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Organization of the rational form of air kinetics in chamber for the heat treatment of food products

Gıda ürünlerinin ısıl işlemi için haznede rasyonel hava kinetiği formunun organizasyonu

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Abstract

In this work, the effectiveness of the turbulent (three-dimensional trajectory) kinetics of air in the cargo volume of thermal chambers under recirculation conditions is substantiated analytically and practical tests of heat treatment of food products by convection. The object of research is the aerodynamic parameters of the air in the zone of processing of sausage products and the temperature in their geometric center. Analytical studies of heat exchange processes were carried out on the basis of using a system of differential equations with the involvement of criterion dependencies and similarity theory, and full-scale studies were carried out on a prototype of a heat chamber with an improved air distribution system. As an experimental material, dummies of boiled sausages-sausage casings stuffed with sawdust-were used to fill the working space of the thermal chamber. In the industrial scale experiments boiled sausages "Likarska" were used. To improve air distribution, the aerodynamic network was equipped with specially designed equipment located in the upper part of the chamber symmetrically to its longitudinal axis. Uniform distribution of air along the periphery of the chamber was provided by a double-discharge centrifugal fan an air ducts of equal static pressure, heating was provided by finned bimetallic heat exchangers. Converging pyramidal nozzles on heat exchangers divided the air entering the peripheral channels of the chamber into two flat streams with adjustable aerodynamic parameters for a certain influence of each on the nature of air movement near the product. Its rational three-dimensional movement, characterized by the Reynolds criterion equal to 8200, and the product heating unevenness of 2 degrees Celsius, was formed by nozzles with geometry: air compression angle -18 degrees, proportionality coefficient of compressed air separation on the main and side flows -14, and the degree of freedom of the main flow-9.09. Thus, the implementation of technical solutions for the organization of three-dimensional air kinetics in a heat chamber under recirculation conditions ensured a sufficiently high uniformity of heat supply to processed products, their quality and safety while reducing the total cost of their production. In addition, the accuracy of engineering calculations when designing air distribution systems increased.

Keywords: Three-Dimensional trajectory, Nozzles, Air flows.

Öz

Bu çalışmada, termal odaların kargo hacmindeki havanın türbülanslı (üç boyutlu yörünge) kinetiğinin devridaim koşulları altında etkinliği, gıda ürünlerinin konveksiyon yoluyla ısıl işleminin analitik ve pratik testleriyle kanıtlanmıştır. Araştırmanın amacı, sosis ürünlerinin işlendiği bölgedeki havanın aerodinamik parametreleri ve geometrik merkezlerindeki sıcaklıktır. Isı değişim süreçlerinin analitik çalışmaları, kriter bağımlılıkları ve benzerlik teorisini içeren bir diferansiyel denklem sistemi kullanılarak gerçekleştirildi ve geliştirilmiş hava dağıtım sistemine sahip bir ısı odasının prototipi üzerinde tam ölçekli çalışmalar yapıldı. Deneysel bir malzeme olarak, termal odanın çalışma alanını doldurmak için haşlanmış sosislerden (talaşla doldurulmuş sosis kılıfları) maketler kullanıldı. Endüstriyel ölçekte yapılan deneylerde haşlanmış "Likarska" sosisleri kullanıldı. Hava dağıtımını iyileştirmek için aerodinamik ağ, odanın üst kısmında uzunlamasına eksenine simetrik olarak yerleştirilmiş özel olarak tasarlanmış ekipmanlarla donatıldı. Havanın odanın çevresi boyunca düzgün dağılımı, çift deşarjlı bir santrifüj fan ve eşit statik basınca sahip süt kanalları ile sağlandı, ısıtma kanatlı bimetalik ısı eşanjörleri ile sağlandı. Isı eşanjörleri üzerindeki yakınsak piramidal nozullar, odanın çevresel kanallarına giren havayı, her birinin ürünün yakınındaki hava hareketinin doğası üzerinde belirli bir etkisi için ayarlanabilir aerodinamik parametrelere sahip iki düz akışa böldü. 8200'e eşit Reynolds kriteri ve 2 santigrat derecelik ürün ısıtma eşitsizliği ile karakterize edilen rasyonel üç boyutlu hareketi, geometriye sahip nozullar tarafından oluşturulmuştur: hava sıkıştırma açısı -18° basınçlı hava ayırmanın orantısal katsayısı. ana ve yan akışlarda -14 ve ana akışın serbestlik derecesi -9.09. Bu nedenle, termal odadaki havanın üç boyutlu kinetiğinin devridaim koşulları altında düzenlenmesi için teknik çözümlerin uygulanması, işlenmiş ürünlere ısı tedarikinde yeterince yüksek bir homojenlik, bunların kalitesi ve güvenliğini sağlarken aynı zamanda genel maliyetleri azaltır. İşlem ayrıca termal ekipmanlarda hava dağıtım sistemleri tasarlanırken mühendislik hesaplamalarının doğruluğu arttırılır.

Anahtar kelimeler: Üç boyutlu yörünge, Nozüller, Hava akışları.

1 Introduction

The analysis of scientific sources [1]-[3] proves that the measure of the efficiency of heat exchange processes in thermal processing chambers for meat and fish products is the reduction of energy costs and the stability of maintaining the optimal operational characteristics of the equipment involved while achieving the normative level of quality and safety

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indicators of finished products. At the same time, one of the most important requirements for the heat treatment process is the uniformity of heat supply to each unit of product in the working area of the chamber. This postulate is the basis of numerous analytical methods of research and scientific theories of the thermal processing of meat products [4]-[6]. Meanwhile, in practice, the organization of the transfer of absolutely the same amount of thermal energy from the flows of the working medium to each individual unit of production is an almost unattainable task. The results of studies [7],[8] indicate that the minimum discrepancy between temperature fields over the volume of the most technically advanced thermal chambers is 3 °C. The effectiveness of supply of the working medium to the working zone of a thermal unit filled with the product being processed are considered in [9]. The most common ways to avoid uneven heating of processed products in a thermal field include an automated control system for equipment operation, which provides for the organization of an alternating (cyclic) change in the speed and direction of movement of the working medium around the product [10]-[13]. Worthy of attention are the results of scientific works [8], [14],[15], the authors of which, simultaneously with conducting complex studies of the processes of convective heat transfer in a prototype of a thermal chamber, situationally finalized the design of its decisive constituent elements (seeFigure 1).

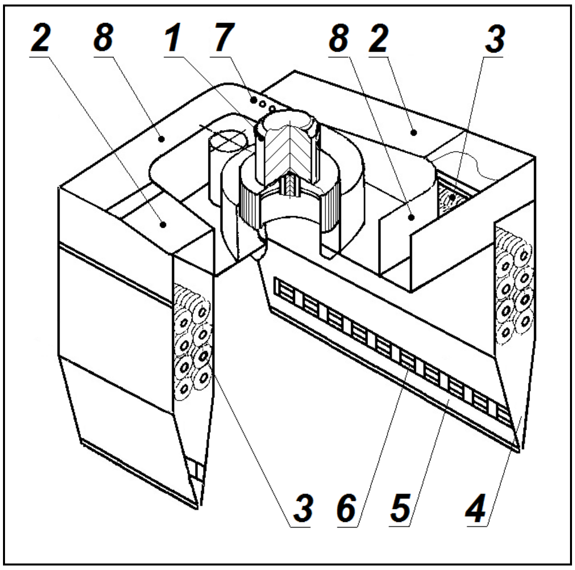

Figure 1. Scheme of the functional module of the experimental heat chamber. 1: Double-discharge centrifugal fan. 2: Air ducts of equal static pressure. 3: Bimetallic heat exchangers. 4: Pyramidal nozzles. 5: Inner side wall of the nozzle. 6: Damper for controlling the amount of lateral air flow. flowing out of the nozzle. 7: Holes with plugs for measuring the head (pressure) of the fan. 8: Angular rotary air ducts.

An important result of this work was the solution of the issue of the formation of the air flows uniformly dispersed along the sides at the entrance to the chamber [15]. The basis for this was the formation of compact flows, identical in physical characteristics, directed from the center to the side walls of the chamber. This was achieved using the developed experimental centrifugal fan with a spiral housing, which had two outlets and an impeller rotated by an electric motor with a vertical drive shaft 1 (Figure 1). The outlines of the spiral housing were developed according to the rule of the design square, provided that the opening and length of the outlet were equal to the half-opening and half-length of the outlet of the conventional spiral housing, and the width of the housing corresponded to the width of the conventional housing. At the second stage of work, compact centrifugal flows were evenly dispersed along the length of the chambers. For this, the following elements of the aerodynamic system were created: air ducts of equal static pressure 2 and finned bimetallic heat exchangers 3, which functionally heated the air and, due to the design features, evenly distributed it over the free section area [14]. The most important issue of determining the form of air kinetics and the method of its organization directly in the working area of the heat chamber, where the proper quality of products is ensured at the stage of bringing them to a state of culinary readiness, remained unresolved in this work.

2 Experimental design and method

To solve this problem, analytical and experimental studies of heat transfer processes by forced convection in the chambers for thermal processing of sausages were carried out with simultaneous situational refinement of the design of air distribution devices.

When conducting analytical studies of the process of heat transfer by forced convection, a system of differential equations was used with the involvement of criterion dependences and the theory of similarity [16],[17].

The kinetics of air in the working zone of the heat chamber was determined by the value of the Reynolds criterion.

2.1 Experimental chamber

Experimental studies were carried out on the basis of the use of an experimental thermal chamber, created during the works [8],[15] after some refinement and unification of its functional module, shown in Figure 1.

According to the principle of operation of the modified functional module, the same type of axisymmetric downward air flows, uniformly dispersed over the area of the living (free) cross-section of the heat exchangers 3, are formed in pyramidal confuser-type nozzles 4 into compressed flat flows flowing out with certain aerodynamic parameters. The development of the movement of these flows occurs amid recirculation in the space limited by the walls and bottom of the chamber. That is why these downward flows, axisymmetric to the center of the chamber, are the source of one reverse flow that directly contacts the product in the working area. To study the influence of the aerodynamic characteristics of downward flows on the inverse kinetics, the sides 5 of the pyramidal nozzles 4 were designed to be movable. They were mounted on the bottom base of the casing of each heat exchanger 3 by means of swivel joints. This made it possible to change the nozzle geometry: the value of the equivalent diameter and the dimensions of the air compression angle. Structural changes in the nozzle had a certain effect on the aerodynamic parameters of downdrafts - speed, range, etc. A schematic representation of changes in the geometry of the pyramidal nozzle in the process of studying the kinetics of the movement of air flows in the chamber is shown in Figure 2.

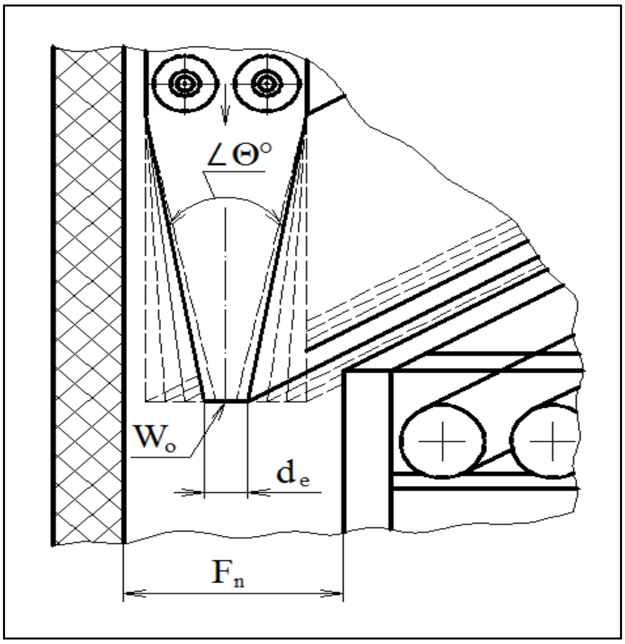

Figure 2. Scheme of changes in the geometry of the pyramidal nozzle in the process of research,

Where:

- $\angle\theta$ – air compression angle in the pyramidal nozzle, deg,
- W_o – average axial velocity of air flow at the nozzle outlet, m/s,
- d_e - the equivalent diameter of the mouth of the pyramidal nozzle, m,
- F_n- area of the peripheral space of the chamber, m^2.

2.2 Mathematical model

To describe the results of studies of the kinetics of the movement of downward air flows in this chamber, a simplified mathematical model was applied with determining factors directly related to the geometric dimensions of the nozzle and peripheral space:

1) The degree of freedom of downward flows – the dimensionless ratio of the area of the free section of the peripheral space (stable parameter) and the equivalent diameter of the throat of the pyramidal nozzle (replaceable parameter):

$$E = \frac{\sqrt{F_n}}{d_e} = \frac{\sqrt{B \cdot L}}{2b_0 \cdot l / b_0 + l} \tag{1}$$

Where:

- F_n, m^2; B, m; L, m – respectively, the area of the living section of the peripheral space of the chamber, its width and length,
- d_e, m; b_0, m; l, m – respectively, the equivalent diameter of the mouth of the pyramidal nozzle, its width and length.

2) Relative distance - the distance from the beginning of the leakage of the downward air flow from the nozzle to the measurement point, expressed in dimensionless form and calculated by the formula:

$$\bar{x} = \alpha \cdot x / \sqrt{F_n} \tag{2}$$

Where:

- α is coefficient of the turbulent structure of the downward flow – an empirical constant characterizing the degree of flow turbulence. The coefficient takes into account the flow conditions in the initial section of the packing, which depend on the opening angle of the downward flow in the process of its development,
- x is the distance from the flow pole (a conditional point at which the isotochs of the main section of the flow converge, characterized by the similarity of dimensionless velocity fields) to the section analyzed at a distance h_0 from the flow pole to the place of leakage (the nozzle mouth), m:

$$h_0 = 0.145 \cdot b_0 / \alpha \tag{3}$$

Where:

- h_0 is the distance from the flow pole to the mouth of the pyramidal packing, m,
- b_0 is the width of the neck of the pyramidal nozzle, m.

2.3 Measurement routine and devices

Tracking the trajectory of the movement of air flows in the volume of the thermal chamber was carried out by a visual method, involving the use of the following devices and techniques: the thinnest silk threads attached to the inner walls of pyramidal nozzles 5; jets of smoke and particles of fine filter paper, which were fed into the suction manifolds of recirculation fans 1 (Figure 1). Observation of the movement of air flows was carried out against the background of illumination, equipped on the opposite side of the chamber.

Determining the speed of movement of air flows was carried out using: hand-held induction anemometer ARI-49, measurement limit 1.0÷30.0 m/s, error ± 0.5 m/s; cup anemometer MS-13, measurement limit 1.0÷20.0 m/s, error ± 0.1 m/s and hot-wire anemometer - TA-LIOT, measurement limit 0.0÷5.0 m/s, error ± 0 .1 m/s.

To simultaneously measure the temperature of air and food products, 12 copper-constantan thermocouples were made from ∅ 0.2 mm wire. The thermocouple length was 10 meters. Each thermocouple is protected along its entire length by a sheath made of PVC tube ∅ 2 mm. The thermocouple readings were taken to a 12-point digital device A565-002-01 with a measurement range from minus 50 °C to 800 °C, accuracy class 0.15/0.05. The assembled thermometric setup was calibrated in the temperature range from 0 to 150 °C.

The pressure was measured using a combined pneumometric nozzle with a cylindrical head (correction factor for the bevel of the nozzle when calibrating h=0.95±1.0) and a differential alcohol micromanometer MMN-240(5)-1.0, accuracy class 1.0.

2.4 Materials

To load the thermal chamber during model experiments the dummies of boiled sausages were used. The said dummies had been made by stuffing sausage casing with sawdust. They had the shape of an oblong cylinder with a diameter of d_k = 0.060 m or d_k = 0.090 m.

For the experiments amid full-scale (industrial) conditions the thermal chamber was loaded with real sausages with a diameter in the lumbar section d_k = 0.095 m. The boiled sausages “Likarska” were used, their formulation and manufacturing routine confirming to the National Standard of Ukraine DSTU 4436:2005.

3 Results and discussion

The known theories of air distribution by compressed jets in a limited space according to a dead-end pattern [18]-[21] do not concern the relationship between jets and the aerodynamic characteristics of the reverse flow formed in the working area under recirculation conditions. Establishing the influence of the aerodynamic parameters of the jets on the regime and speed of the air flow moving side by side but in the opposite direction is an important and at the same time complex task. Specifically, the efficiency of heat exchange actions in thermal chambers depends on its solution. The improvement of these processes is carried out mainly in other ways. The attention of a number of scholars is directed to the development of a mechanical device for rotating product racks in the working area of the chambers [10], the works of other researchers [11],[12] are devoted to the organization of an aerodynamic system with a pulsating supply of the working mixture into sausages; processing of cooked sausages in a liquid heat carrier using vibration [13]. For the thermal chambers of today, the use of automated control systems for the operation of recirculation fans in a cyclic mode is most common. The industrial practice shows the discrepancy between the temperature fields in terms of the volume of the majority of thermal chambers and almost every model has its own significant drawbacks. At the same time, it should be noted that significant positive results in the improvement of the designs of air distribution devices are described in .[3]. Taking into account these developments and own scientific and practical experience in this matter, the authors of this work put forward a hypothesis that the uniformity of temperature fields in the working zone of thermal chambers is a consequence of the developed three-dimensional unsteady structure of the reverse flow kinetics. To verify the validity of this assumption, analytical and experimental studies of heat transfer processes by forced convection in the chambers for thermal processing of sausages were carried out with simultaneous situational refinement of the design of air distribution devices.

Visual studies of the trajectory of air flows in an empty experimental chamber with the heat exchangers turned off from operation made it possible to obtain a general picture of the development of the movement of both descending axisymmetric continuous flat air flows occurring in the peripheral space (channel) limited by the walls and bottom of this equipment according to a dead-end scheme. From the left and right sides of the chamber, air was supplied to its volume from vertical pyramidal nozzles. From the outside, the walls and bottom of the chamber interfered with the free development of flows, and from the inside, the reverse flow, which moved in the working area parallel to the descending ones. In the process of development, the powerful outer parts of each downward flow, compressed by the walls, deviated towards the inner part, less powerful, blurred due to contact with the reverse flow. As a consequence, the range of the downstream was reduced. At the same time, when approaching the bottom of the chamber (dead end), each of the opposite descending air flows was forced to turn 90° to the center of the chamber, and, after contact with each other, the flows mixed, turned 90° again, and in the form of a single reverse flow moved along working area in the direction of the suction manifold of the recirculation fan.

At the same time, it was observed that with an increase in the degree of freedom of descending flows, their range and ability to eject a reverse flow increased. As a result, air turbulence in the working area increased. Structurally, the degree of freedom of descending jets in the peripheral space of the chamber is directly proportional to the size of the air compression angle in the nozzle and is controlled by changing the positions of its movable side sides. Therefore, to confirm the effectiveness of the kinetics of air movement, we simultaneously investigated the dimensions of the angle of air compression in the nozzle, the degrees of freedom of descending jets, and the energy costs to overcome the resistance of the elements of the aerodynamic network involved in this. The results of the dependence of the degree of freedom of descending flows on the value of the angle of air compression in the nozzle are shown in Figure 3.

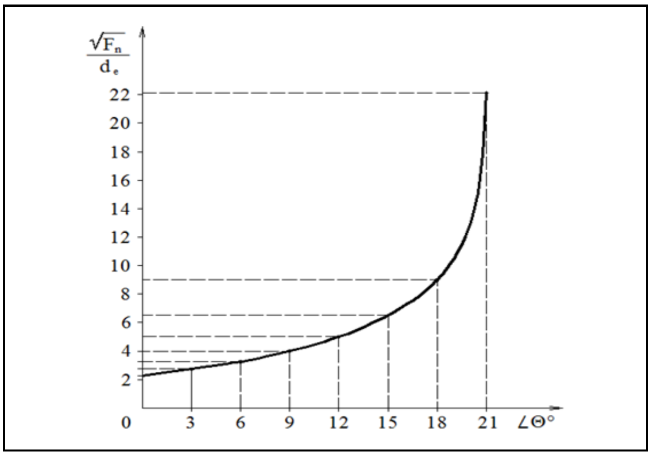

Figure 3. Dependence of the degree of freedom of downward flows on the angle of air compression in the nozzle.

By the nature of the growth of the curve (Figure 3), it was found that the degree of freedom of descending flows reaches its max flow $E = \sqrt{F_n} / d_e = 22$ at the angle of air compression in the nozzle $\angle\theta = 21^0$. At the same time, the results of calculations of the corresponding changes in energy consumption to overcome the resistance of the nozzle proved the feasibility of reducing the angle of air compression to a value of $\angle\ \theta = 18^0$ with the corresponding value of the degree of freedom of downward flow $\sqrt{F_n} / d_e = 9.09$ and the value of the aerodynamic drag of the nozzle ΔP = 120.0 Pa in terms of the drag coefficient ζ=0.07 [22]. An increase in the air compression angle led to a sharp increase in energy costs by almost 200% for each degree.

The conclusion about the rationality of the obtained parameters was confirmed by the results of studies of the dependence of changes in the magnitude of the relative axial velocity of downward flows, measured at a certain distance from the beginning of their leakage from the nozzle to the measurement point (relative distance), on the degree of freedom of these flows in the peripheral channels of the chamber (see Figure 4).

An analysis of the nature of the curves falling in Figure 4 proved that the highest value of the average axial velocity at the bottom of an empty chamber, W_x =4 m/s, is for flows with a degree of freedom $E = \sqrt{F_n}$ / de = 9.09

Thus, to increase the efficiency of air movement in the volume of an unloaded chamber, the rational geometry of the nozzle was experimentally worked out with the geometry of the peripheral space unchanged, which corresponds to the size of the air compression angle in the nozzle – ∠ θ = 18° and the degree of freedom of downward flows $E = \sqrt{F_n} / d_e = 9.09$.

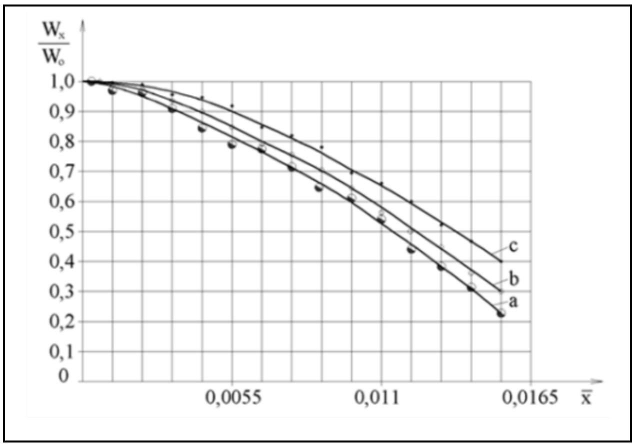

Figure 4. Change in the relative axial velocity of downstream flows when they move along peripheral channels of the chamber at different degrees of freedom, where: $a)\sqrt{F_n} / d_e = 9.09$; $b)\sqrt{F_n} / d_e = 5.3$; $c)\sqrt{F_n} / d_e = 4.2$

Under these conditions, the average axial velocity of air flows at the outlet of the nozzle is W_o = 17.6 m/s, and the coefficient of the turbulent structure of the downward flow is α=0.09.

The study of the kinetics of air flows in the loaded chamber was carried out according to the rational conditions given above, worked out on an empty chamber. For the experiment, the chamber was loaded with multi-tiered carts with dummies of boiled sausages placed in cells, most often having the shape of an oblong cylinder with a diameter of d_k = 0.060 m or d_k = 0.090 m. As a result, according to the size of the diameter, the free area for the passage of the reverse air flow decreased in inverse proportion and, in proportion, in the same place, the mass velocity and aerodynamic resistance to its movement increased. Under these conditions, each of the air flows descending from the nozzles developed in the peripheral space, which had the form of a channel with one air-permeable wall between it and the return flow. The results of experimental and analytical studies of the form of the kinetics of air movement in the working area of the loaded chamber are summarized in Table 1.

Analysis of the results of analytical studies (Table 1) proved that the value of the Reynolds criterion in the working area is higher than Re_{cr} =2300, which indicates a turbulent form of air movement in the living section, the intensity of which is directly proportional to the diameter of the dummy sausages.

The next stage of research on the topic was carried out with imitation of full-scale (industrial) conditions. The efficiency of heat exchange processes between heated air and real sausages with a diameter in the lumbar section d_k=0.095 m was determined in a heat chamber with heat exchangers turned on.

Before that, on the inner side 5 of each pyramidal nozzle at the level of the pole of descending air flows, a linear row of holes with a gate 6 (Figure 1) was formed to select, if necessary, a certain amount of air from the main flow.

The coefficient of proportionality for the division of flows in the nozzle (K_p) into the main flow and side flows was introduced to describe results of the research, the said coefficient mathematically expressed by the following dependence:

$$K_p = \frac{V - V_0'}{V - V_0} \tag{4}$$

Where:

- V - the total cost of the working medium through the nozzle, m³,
- V_0 - the flow rate of the working medium through the throat of the nozzle, m³,
- V'_0 – flow rate of the working medium through the side openings of the nozzle, m³.

A simplified and generalized diagram of the trajectory and motion parameters of descending and return air flows in a chamber loaded with sausages is shown in Figure 5.

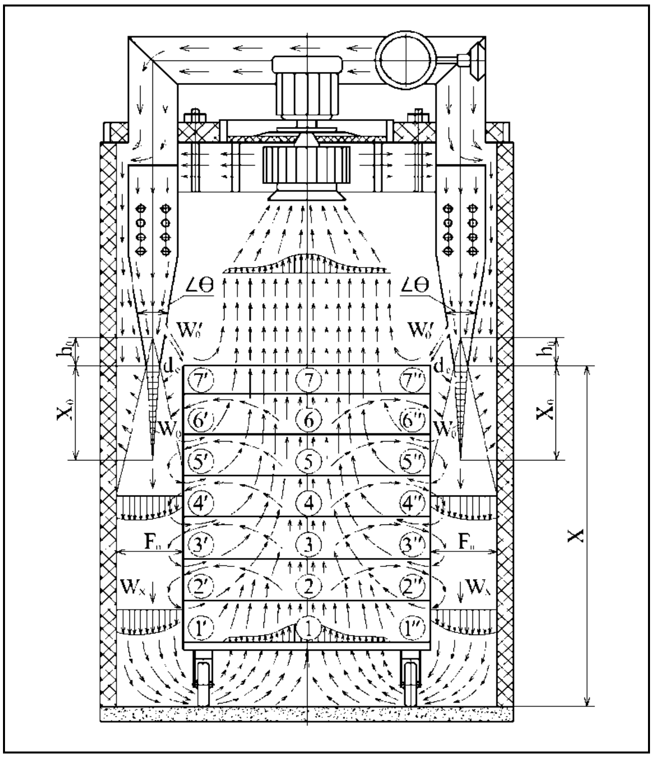

Figure 5. Scheme of the trajectory of air flows in a loaded chamber.

- Variable values (depending on K_p),
- h_o = 0.15 m is the distance from the mouth of the nozzle to the pole of downstream flows,
- X_o = 0.5 m – linear size of the initial section of the movement of downstream flows,
- X = 1.8 m - the linear size of the off-initial section of the movement of downstream flows,
- W_o = 17.6 m/s – axial speed of downstream movement in the initial section,
- W_x = 7.0 m/s – speed of downward flows at the bottom of the chamber,
- W_0' = 7.0 m/s initial velocity of side jets.

Table 1. The results of analytical studies of the kinetics of air in the working area of a heat chamber loaded with dummy sausages

Parameters	Designation / Formula	Unit	Value	
Motor power of recirculation fan *	N_v	kW	2.2	
Performance of recirculation fan*	V_v	m^3/h	6050.0	
Sausage dummy diameter	d_k	m	0.060	0.095
Kinematic viscosity of air	$\nu \cdot 10^6$	m^2/s	22.3	
Air velocity in living section of the camera with dummies	$w_\gamma = V_F / 3600 \cdot Fp. \cdot \gamma$	m/s	1.8	1.96
Reynolds criterion	$Re = w_\gamma \cdot d_k / \nu$	-	4800	8200
Turbulence coefficient of jet structures [23]	$\alpha = tg\,\theta / 3,4$	-	0.066	0.09
Aerodynamic resistance of a rack with products by the value of the drag coefficient ζ=4.5 [22]	ΔP**	Pa	60.0	70.0

*: According to [8],[14]. **: Determined experimentally.

The efficiency of the heat exchange process was determined by comparative results of studies of the temperature of the center of sausage sticks placed on the rack in the defining places (Figure 5), under identical process conditions with a certain change in the proportionality coefficient of the flow division, K_p. The research results are presented in Table 2.

According to the scheme, side jets of hot air selected from the main flow moved across the exhausted reverse flow, preventing its movement to the suction manifold of the recirculation fan. The mixing of the streams contributed to the increase in temperature at the top of the product rack. And the appearance of resistance in the path of the reverse flow, reduced its power and was more intensively ejected by downward flows. As a result, these techniques increased the turbulence of air flows in the working area and contributed to the alignment of temperature fields along the tiers of the rack with products.

When determining the efficiency of the heat exchange process in a loaded thermal chamber, certain conditions and physical parameters determined experimentally and characteristic of a packing with closed side holes are taken as a basis:

- Unchanged parameters,
- Overall dimensions of the chamber, m: B·L·X= 1.8·1.6·3.2,
- Overall dimensions of the rack with products, m: $B_R \cdot l_R \cdot X_R$ = 1.1·1.1·1.8;
- Diameter of sausages, m: d_k = 0.095,
- Air temperature, °C: T_v = 100,
- Duration of the process, min.: τ = 77.4,
- Angle of air compression in the pyramidal nozzle ∠θ = 18°,
- Downstream turbulent structure coefficient α=0.09,
- Degree of freedom of downward flows $E = \sqrt{F_n} / d_e =$ 9,09.

A comparative analysis of the data in Table 2 proves that the best results of the tests were obtained with the value of the coefficient of proportionality of the division of flows in the nozzle K_p = 14.0: the maximum mismatch in the temperature of the centers of sausages located in the middle (axial) part along the height of the rack reaches 2 °C, air temperature – 1.5 °C.

Thus, the implementation of technical solutions for the organization of the three-dimensional form of the kinetics of the working medium in the working area of the chamber made it possible to ensure a sufficiently high uniformity of heat supply to the processed products, its quality and safety while reducing the total cost of the process.

Quite important achievements in this work include the implementation of original design solutions for improving the aerodynamic system of heat chambers. Positive in comparison with other models of thermal chambers are:

- Reducing the duration of the technological process by increasing the efficiency of heat transfer processes,
- Significant simplification of the equipment operation control system in the chamber,
- Stability of maintaining the performance characteristics of recirculation fan electric motors at the proper level due to the exclusion of changes in cyclically repeating loads from the process of their operation. The negative impact of this on electric motors is associated with starting torques, accompanied by a significant excess of the rated current, which, as a result, significantly reduces their service life,
- Exclusion of unnecessary costs of manual labor of operators for moving both trolleys with products and products directly on trolleys in the cargo volume of the chamber, which is usually observed in case of uneven heating,
- Reduction of the duration of the technological process.

4 Conclusion

These studies reasoned the rationality of organizing a turbulent (three-dimensional trajectory) of air kinetics in the working area of a heat chamber under recirculation conditions to ensure uniform heat treatment of sausage products method convection.

Research performance of the research is confirmed by the operational characteristics of the modernized functional scheme and equipment of the aerodynamic network with upper air distribution through peripheral channels symmetrically to the longitudinal axis of the heat chamber.

The uniformity of heat treatment of sausage products by convection was ensured by a double-sided centrifugal fan (instead of two single-sided), which supplied the exhaust air sucked from the chamber through air ducts of equal static pressure to two bimetallic heat exchangers with pyramidal nozzles, the design of which made it possible to regulate the turbulence of heated air in the product processing zone.

It has been established that a rational three-dimensional movement, characterized by the Reynolds criterion equal to Re=8200, and the product heating unevenness of 2 °C, is formed by nozzles with the following geometry: air compression angle -∠θ=18°, proportionality coefficient of compressed air separation for the main and side flows - Kp = 14, and the degree of freedom of the main flow -E=9.09.

Table 2. The effect of the temperature of the center of sausages on the coefficient of proportionality of the flow division in the nozzle*.

The value of the proportionality factor of the flow division, K_p,	Objects of research:		Temperature parameters of objects of research, °C						
	center of sausages, t_C	air temperature, T_v	Designation according to Figure 5: (number of tier with products/distance from the bottom of the chamber, m)						
			1/04	2/0.6	3/0.8	4/1.0	5/1.2	6/1.4	7/1.6
K_p =0	t_C		40.0	39.0	38.0	38.5	40.0	42.0	44.0
		T_v	90.8	90.5	90.1	89.7	89.5	89.0	88.8
K_p =6.6	t_C		42.0	41.0	40,0	38,0	40,0	43,6	44,0
		T_v	90.0	87.5	83.6	83,5	84,0	87,0	89,0
K_p =14.0	t_C		44.0	42.0	42.0	42.0	42.0	42.0	44.0
		T_v	90.0	88.5	88.5	88.5	88.5	88.5	90.0
K_p =33.0	t_C		40.0	39.0	38.0	38.5	42.0	44.0	44.0
		T_v	90.8	90.5	90.3	90.0	89.8	89.5	89.0

*: The temperatures of the center of sausage sticks, located on the sides of the ruck (marks t'_C and t''_C), differ from the corresponding temperatures of the center of sausages with the mark tц (axial line of the rack) by no more than 0.5 °C.

The results of the conducted studies indicate that the implementation of proven technical solutions in the matter of organizing a rational form of air kinetics in the working area of the heat chamber meets not only the requirements of energy efficiency, but also the norms of current standards for the quality and safety of finished products, which, taken together, allow to recommend these results for use both in the development of thermal equipment and in the educational process of technical educational institutions of the corresponding profile.

5 Author contribution statements

In this study, Nina USATENKO contributed to the formation of an idea, literature review, experiments, assessment and mathematical processing of results, writing and editing article, Sergii VERBYTSKYI contributed to the formation of an idea, experiments, evaluation of data, Oleg SHCHESIUK contributed to the literature review, evaluation of the data, article writing and editing, Tetiana KOZIY contributed to the formation of an idea, literature review and experiments.

6 Ethics committee approval and conflict of interest statement

"There is no need to obtain ethics committee approval for the article prepared".

"There is no conflict of interest with any person/institution in the article prepared".

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