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CUTTING FOOD PRODUCTS WITH A WATER-POLYMER JET: SCIENTIFIC AND PRACTICAL ASPECTS

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Abstract

A scientifically grounded hydrodynamic calculation method for determining the optimal parameters of food product cutting using a water-polymer jet has been developed. This method is based on an established criterion that incorporates the relaxation time of the polymer solution and the longitudinal velocity gradient, which occurs during the flow of the polymer solution through the nozzle of the hydro-cutting head. An analytical expression for the relaxation time of the polymer solution has been derived, linking the experimentally observed relaxation time with the extrapolated relaxation time at zero concentration. The validity of this relationship, which connects the relaxation time of the polymer solution with its concentration, temperature, and characteristic viscosity, is confirmed by experimental data on the concentration dependence of the relaxation time for two fractions of polyethylene oxide in water.The developed method for calculating the optimal parameters of food cutting using a water-polymer jet enabled a significant reduction in the working pressure of the hydro-cutting machine – by 4 to 5 times – through the implementation of a high-efficiency cutting process. Under equal conditions, the cutting depth of frozen pork at –25 °C was increased by 2 to 2.3 times compared to water jet cutting, whereas standard equipment achieved only a 1.85 – fold increase. The experimental prototype of the hydro-cutting machine for food products using a water-polymer jet was 10 times less expensive than industrial-grade equipment. The developed method for calculating the optimal parameters for hydrojet water-polymer cutting has confirmed the practical feasibility and economic efficiency of using a water-polymer jet for cutting food products, particularly for deeply frozen products, by implementing a high-efficiency hydro-cutting process.

Keywords: relaxation time; longitudinal velocity gradient; jet; pressure; polyethylene oxide; food products.

РІЗАННЯ ХАРЧОВИХ ПРОДУКТІВ ВОДОПОЛІМЕРНИМ СТРУМЕНЕМ: НАУКОВО-ПРАКТИЧНІ АСПЕКТИ

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Анотація

Науково обґрунтований гідродинамічний розрахунок оптимальних параметрів процесу різання харчових продуктів водополімерним струменем з використанням встановленого критерію, до якого входять час релаксації розчину полімеру та поздовжній градієнт швидкості, який реалізується під час протікання полімерного розчину через сопло гідрорізальної голівки. Для часу релаксації полімерного розчину отриманий аналітичний вираз, що зв'язує експериментально спостерігаємий час релаксації полімерного розчину з часом релаксації за екстраполяції до нульової концентрації. Справедливість знайденого співвідношення, що зв'язує час релаксації полімерного розчину з концентрацією, температурою та характеристичною в'язкістю, підтверджують результати досліджень концентраційної залежності часу релаксації двох фракцій поліетиленоксиду в воді. Розроблений метод розрахунку оптимальних параметрів гідрорізання харчових продуктів водополімерним струменем дозволив на експериментальному зразку гідрорізальної машини знизити раціональний робочий тиск у 4–5 р, і за рівних умов в замороженому до –25 °С м'ясі свинини перевищити глибину різу водяним струменем в 2–2.3 р, а з використанням стандартного обладнання – тільки в 1.85. Дослідний зразок машини для гідрорізання харчових продуктів водополімерним струменем коштує в 10 р менше, ніж промислове обладнання. Розроблений метод дозволив за рахунок реалізації високоефективного процесу гідрорізання підтвердити практичну доцільність та економічну ефективність різання водополімерним струменем харчових продуктів, особливо продуктів глибокого заморожування.

Ключові слова: час релаксації; поздовжній градієнт швидкості; струмінь; тиск; поліетеленоксид; харчові продукти.

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Introduction

Modern food industry technologies aim at continuously improving production processes, specifically reducing energy consumption, enhancing product processing quality, and lowering the cost of final products [1; 2]. The 20-th century introduced numerous groundbreaking discoveries to humanity, including water jet cutting technology, which was considered revolutionary three decades ago. Today, this technique is widely applied in various industries. When a thin water jet increases its velocity and energy to erode a material, it can effectively cut through any material [3; 4]. Therefore, water jet cutting has the potential to serve as an alternative method for processing food products, particularly at low temperatures. The high technological advantages of the hydro-cutting method compared to traditional cutting techniques are the main reason for its extensive use. However, the lack of comprehensive scientific studies on the process of food water jet cutting and the development of corresponding equipment limits its adoption in the food industry [2; 5]. This method holds significant potential for scientific innovation.

One of the key advantages of water jet technology is the computerized control of the cutting process, which enables 3D food processing. By utilizing servo mechanisms, the water jet cutting head can process food products from multiple angles, making cuts of any complexity, at any location, and allowing for programmed adjustments in the parameters of hydro-cutting. This approach streamlines the traditional robotic conveyor line for primary processing into one or more processing points, where the water jet cutting head can perform multiple operations simultaneously [2; 6].

When hydro-cutting food products, a high-speed thin jet of liquid serves as the cutting tool. The properties of the working fluid play a crucial role in determining the water jet's ability to achieve the necessary hydrodynamic characteristics that ensure optimal productivity and the highest cutting surface quality while minimizing energy consumption for jet formation [7; 8]. Reducing energy costs should primarily focus on lowering the working pressure of the fluid at the nozzle inlet to its minimum possible value while still meeting the technological requirements for cutting the product. Thus, selecting the type and composition of the working fluid is a critical factor in developing the technological process for water jet cutting of deep-frozen food products. The relevance of this work is also highlighted by the fact that lowering the temperature of meat, fish, and other food products to −11 °C makes it impossible to use hydro-cutting at pressures below 250–300 MPa, while using higher pressures is economically impractical [5; 9].

One of the innovative directions for improving hydro-cutting technology is the use of a water-polymer jet as the working fluid for cutting food products [10]. Due to its unique properties, the water-polymer jet enables significant efficiency in cutting food products, especially frozen products, which present a challenge for traditional processing methods. Hydro-cutting is a process in which a powerful water jet is used to cut materials. However, the addition of polymers to the water opens new opportunities to enhance the efficiency of this process. A water-polymer jet combines high velocity with the specific properties of polymer solutions, which significantly improve the cutting characteristics of the jet. The uniqueness of this technology lies in its ability to reduce working pressure and energy consumption during the cutting of food products while maintaining or even improving the quality of the results. This makes the cutting process more economically viable and energy-efficient.

Through comprehensive studies of the hydrodynamic processes occurring during the passage of a water-polymer solution through the nozzle of the jet-forming head, the nature of the high efficiency of hydrojet water-polymer cutting of food products was revealed. This efficiency is attributed to the deformation effects that arise during the flow of the solution through the nozzle of the hydrojet's jet-forming head [11; 12]. This comprehensive research allowed the formulation of a new structural concept, whose "common denominator" is the strong deformation impact of the hydrodynamic field on the polymer macromolecules. This deformation immediately triggers rubber-like properties, while the resulting associates – regardless of their nature – exhibit a kind of rubber-like high elasticity.The scientifically grounded approach to developing the technology for hydrojet water-polymer cutting of food products lies in utilizing the rubber-like properties of the polymer solution, which can arise under certain flow conditions through the nozzle of the jet-forming head.

A high-speed water-polymer jet represents a "reinforced" liquid jet with highly extended macromolecular chains and supramolecular structures formed under the influence of extensional flow [13; 14]. This leads to an increase in the compactness of the jet [10; 15–18]. The enhanced compactness of the water-polymer jet contributes to an increase in its cutting ability.

Furthermore, hydro-cutting technologies offer several advantages over traditional mechanical methods of cutting food products. These include reduced thermal impact on the product, preservation of its structural and taste characteristics, and the absence of tools subject to wear and tear [19]. Notably, the process of water-polymer cutting enables food products to be cut at lower pressure, significantly reducing energy consumption in production and extending the service life of equipment [10; 18].

Thus, the relevance of research on water-polymer cutting lies in the need to develop new approaches to optimize this process, aiming to improve the efficiency and profitability of production processes in the food industry. Understanding the mechanisms of supramolecular structure formation in water-polymer solutions [17] makes it possible to create scientifically grounded methods for calculating jet parameters that ensure maximum productivity and quality in food processing.

The formation of dynamic supramolecular structures during the flow of a polymer solution through the jet-forming nozzle depends on the diameter of the nozzle's outlet, the entry angle into the outlet, the hydrodynamic flow regime of the solution, and the polymer's concentration and molecular weight [10; 11; 17]. Not all of these parameters can be strictly quantified, and therefore, when predicting optimal technological parameters for hydro-jet water-polymer processing of food products, it is necessary to use not only precise engineering calculations but also empirically derived criteria.

The purpose of this study is to develop a scientifically grounded method for calculating the optimal parameters for high-efficiency hydro-cutting of food products using a water-polymer jet. This method accounts for the hydrodynamic characteristics of the process and the physicochemical properties of the polymer solution.

Expererimental part

Materials and Methods

Materials. Pork meat frozen to –25 °C. Meat samples were obtained by cutting muscle pieces from an adult pig of medium fatness, which were then combined into the desired sizes [10]. As the water-polymer jet, polyethylene oxide solutions with molecular masses of $2.5 \cdot 10^6$, $4 \cdot 10^6$, and $6 \cdot 10^6$ were used [20].

Experimental methods of study involved the use of a custom-built hydro-stand capable of operating at a working pressure of up to 500 MPa, with the ability to modify and control both integral and differential parameters of the food product cutting process using a water-polymer jet [10; 18]. The practical feasibility of applying the developed method for calculating the optimal parameters of the water-polymer jet cutting process to enhance its efficiency was substantiated by experimental results obtained using a prototype of a universal hydro-cutting machine MCWPJ-100 (*water-polymer jet cutting machine*), shown in Figure 1.

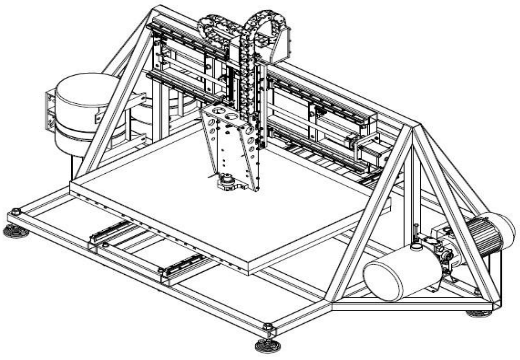


Fig. 1. Experimental prototype of a universal machine MCWPJ-100 for water-polymer jet cutting of food products

The water-polymer jet food-cutting machine is designed to be table-mounted. It includes a pump with a pressure capacity of up to 100 MPa, a receiver, and a tank for the working fluid, which is a polymer solution. To achieve the required low temperatures (ranging from 20 °C to –40 °C), a customized thermostatization and cooling system was utilized [10; 11]. Temperature stabilization was maintained at the specified level with a precision of ±0.1 °C.

Results and discussion

One of the main challenges in developing new approaches to optimize the water-polymer jet cutting process for food products is determining the hydrodynamic parameters of the water jet that ensure maximum performance. These hydrodynamic parameters depend on the optimal ratio between the nozzle outlet diameter, the entry angle into the nozzle, and the speed of the water-polymer jet. These parameters are primarily influenced by the design of the jet-forming head and the hydrodynamic flow regime of the solution, its concentration, and the polymer's molecular weight.

The hydrodynamic calculation of the jet-forming head's operating modes is based on an established criterion [21; 22]

$$\dot{\varepsilon} \cdot \theta_c \geq De_{cr}, \tag{1}$$

which includes the relaxation time of the polymer solution θ_c (the characteristic time of the polymer solution) and the longitudinal velocity gradient $\dot{\varepsilon}$, under which dynamic supramolecular structures form in the solution. Equation (1) should be interpreted as the Deborah number, since the reciprocal of the longitudinal velocity gradient is essentially the timescale of the flow [21]. Thus, the calculation reduces to determining θ_c and $\dot{\varepsilon}$.

The relaxation time can be calculated, and an analytical expression relating relaxation time θ_c to the concentration, temperature, and molecular characteristics of PEO will be derived below. The change in viscosity of an aqueous solution (in g/sm·c) upon the addition of macromolecules follows the law below [23; 24]:

$$\eta_c = \eta_s e^{\psi_m}, \tag{2}$$

where η_s – the viscosity of water (in g/sm·c), ψ_m – the volume fraction of macromolecules.

In turn [23; 24]:

$$[\eta]_0 = F_f \frac{\langle h^2 \rangle^{3/2}}{M}. \tag{3}$$

Here, F_f – is the Flory constant, and $\langle h^2 \rangle$ – is the root-mean-square distance between the ends of the macromolecular chain. Assuming that the root-mean-square radius of the macromolecule $\langle R^2 \rangle = \frac{1}{6} \langle h^2 \rangle$ and its volume $\upsilon_o = \frac{4}{3} \pi \langle R^2 \rangle^{3/2}$, instead of equation (3), we write:

$$[\eta]_0 = 3{,}5 F_f \frac{\upsilon_o}{M} \tag{4}$$

or, when $F_f > 1.7 \cdot 10^{23}$ [23]

$$[\eta]_0 = \frac{\upsilon_o}{M}, \tag{5}$$

where υ_o – is an effective molar volume of the macromolecule in a polymer solution at infinite dilution.

The volume fraction occupied by the polymer macromolecule can be expressed as:

$$\psi_m = \upsilon_c \cdot n_m, \tag{6}$$

where υ_c – is the molar volume of the macromolecule at a given polymer concentration in the solution; n_m is the number of moles per unit volume.

Then, considering formula (5), we can write:

$$\psi_m = \frac{\upsilon_c}{M} \cdot M \cdot n_m = [\eta]_c \cdot C, \tag{7}$$

where $[\eta]_c$ – is the so-called current intrinsic viscosity (in g/sm·c), i.e., the intrinsic viscosity at a given polymer concentration in the solution (in g/sm³), $M \cdot n_m$ is the polymer density expressed in g/sm^3. From this, we derive:

$$\eta_c = \eta_s e^{[\eta]_c \cdot C}$$

or

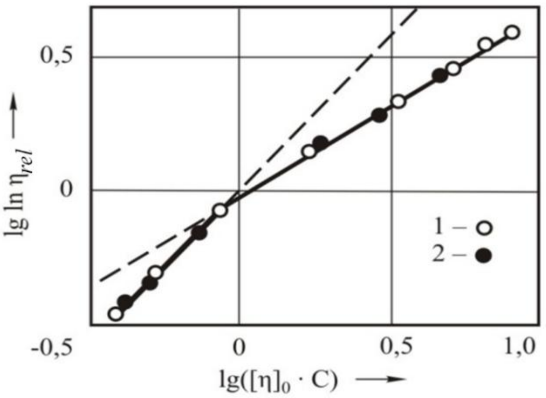
$$\ln \frac{\eta_c}{\eta_s} = \ln \eta_{rel} = [\eta]_c \cdot C \cdot$$

The relaxation time is related (when extrapolated to zero c

$$\theta_0 = A \frac{M [\eta]_0 \eta_s}{RT^o}.$$

The concentration dependence $\ln \eta_{rel}$ in general form according to Fig. 2, is expressed as:

$$\ln \eta_{rel} = ([\eta]_0 \cdot C)^a. \tag{11}$$



M_{PEO}: 1 – 4$\cdot 10^6$, 2 – 2,5$\cdot 10^6$

Fig. 2. The dependence of the relative viscosity of aqueous PEO solutions on concentration

Using equation (9), we obtain:

$$[\eta]_c = \frac{([\eta]_0 \cdot C)^a}{C}. \qquad (12)$$

The results obtained in the work [23] suggest that equation (10) can be generalized for the case of semi-diluted solutions by replacing $[\eta]_0$ with $[\eta]_c$, and η_s – with the viscosity of the aqueous PEO η_c. Then, we get:

$$\theta_c = A\frac{M[\eta]_c \eta_c}{RT^o}. \qquad (13)$$

Using equations (9), (12), and substituting into (13), after some straightforward transformations, we obtain:

$$\theta_c = A\frac{M[\eta]_0 \cdot \eta_s}{RT^o}([\eta]_0 \cdot C)^{a-1} e^{([\eta]_0 \cdot C)^a}$$

Considering equation (10), denoting $[\eta]_0 \cdot C = k$ and substituting into (14), we get:

$$\theta_c = \theta_0 k^{a-1} e^{k^a}.$$

The analysis of experimental data (Fig. 2) shows that in the range of low concentrations, when k<1, the following holds true:

$$\ln \eta_{rel} = k,$$

And at higher concentrations, when k>1, the following holds true:

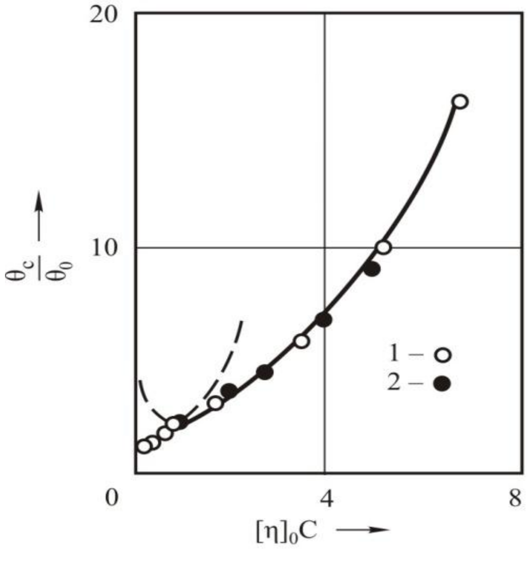
$$\ln \eta_{rel} = k^{2/3}.$$

It is important to emphasize that the transition from a dilute to a concentrated solution regime is defined not by an absolute concentration value, but rather by a dimensionless parameter $k = [\eta]_0 \cdot C$. The region of low concentrations (dilute solutions) is the region where k < 1. The region of high concentrations (concentrated solutions) is the region where k > 1.

Using equations (15), (16), and (16a), we obtain:

$$\theta_c = \begin{cases} \theta_0 e^k & \text{at } k<1 \\ \theta_0 \dfrac{e^{k^{2/3}}}{k^{1/3}} & \text{at } k>1 \end{cases}. \qquad (17)$$

The dependence of θ_c/θ_0 on $[\eta]_0 \cdot C$ for PEO with two molecular weights in water is shown in Fig. 3.



M_{PEO}: 1 – $4 \cdot 10^6$, 2 – $2{,}5 \cdot 10^6$

Fig. 3. Dependence $\frac{\theta_c}{\theta_0}$ on concentration PEO of aqueous solutions

The solid line represents the curve obtained according to equation (17). It is evident that the experimental data points for the corresponding concentration range align satisfactorily with the calculated curve. Thus, equation (17) allows the calculation of the relaxation time of aqueous PEO solutions based on known molecular characteristics of PEO. The effect of temperature in this expression is accounted for by the temperature dependence of θ_0 and k.

The longitudinal velocity gradient that occurs in the inlet section of the nozzle orifice when a polymer solution flows through it is quite difficult to calculate precisely. For design and computational studies of the nozzle (and other elements) of the hydro-cutting jet-forming head, the problem can be simplified to the steady-state flow of a Newtonian fluid in a converging section (a cross-sectional view of the nozzle part of the jet-forming head is shown in Fig. 4).

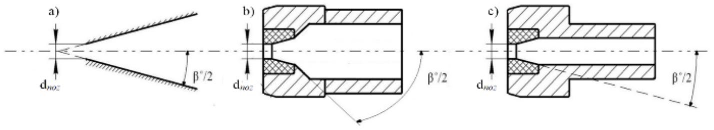


Fig. 4. Cross-sectional view of the inlet section of the nozzle part of the hydro-cutting jet-forming head: a) – Nozzle schematic; b) – Nozzle of the prototype hydro-cutting machine MCWPJ-100; c) – Nozzle of existing hydro-cutting equipment

The natural limitation of using the relationship for the velocity gradient, obtained from solving the problem of Newtonian fluid flow in a converging section, to calculate $\dot{\varepsilon}$ in the flow of an aqueous PEO solution is determined by the flow rates and entry angles. Beyond a critical value, the formation of supramolecular structures in the aqueous polymer solution becomes apparent. Although for subcritical flow regimes of aqueous PEO solutions, the calculated maximum longitudinal velocity gradient will be somewhat overestimated, because the addition of PEO, although not significantly, reduces the longitudinal velocity gradient even in subcritical regimes [12; 22]. Therefore, the critical Deborah number $De_{кр}$ in this case will differ from the value of 0,5 obtained by Zimm [25]. Thus, $De_{кр}$ the critical Deborah number must be determined experimentally. The critical (imaginary) Deborah number is taken as the value at which the cutting ability of the water-polymer jet exceeds that of the water jet.

The exact solution to the flow equation in the converging section was obtained by Boyko and Insarova [26]. Using this solution for the practically relevant flow rates, the expression for the longitudinal velocity gradient in the inlet section of the nozzle of the jet-forming head for not too large β^0 $\left(\beta^0 < \frac{\pi}{2}\right)$ can be written as:

$$\dot{\varepsilon} \approx \frac{2 \cdot Q \cdot tg\frac{\beta^\circ}{2}}{K \cdot d_{noz}}, \tag{18}$$

where Q is the outflow velocity of the polymer solution, K – is the permeability coefficient of the nozzle of the hydro-cutting jet-forming head, d_{noz} is the diameter of the nozzle exit hole, β° – angle measured as indicated in Fig. 3.

Substituting equations (17) and (18) into equation (1), the condition for the formation of dynamic supramolecular structures in aqueous PEO solutions upon their flow through the nozzle, which must be satisfied when designing the configuration of the nozzle (and other elements) of the hydro-cutting jet-forming head, takes the following form, when $[\eta]_0 \cdot C \le 1$:

$$\frac{\theta_0 \cdot \exp\{([\eta]_0 \cdot C)\} 2 \cdot Q \cdot tg\frac{\beta^\circ}{2}}{d_{noz}^3} \ge De_{cr}, \quad at\ \beta^\circ < \frac{\pi}{2}$$

.(19)

Since the critical Deborah number is determined experimentally, it is not an error to replace $K \cdot d_{noz}$ with d_{noz}^3 in equation (19). According to experimental data obtained by Pogrebnyak A. et al. [10], the critical Deborah number can be considered equal to 1.0. This value of the critical Deborah number was empirically derived for practically significant concentration ranges (0.001 %–0.05 %) and molecular weights ($2.5 \cdot 10^6$, $4 \cdot 10^6$, and $6 \cdot 10^6$) of aqueous PEO solutions.

From the obtained relation (19), it follows that the ability to form dynamic supramolecular structures during the flow of an aqueous PEO solution increases with an increase in the angle of entry into the nozzle opening of the hydro-cutting jet-forming head, the jet speed, the concentration, and the molecular weight of PEO, as well as with a decrease in the diameter of the nozzle opening. Therefore, the necessary condition for realizing the increased cutting ability of the water-polymer jet is the fulfillment of condition (19). The calculation of other elements (diameters of the supply channel and inlet openings) of the hydro-cutting jet-forming head, in terms of their influence on the formation of dynamic supramolecular structures, can be done based on the calculated parameters of the nozzle. It is obvious that the longitudinal velocity gradient during the flow of the aqueous PEO solution through any elements of the hydro-cutting jet-forming head, except for the entry section of the nozzle, should not exceed the value given by the following expression $\dot{\varepsilon}_{cr}$. So, optimizing the cutting process involves balancing concentration

C, molecular weight M of PEO and the longitudinal velocity gradient $\dot{\varepsilon}$.

The developed scientifically grounded method for calculating the optimal parameters of hydro-cutting food products with a water-polymer jet has enabled the reduction of the rational working pressure by 4–5 times compared to the pressure used in water jet cutting. This has made it possible to design and manufacture a prototype of a universal hydro-cutting machine, shown in Fig. 1, with a cost 10 times lower than the cost of standard hydro-cutting equipment. The nozzle part of the prototype hydro-cutting machine is shown in Fig. 4. The optimal parameters for hydro-cutting food products with a water-polymer jet, which were implemented using the proposed calculation method that takes into account the hydrodynamic characteristics of the process and the physicochemical properties of the polymer solution, were realized.

The investigation of the effect of polyethylene oxide (PEO) concentration with a molecular weight of $M_{PEO} = 6\cdot10^6$ in the water-polymer jet on the cutting depth in pork samples at a temperature of -25°C and -7°C, a pressure of $\Delta P_o = 100$ MPa, and a jet speed of $V_{p,j} = 0{,}05$ m/s showed that the cutting depth increases sharply with an increase in the PEO concentration in the water-polymer jet, reaching a maximum at an optimal value of $C_{PEO} = 0.008\%$ [10].

Experimental results characterising the effect of the distance from the nozzle cut to the surface of pork meat cut by water-polymer and water jets on the depth of cut are presented in Table.

Table

The effect of the distance from the nozzle cut to the surface of frozen pork meat cut by water-polymer and water jets on the depth of cut

($C_{PEO} = 0.008\%$, $M_{PEO} = 6\cdot10^6$, $\Delta P_o = 100$ MPa, $d_s = 0.60\cdot10^{-3}$ m, $V_{p,j} = 0{,}05$ m/s)

The temperature of the meat t, °C	The depth of cut h, 10^{-3} m							
	The distance from the nozzle cut to the meat surface l_0, 10^{-3} m							
	2.0	3.5	4.0	6.0	10.0	20.0	60.0	90.0
A water-polymer jet								
–25 °C	73	90	95	101	101	95	90	86
–7 °C	113	134	136	145	145	138	128	124
A water jet								
–25 °C	50	61	65	69	64	54	41	35
–7 °C	78	92	94	100	92	79	59	53

It can be seen that across the entire investigated range of distances from the nozzle cut to the pork meat surface under these optimal conditions, the cutting depth of the water-polymer jet in frozen pork at –25 °C and –7 °C using a prototype of the hydro-cutting machine is ~ 1.5–2.5 times greater than the cutting depth achieved with water jet cutting. In contrast, when using a standard industrial unit, the cutting depth is only 1.85 times greater (Pat.74609 Ukraina (2012), Byul. 12. Water-polymer cutting method for frozen food products and materials).

Conclusions

1. The developed scientifically grounded method for calculating the optimal parameters of water-polymer jet cutting of food products has allowed, through the implementation of a highly efficient food cutting process, to reduce the rational working pressure by 4–5 times compared to the pressure used in water jet cutting. This has enabled the development and manufacture of a prototype universal hydro-cutting machine at a cost 10 times lower than that of existing hydro-cutting equipment.
2. A universal high-efficiency hydro-cutting in 3D mode machine MCWPJ-100 using a water-polymer jet has been proposed. Experimental testing of the machine demonstrated the high efficiency of the hydro-jet water-polymer cutting process for pork meat frozen to minus 25 °C, confirming the practical feasibility and economic effectiveness of water-polymer cutting of food products. This also validated the reliability of the developed method for calculating the optimal parameters of high-efficiency hydro-cutting of food products with a water-polymer jet, which takes into account the hydrodynamic characteristics of the process and the physicochemical properties of the polymer solution.
3. The use of polymer solutions as the working fluid requires further research on the interaction between the water-polymer jet and the food product being cut in order to obtain a computational dependence of the cutting depth in the food product on its strength, the optimal

distance between the nozzle cut and the food product surface, the nozzle diameter, polymer concentration and molecular weight, as well as hydraulic and operational parameters, movement speed, and the quality of water-polymer jet formation.

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