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TECHNOLOGICAL PREREQUISITES FOR THE APPLICATION OF PERFORATED DIFFUSION CHANNELS IN THE THERMAL PROCESSING OF WHOLE-MUSCLE MEAT PRODUCTS

The article presents a comprehensive analysis of the technological prerequisites for the use of perforated diffusion channels in the thermal processing of whole-muscle meat products. It is substantiated that the key limiting factors in boiling and smoking processes of large muscle structures are the external mode of heat supply, significant product thickness, long radial diffusion paths within muscle tissue, and the low rate of internal migration of moisture and volatile aromatic compounds. These factors lead to the formation of pronounced temperature and moisture gradients, non-uniform heating of central zones, increased mass losses, and the necessity of excessive thermal load to ensure microbiological safety of the product. Based on a generalization of contemporary research on heat and mass transfer in meat systems, the feasibility of transitioning from regulation of exclusively external process parameters to control of the internal transport architecture of the product is demonstrated. A conceptual model for intensifying heat and mass transfer through the formation of perforated diffusion channels within the product is proposed. These channels create additional internal heat and mass exchange surfaces and provide a combination of radial heat conduction in tissue with convective transport inside the channels. It is shown that reducing the effective diffusion path length contributes to temperature field equalization, acceleration of heating in central zones, improved uniformity of smoke component penetration, and reduction of thermal processing time without deterioration of organoleptic properties. It is substantiated that the application of perforated channels potentially ensures a comprehensive increase in technological efficiency, including stabilization of textural characteristics, reduction of mass losses, optimization of energy and resource consumption, and decreased consumption of smoking materials. The proposed approach has a conceptual character and forms a scientific basis for further experimental studies and the development of innovative technologies for thermal processing of whole-muscle meat products with controlled quality parameters.

Keywords: thermal processing; whole-muscle meat products; heat and mass transfer; perforated diffusion channels; product transport architecture.

Statement of the problem and its relevance. Thermal processing of whole-muscle meat products is a key stage in the formation of their consumer properties, including texture, juiciness, flavor and aroma characteristics, and microbiological safety as described by Lawrie R. A., Ledward D. A. [7] and Toldrá F. [13]. A specific feature of such products is the considerable thickness of muscle tissue and its heterogeneous internal structure, which determines the complex nature of heat and mass transfer during boiling, roasting, and smoking. Unlike comminuted systems, in which size reduction decreases diffusion path length, whole-muscle products are characterized by low

thermal conductivity and limited moisture transfer rates. This results in prolonged thermal processing times and the formation of significant temperature and moisture gradients.

In technological practice, these characteristics manifest as non-uniform heating of the product, increased mass losses, the formation of an overdried surface layer, and insufficient penetration intensity of smoke components into internal zones. Prolongation of thermal processing, in turn, leads to increased energy consumption, higher use of smoking materials, and deterioration of organoleptic properties. Therefore, the search for technological



solutions aimed not only at modifying external process parameters but also at controlling internal transport of heat, moisture, and aromatic compounds within the product is highly relevant.

An analysis of contemporary research indicates that most intensification methods in thermal processing are focused on modifying external process conditions, including increasing medium temperature, applying vacuum, using pulsed heating regimes, or preliminary brine injection. However, such approaches do not eliminate the fundamental limitation associated with the considerable length of diffusion paths within muscle tissue. This necessitates the development of new technological approaches aimed at creating additional internal surfaces for heat and mass exchange.

One promising direction may be the use of perforated diffusion channels that modify the internal transport architecture of the product and potentially contribute to reduced processing time, improved heating uniformity, and enhanced flavor and aroma characteristics of finished products. At the same time, a systematic analysis of the technological prerequisites for applying such channels in the thermal processing of whole-muscle meat products is virtually absent in the scientific literature, which determines the relevance of this study.

Analysis of recent research and publications.

Thermal processing of meat products is characterized by a complex interaction of heat transfer, moisture transfer, and phase transformations within the protein matrix. These processes largely determine the final quality characteristics of the product and are widely described in the works of Incropera F. P. et al. [6] and Singh R. P. and Heldman D. R. [11]. It has been established that the efficiency of boiling, smoking, and drying largely depends on the rate and uniformity of internal heat and moisture transfer, which shape the temperature profile, mass losses, and textural properties of the product. In particular, during drying and smoking of meat, heat and mass exchange both in the processing chamber and inside the product determines changes in temperature, moisture content, and fat content, and also affects the energy efficiency of the process and the consumption of smoking materials.

Fundamental studies on heat transfer in meat conducted by Baldwin D. E. [2] demonstrate that muscle tissue possesses relatively low thermal conductivity, while mass transfer proceeds more slowly than heat transfer. This leads to the formation of temperature gradients and structural heterogeneity during heating. For example, salt diffusion coefficients in meat are several orders of magnitude lower than thermal diffusivity coefficients, confirming the different rates of these processes and the necessity of their integrated consideration in modeling thermal processing, as demonstrated by Sebastian P. et al. [10].

Recent studies on modeling of technological processes demonstrate that control of the temperature profile inside large meat cuts is a critical factor for product safety and quality, as shown by Feyissa A. H. et al. [5]. Mathematical models of thermal processing of cured and smoked pork

loin have shown that the internal temperature of the product significantly depends on its position within the chamber and on processing regimes, and that modeling can be used to optimize processes and reduce energy consumption.

The problem of non-uniform heat and mass transfer is also manifested in boiling and roasting processes, where the interaction between heat flux and moisture migration determines structural changes, mass losses, and crust formation. Studies on simultaneous heat and mass transfer during thermal processing of meat products have shown, as demonstrated by Llave Y. et al. [8], that mass transfer coefficients decrease over the course of heating, which contributes to reduced efficiency of moisture removal and affects process duration as well as final product properties.

Reviews of modern meat thermal processing technologies indicate, as reported by Alfaifi B. M. et al. [1] and Domínguez R. et al. [4], that traditional methods (boiling, roasting, smoking) have a significant impact on physicochemical, sensory, and microbiological characteristics of products, while newer approaches are aimed at improving temperature control and structural uniformity. At the same time, most innovations are focused on modifying external processing conditions rather than internal heat and mass transfer mechanisms.

An analysis of comprehensive review studies on meat thermal treatment shows that various heating methods – from conventional boiling to modern techniques such as sous-vide or microwave processing – affect protein structure, water-holding capacity, and the aromatic profile of products. In this context, uniform internal heating and control of thermal gradients remain key factors in quality formation.

An important feature of thermal processing of large meat cuts, as noted by Pathare P. B. et al. [9], is the phenomenon of internal heat redistribution after heating has ceased (carryover cooking), when heat continues to migrate from the periphery toward the center of the product. This confirms the presence of significant temperature gradients and demonstrates the dependence of their magnitude on the size and density of the product.

Thus, the analysis of the literature indicates that the main technological limitations in the thermal processing of whole-muscle meat products are associated with the external mode of heat supply, the considerable length of diffusion paths, and the slow migration of moisture and aromatic components. Despite the development of modern technologies, systematic approaches to controlling internal heat and mass transfer remain insufficiently explored. This creates prerequisites for the development of new technological solutions, particularly those aimed at forming additional internal surfaces for heat and mass exchange.

Objectives of the article. The purpose of the study is to provide scientific substantiation for the feasibility of using perforated diffusion channels in the thermal processing of whole-muscle meat products based on the analysis of internal heat and mass transfer patterns and to determine the technological prerequisites for their application in

order to increase the efficiency of boiling and smoking processes.

Summary of the main research material. An analysis of contemporary studies indicates that a key factor determining the efficiency of thermal processing of meat products is the formation of the temperature profile within the product. Modeling of cured and smoked product manufacturing processes has shown [12] that temperature at different points of the product differs significantly depending on the processing stage, and its spatial distribution determines product quality and microbiological safety. In particular, during smoking followed by steam cooking, convective heat supply from the surface is the dominant heating mechanism, whereas internal heat transfer proceeds considerably more slowly, resulting in the formation of temperature gradients between the surface and the center of the product [14].

Such non-uniform heating is characteristic of most thermal processing methods. A review of studies on meat cooking processes shows that heat and mass transfer arise due to temperature and moisture differences between the product and the surrounding environment, while the rate of these processes depends on temperature, air velocity, product geometry, and the heating method. In this context, surface moisture evaporation and internal water diffusion are interrelated processes that determine mass losses and textural changes in the product.

A significant feature of meat thermal processing is the different rates of heat and moisture transfer. Theoretical and experimental studies have demonstrated that moisture migration during meat cooking can be described using swelling and shrinking models of polymer gels, reflecting the complex behavior of the protein matrix during heating. This indicates that internal mass transfer is constrained by tissue structure and is accompanied by deformations that influence process kinetics.

An important factor is also the influence of product dimensions on the intensity of mass transfer. Studies have shown that mass transfer coefficients significantly depend on the geometric characteristics of meat samples, confirming the decisive role of product thickness in determining the rate of heat and mass exchange processes. As product size increases, the time required to reach the target temperature at the center increases, and structural uniformity deteriorates.

An additional manifestation of these phenomena is the necessity of excessive thermal load to ensure product safety. Reviews of engineering aspects of heat transfer in the food industry indicate that, in order to guarantee microbiological safety, temperatures or processing times exceeding the strictly required levels are often applied, leading to quality losses and increased energy consumption.

In smoking processes, these limitations are further compounded by the surface-driven nature of mass transfer of aromatic components. The formation of flavor and aroma in meat products is largely associated with Maillard reactions and the penetration of volatile compounds; however, diffusion of these substances into the product

matrix is slow and depends on temperature, humidity, and tissue structure. This explains aroma non-uniformity and the need for prolonged smoking regimes.

The generalization of the above data allows concluding that the main technological limitations in the thermal processing of whole-muscle meat products are associated with:

- the external mode of heat supply;
- the considerable length of diffusion paths within muscle tissue;
- slow internal migration of moisture and aromatic compounds;
- the dependence of process kinetics on the geometric parameters of the product;
- the necessity of increased thermal loads to ensure safety.

Thus, effective improvement of the technological efficiency of thermal processing requires not only optimization of external process parameters but also the development of new approaches to controlling internal heat and mass transfer [3]. This creates prerequisites for the application of technological solutions aimed at shortening diffusion paths and forming additional internal surfaces for heat and mass exchange, including the use of perforated diffusion channels.

An analysis of thermal processing of meat products indicates that the dominant limiting factor is the external nature of heat supply and mass transfer. Traditionally, heat, moisture, and smoke components enter the product through its surface, resulting in radial transport of substances and heat and leading to significant temperature and moisture gradients. In whole-muscle products of substantial thickness, this mechanism causes prolonged processing time, increased mass losses, and non-uniform organoleptic characteristics.

In this context, an approach based on the formation of additional internal heat and mass exchange surfaces appears promising. One possible implementation of such an approach is the creation of perforated diffusion channels within the product, which modify the internal transport architecture of the meat system (Fig. 1). Unlike a solid structure in which heat and moisture migrate through tissue over considerable distances, the presence of channels forms localized zones of intensified heat and mass exchange, potentially shortening diffusion paths and contributing to a more uniform distribution of process parameters.

From a physical perspective, perforated channels may function as internal heat-exchange elements in which convective heat and mass transfer with the thermal processing medium takes place. As a result, a combined transfer mechanism is formed, including radial heat conduction within the tissue and convective transport inside the channel. Such a structure creates conditions for reducing temperature gradients, accelerating heating of the central zones of the product, and decreasing the need for excessive thermal loads.

An important feature of perforated channels is their potential involvement in mass transfer processes during

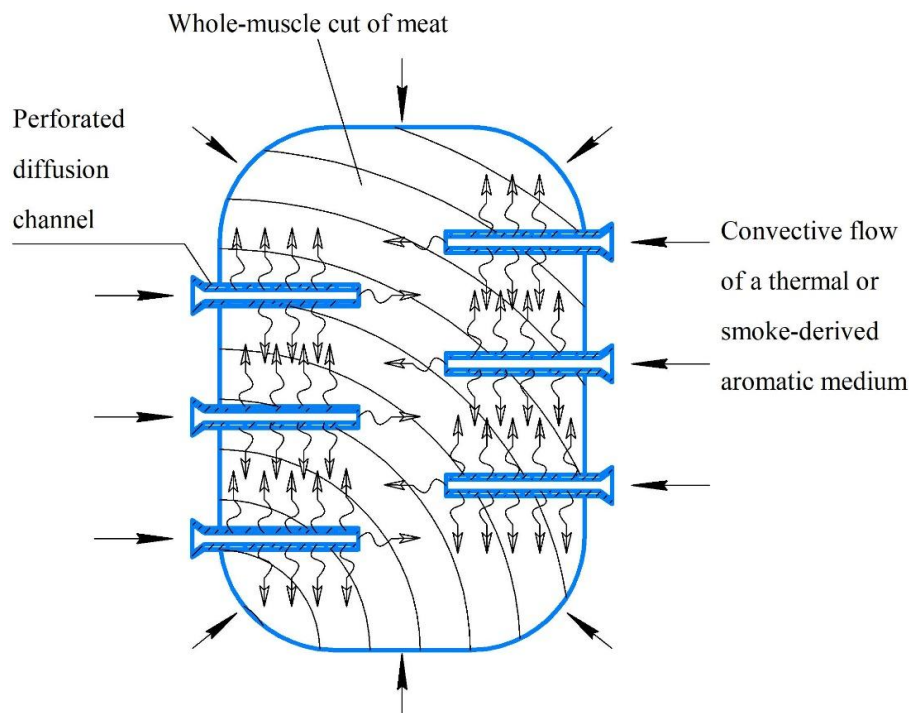


Figure 1 – Conceptual model of heat and mass transfer in a whole-muscle meat product with perforated diffusion channels

Source: developed by the authors

smoking. The presence of internal channels creates additional surfaces for the deposition of volatile smoke components and promotes bidirectional mass transfer of aromatic substances – from the external surface of the product and from internal zones. This potentially enhances the uniformity of flavor and aroma characteristics and reduces smoking duration.

From a technological standpoint, the use of perforated diffusion channels may be considered as a method of controlling the internal thermo-moisture state of the product. Shortening diffusion paths contributes to intensification of moisture removal and reduction of mass losses, while more uniform heating ensures stability of textural properties. In addition, improved efficiency of heat and mass exchange creates prerequisites for reducing energy and resource consumption, including the use of smoking materials and overall processing time.

Conceptually, the influence of perforated diffusion channels on the thermal processing of whole-muscle meat products can be represented by a model that includes:

- the formation of internal zones of convective heat and mass exchange;
- shortening of the radial diffusion path within muscle tissue;
- equalization of temperature and moisture fields;
- increased intensity of penetration of aromatic components;
- reduction of technological operation time.

Thus, the use of perforated diffusion channels may be considered a promising technological approach for

intensifying the thermal processing of whole-muscle meat products, combining physical mechanisms of diffusion path reduction and the formation of additional heat and mass exchange surfaces. The proposed concept establishes a theoretical basis for further experimental research and the development of efficient thermal processing technologies for delicatessen meat products.

Such a concept implies modification of heat and mass exchange mechanisms in whole-muscle meat products during thermal processing, resulting in a number of potential technological effects. Primarily, shortening diffusion paths and forming additional internal heat exchange surfaces create conditions for more uniform heating of the product. This may contribute to reducing temperature gradients between the surface and the center of the product, which in turn makes it possible to shorten processing time without the risk of insufficient heating of central zones.

Uniformity of the temperature field has a direct impact on the structural properties of muscle tissue. Excessive heating of peripheral layers under conventional thermal processing regimes leads to intensive protein denaturation, reduced water-holding capacity, and the formation of an overdried surface layer. In the case of perforated channel application, a more balanced thermal regime is expected, which may contribute to the preservation of juiciness and stability of textural characteristics of the product.

An important aspect is the influence of the channels on moisture transfer processes. Intensification of internal heat exchange is accompanied by accelerated evaporation and redistribution of moisture, which potentially reduces mass

losses and promotes the formation of a more homogeneous product structure. Shortening the duration of exposure to high temperatures may also positively affect the preservation of functional properties of proteins and lipids.

From the standpoint of resource efficiency, the use of perforated diffusion channels potentially contributes to reduced energy consumption and lower use of smoking materials. Shortening the duration of thermal processing decreases thermal energy expenditure, while intensification of smoke component penetration may reduce the need for prolonged smoking. This is particularly relevant under current requirements for energy efficiency and rational resource utilization in the food industry.

Practical implementation of the perforated diffusion channel concept may involve the use of removable or reusable structural elements inserted into the product prior to thermal processing and removed after completion of the process. Such an approach makes it possible to adapt channel geometry to product dimensions and ensures technological flexibility. In addition, the channels may be combined with other intensification methods, including preliminary marination or the application of pulsed heating regimes.

Thus, the expected technological effects of applying perforated diffusion channels include improved heating uniformity, enhanced organoleptic characteristics, reduced thermal processing time, and decreased resource consumption. The combination of these factors allows the proposed approach to be considered a promising direction in the development of thermal processing technologies for whole-muscle meat products.

Conclusions. The analysis of literature sources has shown that the main technological limitations in the

thermal processing of whole-muscle meat products are associated with the external mode of heat supply, the considerable length of diffusion paths, and the slow migration of moisture and aromatic components within the product matrix. These factors result in non-uniform heating, increased mass losses, and prolonged processing time.

The feasibility of intensifying internal heat and mass transfer as a key direction for improving the technological efficiency of thermal processing of whole-muscle meat products has been substantiated. This approach makes it possible to reduce temperature and moisture gradients and to stabilize product quality parameters.

A concept of using perforated diffusion channels as a technological method for forming additional internal heat and mass exchange surfaces has been proposed. This approach contributes to shortening diffusion paths, equalizing the temperature field, and intensifying the penetration of smoke components.

It has been demonstrated that the application of perforated diffusion channels potentially ensures a comprehensive improvement in the efficiency of thermal processing technology, including enhanced heating uniformity, improved flavor and aroma characteristics, reduced processing time, and decreased energy and resource consumption.

It has been established that the proposed approach has a conceptual character and creates scientific prerequisites for further experimental studies aimed at determining optimal channel parameters and developing efficient thermal processing technologies for whole-muscle meat products.

Patent applications have been filed for the developed methods of boiling and smoking meat products.

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ТЕХНОЛОГІЧНІ ПЕРЕДУМОВИ ВИКОРИСТАННЯ ПЕРФОРОВАНИХ ДИФУЗІЙНИХ КАНАЛІВ ПРИ ТЕРМООБРОБЦІ ЦІЛЬНОМ'ЯЗОВИХ М'ЯСНИХ ВИРОБІВ

У статті здійснено комплексний аналіз технологічних передумов використання перфорованих дифузійних каналів при термообробці цільном'язових м'ясних виробів. Обґрунтовано, що визначальними обмежувальними чинниками процесів варіння та копчення великих м'язових структур є зовнішній характер тепlopідведення, значна товщина виробів, велика довжина радіальних дифузійних шляхів у м'язовій тканині та низька швидкість внутрішньої міграції вологи й летких ароматичних сполук. Це зумовлює формування виражених температурних і вологісних градієнтів, нерівномірність прогріву центральних зон, підвищені втрати маси та необхідність надлишкового теплового навантаження для забезпечення мікробіологічної безпечності продукції. На основі узагальнення сучасних досліджень тепломасоперенесення у м'ясних системах доведено доцільність переходу від регулювання виключно зовнішніх параметрів процесу до керування внутрішньою транспортною архітектурою продукту. Запропоновано концептуальну модель інтенсифікації тепломасоперенесення шляхом формування у виробі перфорованих дифузійних каналів, які створюють додаткові внутрішні поверхні тепло- і масообміну та забезпечують поєднання радіальної теплопровідності тканини з конвективним переносом у каналах. Показано, що скорочення ефективної довжини дифузійних шляхів сприяє вирівнюванню температурного поля, прискоренню прогріву центральних зон, підвищенню рівномірності проникнення копильних компонентів і зменшенню тривалості термообробки без погіршення органолептичних показників. Обґрунтовано, що застосування перфорованих каналів потенційно забезпечує комплексне підвищення технологічної ефективності, зокрема стабілізацію текстурних характеристик, зниження втрат маси, оптимізацію енергетичних ресурсів та скорочення витрат копильних матеріалів. Запропонований підхід має концептуальний характер і формує наукову основу для подальших експериментальних досліджень та розробки інноваційних технологій термообробки цільноом'язових м'ясних виробів із керованими показниками якості.

Ключові слова: термообробка; цільноом'язові м'ясні вироби; тепломасоперенесення; перфоровані дифузійні канали; транспортна архітектура продукту.

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