kW·h/kg, $\eta_h = 91{,}3\%$, $\eta_{ex} = 73{,}3\%$, $\eta_{en} = 75{,}8\%$, $\eta_{ef} = 83\%$) confirmed that the developed apparatus demonstrates high energy efficiency and implements rational process parameters.

2. The calculation of thermal processing indicators for meat in the dual-sided frying apparatus with HCCT under compression ($b_e = 0{,}260$ kW·h/kg, $\eta_h = 87{,}44\%$, $\eta_{ex} = 61{,}93\%$, $\eta_{ef} = 75{,}40$, $\eta_{en} = 65{,}93\%$) confirmed that the developed apparatus also shows high energy efficiency and rational process parameters.

3. The economic benefit of implementing the dual-sided electric frying apparatus lies in significant savings in electricity and meat raw materials, amounting to 1255,86 EUR per 1000 kg of finished portioned fried natural meat products compared to the SESC-0.2 frying pan, 567,15 EUR compared to the Elio L device, and 68,52 EUR compared to the PUCCU-1 compression frying device.

4. The economic benefit of implementing the dual-sided frying apparatus with HCCT in FCC under compression lies in replacing high-grade raw material with lower-grade alternatives and amounts to no less than 768,35 EUR per 1000 kg of finished portioned fried natural meat products.

5. The developed technological chain and sequence for the production of portioned fried natural meat products and their high-readiness semi-finished counterparts enable the minimization of specific electricity consumption, reduction of meat raw material losses and manual labor, ensure the best quality and yield of the final product, and create extensive opportunities for mechanization and

automation of both semi-finished and finished product production.

6. The social efficiency of the scientific and technical developments lies in ensuring the safety of fried meat products for consumers, reducing their cost, and improving working conditions for personnel.

CONCLUSIONS

1. Based on the conducted analysis of existing meat frying processes, technological requirements for the process and equipment of conductive frying were formulated. These include reducing the process temperature to 423 K, minimizing product flipping during frying, shortening the frying time, reducing contact with fat, and preserving moisture in the surface layers of the product. Detailed technological requirements for the conductive frying of meat using HCCT were also defined. These emphasize ensuring maximum surface contact between the product and the heating surface, preventing product surface deformation during frying, maximizing the retention of native meat moisture (sufficient for collagen hydrolysis and disaggregation), and eliminating conditions for the formation of heterocyclic amines (HAs).

2. A novel methodology for evaluating the energy efficiency of conductive meat frying processes and equipment was developed. It is based on specific energy consumption b_{e} (kWh/kg), thermal efficiency η_t, exergetic efficiency η_{ex}, energy efficiency η_{en}, and overall process efficiency η_{ef}. An energy efficiency analysis of these processes in the respective devices was carried out, which allowed formulating strategies for improving energy efficiency and resource conservation. These include increasing the

heat exchange area and meat contact area with the frying surfaces during double-sided heat supply, enhancing the heat transfer coefficient from the surfaces to the meat, changing the thermophysical properties of meat-particularly increasing the thermal conductivity λ_m, and reducing the meat thickness from δ_m to effective thickness δ_{ef} via pressure or electric current application.

3. An analytical model of double-sided frying processes under the influence of electrophysical methods was justified. These processes were proposed to be divided into three main stages by duration, with the second stage being the most energy-intensive due to continuous evaporation and condensation of water vapor transferring heat through the meat's surface layer. A solution was proposed for the unsteady heat conduction equation (thermal model) during double-sided frying, including HCCT-based processes.

4. A methodology was developed to determine the heat transfer and heat exchange coefficients from the frying surfaces to the meat in the surface layers during the second stage of the process. This was based on actual thermodynamic processes occurring in the capillary menisci of the product's surface layers.

5. Patterns of substance flow within meat under the influence of electric current, thermal flux, excess pressure, and their combined effects were identified. Based on this and the defined technological requirements, ranges of optimal process parameters

for double-sided meat frying, including HCCT-based methods, were substantiated.

6. The study identified rational parameters for double-sided frying under electric current: surface temperature ≤ 423 K, applied voltage $U = 27$ V, frequency f=0.5 Hz, excess pressure p=(800...1100) Pa, total heat flux Q=(77...83) W or specific heat flux q=($38,5 \cdot 10^3$...$41,5 \cdot 10^3$) W/m². These conditions allow achieving maximum yield (91.5% from chilled and 93% from frozen semi-finished products) with minimal frying duration (τ=75 s for chilled and τ=150 s for frozen products).

7. For conductive frying with HCCT in FCC under compression, the rational parameters were found to be: frying surface or FCC temperature of 423 K, steam overpressure p_{lim} p due to compression, and specific heat flux of $38,5 \cdot 10^3$…$41,5 \cdot 10^3$ W/m². This allows obtaining a ready product with an 82% yield in 120 seconds.

8. The evaporation and condensation durations in the capillary menisci of surface meat layers varied from $111 \cdot 10^{-6}$ to $400 \cdot 10^{-6}$ s under electric current frying and from $50 \cdot 10^{-6}$ to $333,3 \cdot 10^{-6}$ s for HCCT-based frying in FCC. The overall heat transfer and heat exchange coefficients were $k = 9626$ W/(m²·K) and $\alpha = 19252$ W/(m²·K) for the first method, and $k = 9500$ W/(m²·K), $\alpha = 19000$ W/(m²·K) for the second.

9. Two devices were developed: one for double-sided meat frying under electric current, and another for frying with HCCT in FCC under excess pressure.

Their technical and energy efficiency indicators were determined under production conditions. For the first device: $b_e = 0{,}132$ kWh/kg, $\eta_t = 91{,}3$, $\eta_{ex} = 73{,}3\%$, $\eta_{en} = 75{,}8$, $\eta_{ef} = 83\%$; for the second: $b_e = 0{,}260$ kWh/kg, $\eta_t = 87{,}44\%$, $\eta_{ex} = 61{,}93\%$, $\eta_{ef} = 75{,}40\%$, $\eta_{en} = 65{,}93\%$.

10. The socio-economic effectiveness of implementing these developments in restaurant enterprises was evaluated. Economic benefits per 1000 kg of finished natural portioned fried meat products amounted to at least EUR 768,35 for the HCCT-in-FCC device (due to substitution of high-grade meat with lower-grade raw material), and EUR 1255,86 for the electric current frying device compared to the SESM-0.2 pan, EUR 567,15 compared to the Elio L double-sided fryer, and EUR 68,52 compared to the PUSKU-1 fryer under pressure – primarily due to significant savings in electricity and raw meat. The social impact of these scientific and technical developments includes safer meat products, reduced product cost, and improved working conditions for staff. The developed models and research findings have been integrated into the educational process at PUET and KhSUFT. The technical specifications and design documentation for the developed equipment have been transferred for implementation to PJSC «Poltava Machine-Building Plant».

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