Intensification of water jet cutting process in deep-frozen food products

Andriy Pogrebnyak[1], Maxim Korneyev[1], Volodymyr Pogrebnyak[2], Olena Yudina[1], Natalia Nebaba[1], Olena Vishnikina[1]

1 – University of Customs and Finance, Dnipro, Ukraine
2 – Ivano-Frankivsk National Technical University of Oil and Gas, Ivano-Frankivsk, Ukraine

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Corresponding author:

Andriy Pogrebnyak
E-mail:
pogrebnyak.av1985@gmail.com

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Abstract

Introduction. The study aims to enhance the hydro-cutting process by modifying the working fluid using water, water-ice and water-nitrogen jets when cutting deep-frozen food products.

Materials and methods. *Materials:* Hake fish fillets, beef meat, and ice samples at -30 °C as a model sample of meat at -25 °C. *Experimental Methods:* Hydro-cutting unit is utilized to cut food products with a water jet. The experiments were conducted at food temperatures ranging from -3 to -25 °C, with pressure variations from 50 MPa to 500 MPa, nozzle diameters of $0.2 \cdot 10^{-3}$ to $0.8 \cdot 10^{-3}$ m and the speed of movement of the jet of the working liquid relative to the sample of the food product of 0.01 to 0.07 m/s.

Results and discussions. It was found that the increasing the pressure from 200 to 500 MPa results in a nearly 21-fold and 6-fold increase in the depth of cut for nozzles with diameters of 0.2×10^{-3} and 0.4×10^{-3} m, respectively. Additionally, increasing the nozzle opening diameter leads to an increase in the depth of cut in the frozen food product. At the same time, the maximum cutting depth in the food product at the temperature of -11 °C did not exceed $82,5 \times 10^{-3}$ m with the pressure of 500 MPa. Reducing the temperature of the food product to -11 °C and below excludes the possibility of using water jet cutting at the pressure of 250–300 MPa, and the necessity of creating pressures above 300 MPa causes a sharp increase in the cost of water jet cutting equipment. Experimental verification was conducted to evaluate the feasibility of using a water jet with small ice particles to enhance the hydro-cutting. The process of hydro-cutting deep-frozen food products can be intensified by adding small ice particles to the water jet, which is highly effective but also expensive. Alternatively, a water-nitrogen jet that employs ice microparticles as an abrasive, formed by cooling the water jet with liquid nitrogen vapour, is a cost-effective way to significantly improve the water jet cutting process for deep-frozen food products.

Conclusions. To significantly intensify the hydro-cutting process of deep-frozen food products, it is most expedient to use a water-nitrogen jet as the working fluid, in which ice microparticles are formed in the process of cooling a water jet with vapours of liquid nitrogen.

Introduction

The development of innovative cutting equipment poses a significant challenge to the food industry. The current methods and equipment utilized presents significant drawbacks. These include equipment maintenance hazards, high noise and vibration levels, unsatisfactory sanitary conditions, potential introduction of metal microparticles, rapid dullness and the need for frequent sharpening and replacement of the working tool, wide cutting widths resulting in additional product loss, difficulties in cutting of deep-frozen food products, and others (Cui et al., 2022; Xu et al., 2022).

The XX century brought numerous ground-breaking discoveries to humanity, including the technology of water jet cutting, which was hailed as the future three decades ago. Currently, this technique is widely utilized across several industries. If a thin water jet increases its velocity and energy to cause erosion of a material, it can have a cutting effect on any material (Duspara et al., 2018; Gyliene et al., 2014). Hence, water jet cutting process can be an alternative method of cutting food products, particularly at low temperatures, without the mentioned drawbacks. The hydro-cutting method's high manufacturability compared to traditional ones is the mail reason for its widespread use. However, the lack of comprehensive research on the process of food water jet cutting and equipment development hinders its implementation in the food industry (Ranjan et at., 2022; Xu et al., 2022).

One of the main benefits of water jet technology is the computerized control of the water jet cutting process, enabling 3D food processing. Utilizing servos, the water jet cutting head can process the food product from various sides, while making cuts of any complexity, at any location, and with programmed changes in the parameters of hydro-cutting food products. This will enable a traditional robotic conveyor line for primary processing to be streamlined into one (or more) processing points, where the water jet cutting head can execute multiple operations simultaneously (Xu et al., 2022).

Hydro-cutting is a thin, high-speed liquid jet that serves as the cutting tool for food. The properties of the working fluid determine the water jet's ability to acquire the necessary hydrodynamic features that guarantee optimal productivity and the highest cutting surface quality while consuming minimum energy for jet formation. Minimizing energy costs should involve reducing the working pressure of the fluid in front of the nozzle to its lowest possible value, while also meeting the technological requirements for cutting the product. Determining the type and composition of the working fluid is a key point in the development of a technological process for water jet cutting of deep-frozen food products. The relevance of the study is also due to the fact that lowering the temperature of meat, fish and other food products to -11 °C excludes the possibility of using water cutting at pressures less than 250–300 MPa, meanwhile the use of higher pressures is economically unprofitable (Pogrebnyak, 2020; Ranjan et at., 2022).

The aim of the research was to intensify the water jet cutting process by using a water jet with ice particles and a water-nitrogen jet when cutting deep-frozen food products.

Materials and methods

Materials

Hake fish fillets and beef meat were used in the study. The meat samples were obtained by cutting pieces of muscle from a medium-fat adult cow and then combined into desired sizes. For the fish samples, multiple layers were combined to achieve the desired size. As a model for meat samples at - 25 °C, ice samples at - 30 °C were used. It was shown that the most accurate criterion for measuring the resistance of frozen food products to water jet cutting is their uniaxial compression strength. Thus, the use of ice as a model for meat samples in water jet cutting experiments is justified, as the uniaxial compressive strength of ice at - 30 °C and meat frozen to - 25 °C is identical.

Experimental research methods

Water jet cutting unit with a maximum working pressure of 500 MPa (Pogrebnyak et al., 2020) that was able to alter and regulate integral and differential parameters during the food-cutting process using a water jet. In order to achieve the required low temperatures (of up to - 40 °C), utilized customized thermostatization and cooling system for the receiver filled with a working fluid (Pogrebnyak et al., 2017, 1992). The temperature was maintained at the specified level with precision up to ±0.1 °C.

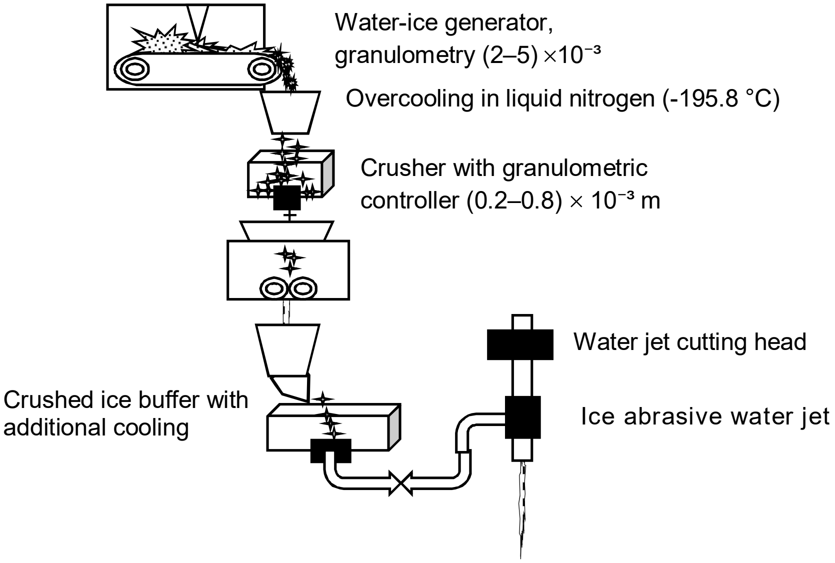

Figure 1. Schematic diagram of the technological process for obtaining a water jet containing ice particles as an abrasive

The error in determining (in %) was: for the depth of cutting – ±0.5÷1; for the velocity of movement of the jet of the working liquid relative to the sample of the food product – ±1; for the temperature of the food product – ±0.5; for the pressure – ±1.

Results and discussion

Pure water jet cutting

The application of pure water jets as cutting tools for food products has proven to be advantageous. Table 1 displays results from hydro-cutting of frozen fish.

Table 1

Water pressure effect on depth of cut in block samples from hake fillets at temperature -11°C

d_o, m	Depth of cut, h, m×10^{-3}, at ΔP, MPa						
	100	150	200	250	300	400	500
0.2 x 10^{-3}	0.6	1.1	3.0	5.1	10.2	38.1	61.8
0.3 x 10^{-3}	2.9	4.5	7.2	13.6	21.4	48.8	69.3
0.4 x 10^{-3}	5.9	10.6	14.6	19.2	34.9	62.5	82.5
0.6 x10^{-3}	16.7	21.1	25.7	35.3	-	-	-
0.8 x10^{-3}	23.6	31.4	36.7	-	-	-	-

Note: d_o is a nozzle diameter

The velocity of the water jet (Vn) remained constant at 25×10^{-3} m/s compared to a block sample of hake fillet, while the distance (l) between the nozzle cutter and the sample surface was 5x10^{-3} m. The analysis of experimental data indicates that the depth of cut (h) in frozen fish rises with increasing water pressure across the entire range of values. For instance, elevating the pressure (ΔP) from 200 to 500 MPa leads to an increase in the depth of cut for nozzles with diameters (d_o) equal to 0.2×10^{-3} m and 0.4×10^{-3} m by almost 21 and 6 times, respectively. Enlarging of the nozzle orifice diameter, results in a greater depth of cut in frozen fish (Table 1). In this case, the maximum depth of cut in a block sample from hake fillet with a temperature (t) of -11 °C was 82.5×10^{-3} m, which was observed at a pressure of 500 MPa and a nozzle diameter of 0.4×10^{-3} m. The depth of cut in frozen fish samples at - 25 °C will be even smaller.

The impact of high-speed water jet displacement velocity on the depth of cut in a block sample of hake fillet are shown in Table 2.

Table 2

Influence of jet velocity on depth of cut in block samples of hake fish fillet at temperature -3°C

ΔP, MPa	Depth of cut h, m x 10^{-3}, at V_n × 10^{-3} m/s					
	1	5	10	25	40	50
150	76.4	47.1	36.1	9.2	6.25	2.3
200	98.6	72.3	47.2	27.4	17.25	11.8
250	127.2	105.7	84.1	64.1	40	21.7
300	145.1	128.6	102.4	84.2	55	28.4

The depth of cut decreases rapidly with increasing water jet travel speed throughout the investigated pressure range from 150 to 300 MPa. The working depth of cut are achieved on frozen fish samples up to -3 °C only at relatively low velocities of water jet movement ranging from 10^{-3} to 10^{-2} m/s. The data indicate that water jet cutting at pressures below 250–300 MPa is not possible when food product temperature decreases to -11 °C and below. The working conditions, including high pressure and low water jet velocity, do not yield maximum productivity for water cutting and result in high energy consumption for jet formation. These factors led to the need for an intensified cutting process for frozen foods with temperatures ranging from -11 to -25 °C and below, which is of practical importance.

It is important to note one significant negative effect that arises at high operating pressures – a substantial rise in water jet temperature passing through the nozzle of the jet-forming head. Increasing the water jet pressure results in a rise in temperature. However, this poses limitations on the use of high pressures (max 700 MPa), as exceeding 100 °C would impair water jet functionality. Moreover, elevated water jet temperature can compromise the quality of the cut food product.

One way to enhance the efficiency of the water jet cutting process, which significantly expands its technological capabilities, is to introduce abrasive additives into the cutting fluid jet (Liu et al., 2019; Natarajan et al., 2020). Water jet cutting involves abrasive particles being propelled by a liquid jet to affect the material being cut.

Ice abrasive water jet

Pure water jet cutting and especially abrasive water jet cutting are a complex physical process that depends on various factors. The influence of these factors on the cutting process is complex and interdependent, with a result that is difficult to predict, depending on the material to be cut. Currently, specific hydro-cutting units are developed for each industry, which can work with pure water or by accelerating abrasive particles. Each hydro-cutting unit design has a distinctive characteristic parameter that signifies the efficiency of the hydro-cutting process. The parameter depends on the design, geometric features, and manufacturing quality of individual parts of the hydro-cutting equipment, the material properties of the substance being cut, and the choice of abrasive used in hydro abrasive cutting (Liu, 2019; Ranjan et al., 2022; Wang and Shanmugam, 2009).

Currently, the following abrasive materials are used: garnet, aluminium oxide, silicon carbide, steel shot, copper slag, silica sand (silicon dioxide), and glass chips (Perec and Tavodova, 2016; Ranjan et at., 2022). Silica sand is the most commonly used, primarily because of its low cost. Obviously, none of the abrasive materials used in practice can be applied to the abrasive water jet cutting of frozen foods. In this situation, a promising way to increase the efficiency of the process of water jet cutting frozen food products can be the use of ice abrasive water jet, i.e. when the abrasive material is small ice particles.

It is also important to note that ice abrasive water jets in the food industry may also have prospects for use in cleaning the internal surfaces of food equipment and in the development of technology for hydrodemolition of meat from bones.

Experimental verification was conducted to explore the use of a water jet, infused with small ice particles, to enhance hydro-cutting of deep-frozen food products. The process model, as depicted in Figure 1, was implemented on model meat samples using ice with a temperature of -30 °C. It has been found that significant depths of cut are achievable in frozen meat at -25 °C and model meat samples (made from ice) at -30 °C at working pressures of 100 MPa and water jet velocities of $(15–25)\text{x}10^{-3}$ m/s. At a pressure of 150 MPa and with a nozzle diameter of 0.4×10^{-3} m, the hydro-cutting process using a hydro-abrasive jet on frozen meat samples and model meat samples at -25 °C and -30 °C, respectively, resulted in a 0.15–0.20 m cut depth. The use of small ice particles as abrasives significantly increased the efficiency of the process under these conditions. Thus, for instance, if in the model meat sample the cutting depth with a jet of pure water was 2.3×10^{-3} m at $\Delta P=100$ MPa; $d_o=0.6\cdot10^{-3}$ m; $V_n=25\times10^{-3}$ m/s, then using small ice particles as abrasive material under the same conditions we obtained a through cut of the sample (the sample thickness 0.4 m) with a high quality of the cut surface.

Consequently, it can be concluded that the process of intensifying the water jet cutting of deep-frozen food products, by adding small ice particles to the water jet, is highly efficient. However, due to the complexity and high cost of obtaining an ice abrasive water jet (Figure 1), their utilization in the food industry is still economically limited (Kuzkin et al., 2019; Zhuravka et al., 2023).

Thermal effects in the flow of a water through a nozzle

The proper selection of the water jet formation system design and thermophysical conditions for water flow through the hydraulic cutting head should result in enhanced efficiency of the hydraulic cutting process. Misunderstandings and misconceptions in the interpretation of experimental results surrounding the phenomena that occur in the jet-forming hydro-cutting head during water flow are largely due to the presence of thermophysical effects. At the formation of a water jet during water flow through the jet-forming head, various thermal effects can influence both the technological process of hydro-cutting of food products and the parameters of hydro-cutting equipment. To intensify the process of water jet cutting of frozen food products, it is necessary to investigate the thermal effects arising from the flow of water through the water jet cutting jet-forming head. The temperature change of the water jet during formation is a crucial consideration.

Water flows out of the jet-forming nozzle due to a decrease in pressure to atmospheric levels, resulting in the expansion of the water flow and a process of water throttling. Consequently, a change in temperature of the water jet should occur. This expansion of a liquid flowing through a small hole from high to low pressure is known as Joule-Thomson effect in thermodynamics (Schroeder, 2000). During a flow of water, the enthalpy remains constant while the temperature of the water adjusts. Every fluid has a Joule-Thomson inversion temperature, where expansion at constant enthalpy results in a temperature rise when above the threshold and cooling when below it. The inversion temperature varies according to pressure and is below room temperature for water. Therefore, isoenthalpic expansion can raise the temperature of water above room temperature. Let's examine the temperature alteration of a high-speed water stream generated by passing through a water jet's nozzle at isoenthalpic throttling between two pressures: P_1 (pressure in the inlet domain of the water jet nozzle) and P_2 (atmospheric pressure).

The function below expresses the total enthalpy differential, I.

$$dI = C_p dT + V\left(1 - T/V\left(\frac{\partial V}{\partial T}\right)_p\right)dP, \tag{1}$$

where C_p is water heat capacity at constant pressure;

T is temperature, °K;

V is volume of water, m^3.

For isentropic processes when l = constant, the relationship between pressure and temperature is as follows:

$$dT = V / C_p\left(1 - T / V\left(\frac{\partial V}{\partial T}\right)_p\right)dP \tag{2}$$

Coefficient

$$K = V / C_p\left(1 - T / V\left(\frac{\partial V}{\partial T}\right)_p\right)dP \tag{3}$$

is referred to as the Joule-Thomson differential coefficient. It can be approximated that

$$\Delta T = -K \cdot \Delta P, \tag{4}$$

where $\Delta T = t_2 - t_1$ represents the temperature difference between the water jet at the nozzle outlet and in the receiver, while $\Delta P = P_1 - P_2$ refers to the pressure disparity between the inlet region of the water jet nozzle and the atmosphere (at the nozzle outlet). The Joule-Thomson coefficient K can be determined experimentally. Table 3 presents the water jet temperature variation data resulting from water flow through the nozzle of the hydro-cutting jet-forming head at different operating pressures.

Table 3

Temperature of the water jet formed by the hydro-cutting jet forming head at different operating pressures

Nozzle diameter d_o, 10^{-3} m	Pressure ΔP, MPa	$t_2 - t_1 = \Delta T$, °C	K, °C/MPa
0.30	500	46.7	0.0934
	300	27.9	0.0930
	200	18.6	0.0930
	100	9.3	0.0930
	50	4.6	0.0920
0.60	300	27.6	0.0920
	200	18.4	0.0920
	100	9.24	0.0924

Note: V_n is a speed of movement of the jet of the working liquid relative to the sample surface.

The rise in the water jet temperature flowing through the nozzle of the jet-forming head results from the Joule-Thomson effect. This inference is drawn from a comparison of water jet temperature with the jet temperature of other liquids. The comparative study reveals that the temperature of the water jet increases largely when the hydro-cutting jet-forming head is employed with a working fluid having a lower heat capacity. The temperature of the technical oil jet, at a pressure of 500 MPa, reached 200 °C. It is evident that the nozzle diameter has a slight impact on the jet's temperature during throttling, with higher diameters causing a less significant increase. Table 1's experimental data enables the determination of the Joule-Thomson coefficient K (4) for water, which was discovered to be 0.0927 °C/MPa.

The experimental results under consideration hold crucial importance in designing and calculating equipment for implementing the water jet cutting process. It raises the question of how much pressure can be increased while developing adequate equipment. If water serves as a working fluid, it is evident that water jet cutting of food products will be feasible only if the temperature of the water jet does not cross 100 °C. It is evident from the above discussion that the highest attainable velocity of the water jet exiting the nozzle under high pressure is limited by the Joule-Thomson effect. This means that the water jet's temperature can rise to the point where it becomes vapour at a certain pressure value. It was shown that without special water jet cooling methods, the temperature of the water jet exceeds 100 °C at a pressure of 700 MPa for nozzles with orifice diameters from 0.3×10^{-3} to 0.6×10^{-3} m.

Cutting under using water jet negative temperature

It is necessary to fully understand and improve the process of water jet cutting, particularly under reduced and negative temperature conditions. To achieve this understanding, it is important to consider the anomalous properties of water, specifically its liquid state, when using a water jet cutting food products at reduced temperatures. One distinguishing feature of water from other liquids is its decrease in crystallization temperature with increasing pressure (Yasutomi, 2021). The crystallization curve on the state diagram of water, increasing pressure up to 207 MPa, veers to the left up to - 22 °C. This characteristic on the water phase diagram permits the water jet's temperature to be lowered below freezing without transitioning into a solid state, such as ice. For instance, this can be achieved in the receiver of a hydraulic cutting unit at an operating pressure of 207 MPa where the pure water can be cooled down to -22 °C.

Thus, if the temperature of the working fluid (water) in the receiver is cooled to -15 °C, it is possible to obtain a temperature of -1.0 °C for the water jet at the nozzle outlet by applying a pressure of 150 MPa, according to equation (4) and the data presented in Table 3. It was experimentally determined that compressing water to 150 MPa and then throttling it through a 0.3×10^{-3} m diameter nozzle results in a temperature increase of 14 °C. By cooling the water in the receiver to -15 °C at 150 MPa, a water jet with a temperature of -1.0 °C can be obtained at the nozzle outlet. In this case, a super cooled water jet is produced, and upon exiting the nozzle, ice microcrystals should form due to the water transitioning to a crystalline state at temperatures below 0 °C and atmospheric pressure. These microcrystals can serve as abrasive additives.

An experimental study was conducted to investigate the influence of water jet temperature on the depth of cut for samples of beef meat and hake fish fillets. The tests were carried out at a temperature of minus 25 °C, with pressures of 50 and 150 MPa, a nozzle diameter of 0.3×10^{-3} m, and a speed of hydro jet movement relative to the frozen meat sample of 15×10^{-3} m/sec. The shearing distance from the nozzle to the surface of the frozen food product being cut was equal to the optimal value. Table 4 displays the data indicating the impact of water jet temperature on the depth of cut in beef samples chilled to - 25 °C.

Table 4

Effect of water jet temperature on depth of cut in frozen beef meat

$d_o = 0.3\times10^{-3}$ m, $V_n = 15\times10^{-3}$ m/s, $l = l_{opt} = 9\times10^{-3}$ m, $t_{meat} = -25$ °C

t, °C	ΔP, MPa	h, 10^{-3} m
4	150	124
	50	27
-0.5	150	160
	50	41
-1.0	150	>200
	50	74

Note: d_o – a nozzle diameter;
V_n – a speed of movement of the jet of the working liquid relative to the sample surface; l – distance between the nozzle cutter and the sample surface; t_{meat} – temperature of meat; t – temperature water jet; ΔP – working pressure; h – depth of cut.

It is evident that the depth of the cut, *h*, monotonically increases as the temperature of the water jet decreases to 0 °C. This increase in *h* with decreasing temperature of the water jet is primarily due to the increase in surface tension and viscosity of water, which enhances its compactness. A decrease in water temperature to -1.0 °C (Table 4) leads to a sudden increase up to 30 and 50% for pressures of 150 MPa and 50 MPa, respectively, in the depth of cut. The change in depth of cut of a frozen food product when the water jet temperature is at or below -1.0 °C is a strong indication that microparticles – ice crystals – are formed in the water jet from the moment of its emergence from the air medium, and that these microparticles play the same role as the pre-prepared small ice particles introduced into the pure water jet.

Thus, the data confirm a significant increase in the efficiency of water jet cutting food products at reduced and especially negative (-1 °C and below) temperatures of the pure water jet.

Water-nitrogen jet cutting

The water jet method of processing of food requires the hydraulic cutting unit to be equipped with a nitrogen vapour supply system to the collimator, which can be easily realized using liquid nitrogen vapour. The supply system for nitrogen vapour is straightforward – a Dewar container with liquid nitrogen from which vapour flows into the collimator via a throttling orifice. All parts of the liquid nitrogen supply system require a thermally insulating coating.

It was found under the specified conditions for cutting a sample of beef meat that the efficiency of the process for water jet cutting of food products using the water-nitrogen method significantly increased (Table 5).

Table 5

Effect of pressure on the depth of cut in frozen of beef meat by water and water-nitrogen jets

$d_o = 0.3\times10^{-3}$ m, $V_n = 15\times10^{-3}$ m/s, $l = l_{opt} = 9\times10^{-3}$ m, $t_{meat} = -25$ °C, $C_{opt,nitrogen} = 20$ %

ΔP, MPa	**Depth of cut h, 10^{-3} m**	
	Water jet cutting a beef meat	Water-nitrogen jet cutting an ice samples at -30 °C as a model sample of meat at -25 °C
50	1.3	80
100	2.2	120
150	3.5	>200

Note: d_o – nozzle diameter;
V_n – speed of movement of the jet of the working liquid relative to the sample surface;
l – distance between the nozzle cutter and the sample surface;
t_{meat} – temperature meat; $C_{opt,nitrogen}$ – optimal concentration of liquid nitrogen;
ΔP – working pressure; h – depth of cut.

It can be concluded that when dealing with deep-frozen beef meat, the depth of cut achieved by the water-nitrogen jet is several times greater than that achieved by the water jet, when all conditions are the same and the collimator receives an optimal concentration (20%) of liquid nitrogen. It was found that cutting a model meat (ice) sample at a temperature of -30 °C with a water-nitrogen jet resulted in a cut depth of over 0.2 m. The analysis of experimental results on the thermal effects of hydro-cutting reveals that the process can be intensified when a water-nitrogen jet, containing ice microcrystallites formed through cooling by liquid nitrogen vapours, is used as an abrasive. This technique shows high practical usefulness for cutting deeply frozen food products.

Conclusions

1. Experimental verification indicated that using a water jet with ice particles to perform hydro-cutting on deep-frozen food products is possible. The method of intensifying of water jet cutting process in deep-frozen food products by introducing small ice particles into the water jet has proven to be highly efficient. However, due to the complex and costly process of obtaining an ice abrasive water jet, it is not currently feasible for use in the food industry.
2. It was shown that the temperature increase of the water jet formed by the flow of water through the nozzle of the hydro-cutting jet-forming head is due to the Joule-Thomson effect. Utilizing the calculated dependence of the water jet temperature increase from the throttling effect, we can estimate the threshold pressure value beyond which the process of cutting deep-frozen food products with a water jet is not feasible.
3. It was demonstrated that the implementation of water-nitrogen jets, in which ice microparticles formed during cooling of the pure water jet by liquid nitrogen vapour serve as the abrasive, yields a highly effective method for water jet cutting of frozen food products.

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