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CALCULATION OF HYDRAULIC LOSSES IN A PIPELINE TAKING INTO CONSIDERATION THE DEPENDENCE OF MINCED MEAT DENSITY AND RHEOLOGICAL PARAMETERS ON PRESSURE

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Abstract

The article highlights the development of a method for calculating hydraulic losses in interoperation transportation systems taking into account the dependence of minced meat density and rheological parameters on pressure. These dependencies were taken from the experimental data of the well-known monograph written by A. V. Gorbatov. Minced meat density, its flow index, and texture index decrease along the pipeline axis together with the pressure level decreasing. As a result, the specific pressure losses caused by friction decrease from the inlet to the outlet of the pipeline. The Cauchy problem was formulated to determine the excessive pressure at the pipeline inlet. This pressure is necessary to determine the required pumping pressure and accordingly select the pumping equipment. The solution of the differential equation was found numerically for different values of the determining parameters. The range of parameter variation was the same as in the above-mentioned monograph: moisture content of minced meat 1.86–2.70 kg/kg, excessive pressure up to 1 MPa, internal pipeline diameter 55–80 mm, temperature 3–23 °C, mass flow rate of minced meat — up to 4 kg/s. The percentage by which the pumping pressure calculated taking into consideration the dependence of the minced meat properties on pressure (the full calculation) was determined to be greater than the value calculated without considering this dependence (the simplified calculation). Under these conditions, the error of the simplified calculation compared to the full calculation can exceed 50 %. In all cases, as hydraulic losses increase, so does the required correction to the calculated pumping pressure. The dependence of the correction factor on the pumping pressure calculated using the simplified (traditional) method was plotted, ignoring the dependence of the density and rheological parameters of the minced meat on pressure. This dependence provides for an approximate estimation of the required increase in the pumping pressure found via the simplified method.

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Introduction

When designing production lines for production of sausages and other minced meat food products, a rational choice of interoperation transport system is crucial. This article examines the problem of calculating the pressure drop ΔP along a pipeline length in those systems. This issue is covered in a special section of the well-known monograph written by A. V. Gorbatov [1]. This monograph specified that rheological parameters and the density of minced meat, ρ, play significant role in calculating of ΔP value.

As is known, the rheological properties of minced meat are well described by the power-law fluid model up to certain values of ω [2,3]:

$$\tau = K \times \omega^m, \tag{1}$$

where: τ — is shear stress, Pa; m — is dimensionless flow index; K — is liquid texture index, Pa·s^m; ω — is velocity shear (gradient), $s^{-1.}$

For example, in [2], based on the results of an experimental study, a diagram is presented in coordinates (τ–ω), which shows that formula (1) can be used to calculate the shear stress in the analyzed minced chicken meat when the velocity shears from zero to approximately 45 $s^{-1.}$

The research [1] presents the results of a comprehensive set of experimental and theoretical studies of dependence of density values ρ, K, m of minced meat on various factors, including composition, temperature, humidity, fat content, etc. Subsequently, many of the results and conclusions [1] were used in the studies of other researchers and in practice. These results were confirmed and further developed.

Wide range of studies has been devoted to the effect of various additives on the rheological properties of minced meat. For example, [3] presents the results of an experimental study of shear stress in minced meat systems in cases of adding flour (chickpea, flaxseed, buckwheat, and rice flour). The dependence of the effective viscosity of the minced meat on velocity shear is presented. The least rate of structural breakdown was detected in the sample with chickpea flour addition, while the highest rate was found in the sample with buckwheat flour.

Authors of the study [4] experimented with the frozen minced meat samples with fat content of 2 %, 10 %, and 18 %, the samples were defrosted via various methods (defrosting in a refrigerator at an ambient temperature of +4 °C, defrosting under running cold water (+4 °C), and ohmic defrosting at various voltages). The viscoelastic properties were determined using rheological tests (tests for oscillation and creep/reconditioning tests). The values of elasticity modulus while storage, elasticity loss modulus, complex elasticity modulus, loss angle tangent modulus, dynamic viscosity modulus, and complex viscosity modulus of the minced meat samples increased along with increasing fat content. With increasing frequency, the elasticity modulus of the minced meat samples increased, but the dynamic viscosity values decreased.

The article [5] describes an experiment to develop minced meat recipes for poultry-based semi-finished food products. The authors sought for optimization of recipe ingredients compatibility in order to create a balanced meat system. Modelled recipes included meat of various cattle and poultry species, offal, and dairy products. The rheological properties of the obtained minced meat systems were studied.

Rheological properties, microstructure and stability of meat emulsions, stabilized with surfactants were discussed in [6]. Research has shown that Pickering emulsions are the potential filler particles for increasing the moisture stability of meat gels, as well as the fat substitutes for protecting lipids from oxidation.

The article [7] studies texture properties, colloidal interactions and rheological properties of meat emulsified systems with flax flour and tomato powder addition. The cooked sausages that contained 3 % of each additive showed the highest values of hardness and cohesive capacity in comparison with the reference samples. These regularities were confirmed by the higher values of elasticity parameter.

Li et al. [8] studied the effect of adding peanut, corn, soybean, and sunflower oils on the gelling and rheological properties of chicken meat-based emulsions. Vegetable oils improved emulsion stability, increased effective viscosity, and increased elasticity. The addition of sunflower oil had the greatest effect.

A study [9] examined the effect of insoluble tiger nut dietary fiber on the rheological properties and protein digestibility of low-fat meat emulsions. The results showed that this additive (3 % by weight) increased the elastic modulus and improved the processing properties of low-fat pork meat emulsions. Moreover, these properties were better than those of the high-fat reference emulsions.

An experimental study of the properties of emulsions made from four types of meat (fish, beef, sheep, and pork) was conducted in [10]. Rheological parameters were measured under deformation and vibration conditions. The samples made from fish and mammals vary significantly in their rheological properties and microstructural characteristics. Pork-based samples were found to possess the highest strength and the most compact gel structure.

Zheng et al. [11] studied the properties of minced chicken breast samples in which amidated pectins were used as natural lipid substitutes. These samples featured higher viscosity and gelling ability in comparison with the reference sample. After heat treatment, no significant differences in color and texture profile characteristics were found in any of the samples.

The authors [12] investigated the influence of chicken slaughter by-products (chicken legs and heads) on the chemical and rheological properties of minced meat. Chicken legs and heads were prepared as a ground mass and as a dry powder. Six types of samples were prepared with the addition of ground mass and powder made from chicken legs and heads in various proportions, legs and heads together and separately. It was found that adding this powder significantly increased the moisture-binding capacity and yield strength of the minced meat.

The article [13] is devoted to the study of the effect of temperature (4–50 °C) and sodium bicarbonate (0.4 %) on the solubility, protein aggregation and rheological properties of low-salt chicken meat emulsion. Along with increasing temperature the solubility and effective viscosity initially increased, reaching maximum values at 30 °C, and then they decreased. It was determined that the combination of sodium bicarbonate with a temperature of about 30 °C can change the structure of chicken protein under low salt content conditions.

The effect of high pressure (up to 80 MPa) and heat treatment (80 °C, 30 min) with the addition of modified protein on the rheological properties and taste of a pork emulsion product with reduced phosphate content was investigated in [14]. The results showed that the addition of such an additive, coupled with high pressure and heat treatment, significantly improved the stability, textural characteristics, and taste of the products. The authors believe that these improvements are associated with rheological and structural changes in the meat emulsions and recommend them for the production of meat products with reduced phosphate content.

There are not so many studies on the rheological properties of minced meat transported through pipelines. Some innovations and improvements have been made to the calculations of pressure drop along the pipeline in order to prevent it [15–18]. Thus, according to the data of [15], in the measured range of shear velocities, the texture flow index does not depend on the pipe diameter. To calculate the value of K of minced meat in the pipeline, an empirical formula was obtained. The effect of temperature on the rheological parameters of meat mixtures was analyzed in a number of works [17,18]. The authors of the article [18] showed that in the hydraulic calculation of pipeline systems assigned for minced meat transportation, it is necessary to take into account the characteristics of the pumps and determine the parameters (flow rate, pumping pressure, spent power, efficiency) at the operation point of the pumping unit.

The change in excessive pressure P is a well-known feature of pipeline systems used for interoperation transportation: it varies from the highest value at the inlet down to the lowest value at the outlet. In [1], the results of an experimental study of the dependence of the density and rheological parameters of minced meat on pressure were presented. Empirical formulas for those dependencies were proposed for "Doctorskaya" sausage mince and "Russian" sausages mince (hereinafter referred to as RSM). The phenomenon of increase in the density and viscosity of minced meat systems along with increasing pressure was confirmed in studies conducted by Golovanets et al. [19].

In all the above-mentioned studies, the dependence of density and rheological parameters of minced meat on pressure was not considered in hydraulic losses calculations. The approach [1] to the hydraulic calculation of process pipelines was retained: the density and rheological parameters were assumed to be constant all along the pipe axis.

The purpose of this article is to develop a method for calculating hydraulic losses in interoperation transportation systems, taking into consideration the dependence of minced meat density and rheological parameters on pressure. The relevance of this study is based on the need to improve mathematical models and calculation methods for pipeline transportation of minced meat for development of digital clones of production processes.

Research tasks:

1. Assessment the experimental data [1] sufficiency for their use in hydraulic calculations of minced meat pipeline transportation;
2. Development of a method for calculating hydraulic losses in a pipeline, taking into consideration the dependence of minced meat density and rheological parameters on pressure;
3. Exploring the impact of various factors (moisture content of minced meat, mass flow rate, pipeline diameter, temperature) on the error of calculation results without taking into consideration the dependence of minced meat density and rheological parameters on pressure.

Objects and methods

A system for interoperation transportation of minced meat through cylindrical pipes is the object of this research. The subject of the research is the effect of pressure on minced meat density and rheological properties on hydraulic losses during minced meat movement through the pipe.

This article uses the findings of dependence of density on pressure [20] observed in three samples of "Russian" sausages mince (RSM), minced in a mincer with mesh diameter of 3 mm of holes. Sample of RSM-1 has a fat content $\varphi = 0.1826$ kg/kg, moisture content $U = 2.06$ kg/kg; RSM-2: $\varphi = 0.1544$ kg/kg, $U = 2.55$ kg/kg; RSM-3: $\varphi = 0.127$ kg/kg, $U = 2.70$ kg/kg.

In [20] an empirical formula is given for calculating the density of sausage mince, obtained as a result of generalizing experimental data:

$$\rho = F_1(\varphi, U, p) = \\ = 1037 - (290 \cdot \varphi + 10{,}5U) + 22 \times \lg(p \times 10^5), \qquad (2)$$

where: ρ — is density of minced meat, kg/ $m^{3;}$ φ — is fat content, kg/kg; U — is moisture content, kg/kg; p — is dimensionless excessive pressure (excessive pressure referenced to atmospheric pressure): $p = P/P_{A.}$

Formula (2) was obtained for a wide range of pressures ($p = 0.1-16$). The error in calculating the density as per (2) does not exceed 4%.

Formula (2) shows that density dependence not only on excessive pressure but also on the fat content and moisture content of the minced meat was obtained. In this article the authors confine themselves to the dependence of density on p for the determined RSM samples:

$$\rho = \mathrm{F}_{2i}(\mathrm{p}) = \rho_{0i} + 22 \times \lg \mathrm{p}, \qquad (3)$$

where: the first term in (3) is calculated using the known values of φ and U: for RSM-1 $\rho_{01} = 1072.4$ kg/m^3, for RSM-2 $\rho_{02} = 1075.4$ kg/$m^{3,}$ for RSM-3 $\rho_{03} = 1081.8$ kg/m^3; index 22 in formula (3) is dimensional (kg/m^3).

It is necessary to note that density changes only slightly with an increase in dimensionless excessive pressure from $p = 0.1$ to $p = 10$, and amounts to no more than 4.2% for three RSM samples being considered.

For m and K parameters of sausage mince given in [21] empirical formulas are given. For RSM they can be written in the following way:

$$m = 0{,}732 \times (1 + 0{,}091 \times \lg(1 + p) + 0{,}0017 \times \mathrm{t}, \qquad (4)$$

$$K = 64 \times (1 - 0{,}02 \cdot t) \times \\ \times \exp[-10{,}8 \times (W - 0{,}48) \times (1 - 0{,}173 \times \lg(1 + p))], \qquad (5)$$

where: $W = U(1 + U)$ — is relative humidity of RSM, kg/kg; t — temperature, °C.

The dependence of rheological parameters on pressure is more significant than that of density. As the dimensionless excessive pressure changes from zero to ten, the value of m increases by approximately 9%, and K increases by more than 45%.

In [1] the limits of formulas applicability are indicated: (1) — is applicable up to $p = 16$, (4) and (5) — up to $p = 10$. In industrial conditions they try to use systems of interoperation transportation of minced meat with a pumping pressure of less than 1 MPa ($p = 10$). It is known that higher pressure can lead to overgrinding of minced meat and its quality worsening [1]. Pumping equipment is selected to provide a relevant level of pumping pressure [22, 23]. Therefore, the experimental data and the analytical dependencies of the density and rheological parameters of RSM on excessive pressure proposed on their basis from the article [1] are quite sufficient for calculating the hydraulic losses along the length of the pipeline used in industrial conditions for transporting minced meat. Therefore, the first task of the research is solved.

We assume that RSM flow in the pipeline occurs in laminar mode. Pressure losses along the pipeline during laminar fluid flow (including non-Newtonian fluid) can be calculated using the well-known Darcy-Weisbach formula:

$$\Delta P = \frac{\lambda}{2}\cdot\frac{L}{D}\cdot\rho\cdot V^2, \lambda = \frac{64}{\text{Re}}, \qquad (6)$$

where: λ — is the index of friction losses along the pipeline length; L — is pipeline length, m; D — is the pipeline internal diameter, m; ρ — is the liquid density, kg/ m^3; V — is average (in cross-section) velocity of mince flow in the pipeline, m/s; $\text{Re} = \rho\cdot D\cdot V/\mu$ — Reynolds number; μ — is the index of dynamic viscosity of the liquid, Pa·s.

But when transporting a power-law fluid, in particular, minced meat, instead of the usual Reynolds number Re, its analogue for a power-law fluid Re_{PL} should be substituted into formula (6), as in [18,24]:

$$\text{Re}_{PL} = \frac{V^{2-m}D^{m}\rho}{8^{m-1}K\cdot\left(\frac{3m+1}{4m}\right)^{m}}, \qquad (7)$$

Where: Re_{PL} _ is the analogue of Reynolds number for a power-law fluid; V — is the average flow velocity in the pipeline; m — is flow index; D — is the pipeline internal diameter; ρ — is minced meat density; K — is the index of minced meat texture.

This article takes into consideration the fact that the minced meat density does not remain constant, and decreases along the length of the pipeline together with the pressure [1]. Therefore, we will calculate the velocity based on the mass flow rate G (kg/s), which remains constant: $V = G/(\rho\cdot S)$, where $S = 0.25\cdot\pi\cdot D^2$ is the cross-sectional area of the pipeline, m^2. By substituting (7) into (6) and dividing by L, the value of specific pressure losses along the length of the pipeline is obtained:

$$I = \frac{\Delta P}{L} = \frac{2^{3\cdot m+2}}{D^{m+1}}\cdot K\cdot\left(\frac{3\cdot m+1}{4\cdot m}\right)^{m}\cdot\left(\frac{G}{\rho\cdot S}\right)^{m}. \qquad (8)$$

In previously published studies [14,17,18], the values of m, K, and ρ were assumed to be constant along the pipeline length. Therefore, to calculate pressure losses, the value I was simply multiplied by L.

According to formulas (3)–(5), m, K, and ρ depend on the dimensionless excessive pressure p, temperature t, fat content φ, and moisture content W. We assume that in the problem of determining pressure losses, the values φ, W, t, G, D, and L are the parameters. They do not change for the given pipeline and for the sample of minced meat. Then, the value of the specific pressure loss is a function of only one argument — the dimensionless excessive pressure: $I = f(p)$.

To determine the pressure loss along the length of a pipeline when transporting a given sample of minced meat, it is necessary to find a solution to Cauchy problem:

$$\frac{dp}{dY} = f(p), \; p(0) = p_0, \qquad (9)$$

where: Y — is coordinate measured along the pipe axis from the outlet to the inlet, m; p_0 — is dimensionless excessive pressure at the outlet of the pipe.

Next, we assume that the pressure at the outlet is atmospheric, therefore $p_0 = 0$.

The Cauchy problem (9) in general has no analytical solution, therefore a numerical finite-difference method was used, implemented in the Mathcad environment with the help of Given-Odesolve operators combination.

The obtained value of the dimensionless excessive pressure at the pipeline inlet $p(\text{L})$ is the sought-after value of pressure loss along the pipeline length Δp_1. Thus, the second task of the research is solved — a method for calculating hydraulic losses in a pipeline was developed taking into consideration the dependence of minced meat density and rheological parameters on pressure.

For comparison, a simplified calculation was performed, determining the value of $\Delta p_0 = I_0\cdot L$, where the value I_0 was calculated using formula (8). Moreover, m, K, ρ were considered as constant, equal to the corresponding values at atmospheric pressure.

The error in calculating hydraulic losses with and without considering the dependence of minced meat parameters on pressure (full calculation and simplified calculation) was calculated via the formula:

$$\varepsilon = 100\cdot\left(\Delta p_1/\Delta p_0 - 1\right). \qquad (10)$$

As shown, while increasing excessive pressure, the density of RSM changes notably less than does the viscosity. Therefore, a calculation of the hydraulic losses Δp_2 was performed under the condition that the values of m and K depend on the excessive pressure, and ρ along the pipe axis remains constant, equal to its value at atmospheric pressure. The calculation error introduced by the density constancy was estimated using formula (11).

$$e = 100\cdot\left(\Delta p_1/\Delta p_2 - 1\right). \qquad (11)$$

Results and discussion

Figure 1 shows the results of calculations via formula (8) for the dependence of specific hydraulic losses on excessive pressure at six values of RSM mass flow rate. The increase in I with increasing G corresponds to the well-known physical effect of the influence of dynamic pressure on hydraulic losses. Thus, an increase of G from 0.3 to 4 kg/s at $P = 0$ led to an increase of I by 6.7 times, and at $P = 1$ MPa — by 8 times. The increase of I along with excessive pressure growth is a feature of the proposed method. According to Figure 1, at $G = 4$ kg/s, if the excessive pressure rises from zero to 1 MPa, the value of I will increase by 95.4 %. At $G = 0.3$ kg/s, it will increase by 63.2 %.

The physical reason for this phenomenon is that increasing pressure leads to an increase in the minced meat viscosity. The higher the viscosity of the mass, the greater the hydraulic losses. It is necessary to note that while the minced meat moves through the pipeline, the excessive

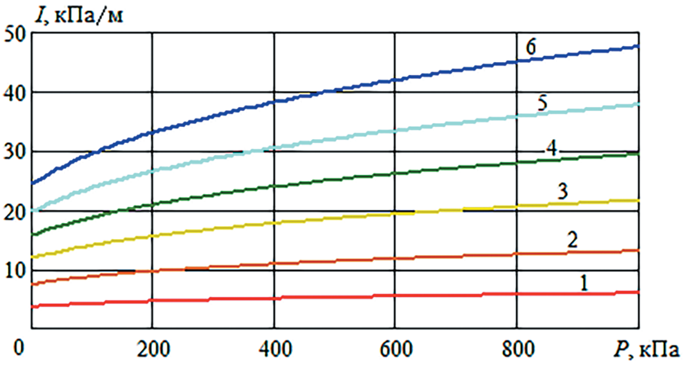

Figure 1. Results of calculating the dependence of specific hydraulic losses on excessive pressure for RSM at 3 °C, $W = 0.673$, $D = 60$ mm and different values of mass flow rate: 1 — $G = 0.3$ kg/s, 2 — $G = 0.8$ kg/s, 3 — $G = 1.5$ kg/s, 4 — $G = 2.2$ kg/s, 5 — $G = 3$ kg/s, 6 — $G = 4$ kg/s

pressure decreases from the inlet to the outlet. Consequently, the viscosity and specific pressure losses decrease.

The results of solving the Cauchy problem (9) are numerically presented in the Figures 2 and 3. In all calculations the pipe length was assumed to be constant, $L = 20$ m. The X coordinate was measured from the pipe inlet: $X = L - Y$. For each set of parameters, the pressure change along the pipe axis was calculated twice: taking into account the dependence of the density and rheological parameters of the FRS on excessive pressure (solid lines in the Figure 2) and without taking this dependence into account (dashed lines in the Figure 3). The latter calculation should be called as simplified.

The dashed lines in the Figure 2 correspond to the hydraulic calculation for a power-law fluid flow, where density and rheological parameters are not dependent on excessive pressure. Therefore, they linearly decrease along the pipe axis. As G increases, hydraulic losses increase. In the Figure 2, the greater G — the higher the dashed lines are located, due to the dependence of density and rheological parameters on pressure. Their deviation from straight lines is noticeable, especially at high mass flow rates.

The RSM density along the pipe axis decreases slightly: by 1.4 % at $G = 0.3$ kg/s and by 5.5 % at $G = 4$ kg/s. Therefore, the increase in the RSM flow velocity from the pipe inlet to the outlet is small. Under the similar conditions, the texture index decreases by 8.6 and 27.9 %, respectively. Both of these latter changes contribute to increase in the Reynolds number along the pipe axis. Figure 3 shows the results of its calculation using formula (7). The calculations were performed taking into account the pressure drop along the pipe axis, found using differential equation (9).

According to Figure 3, the value Re_{PL} increases from 22.0 at the pipe inlet up to 41.8 at the outlet (89.5 % increase) at $G = 4$ kg/s. At $G = 0.3$ kg/s, this increase goes from 1.39 up to 1.59 (14.1 % increase). This indicates that the flow regime in the pipeline remained laminar under all studied conditions. Therefore, using the formulas (6) and (7) is copmletely justified.

All calculations via the proposed method were then performed with varying one of the following factors: pipeline diameter, RSM moisture content, and temperature. For comparison, the Figure 4 shows the dependence of the dimensionless pressure drop across a pipe of a given length L for two diameters, taking into account the dependence of the density and rheological parameters of RSM on excessive pressure (solid lines for $\Delta p_{1)}$ and without this dependence (dashed lines for $\Delta p_{0)}$. It is evident that the solid lines extend significantly above the dashed lines. Moreover, this difference increases along with increasing RSM mass flow rate.

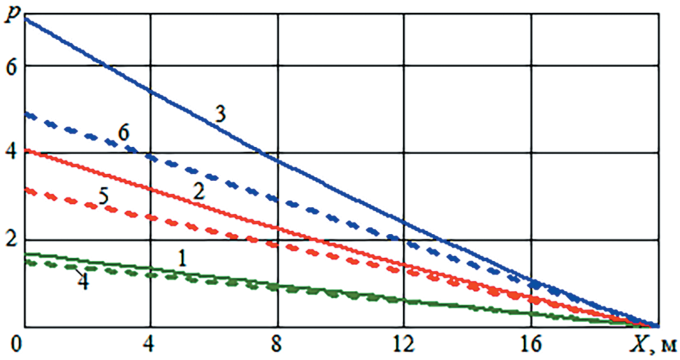

Figure 2. Results of calculating the dimensionless excessive pressure along the pipe axis taking into consideration (lines 1, 2, 3) and not taking into consideration (lines 4, 5, 6) the dependence of the RSM density and rheological parameters on pressure at 3 °C, $W = 0.673$, $D = 60$ mm and different values of mass flow rate: 1 and 4 — $G = 0.8$ kg/s, 2 and 5 — $G = 2.2$ kg/s, 3 and 6 — $G = 4$ kg/s

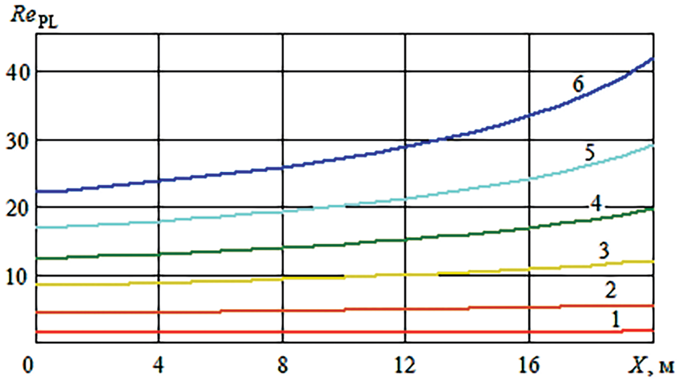

Figure 3. Results of calculating the Reynolds number analogue along the pipe axis at 3 °C, $W = 0.673$, $D = 60$ mm and different values of mass flow rate: 1 — $G = 0.3$ kg/s, 2 — $G = 0.8$ kg/s, 3 — $G = 1.5$ kg/s, 4 — $G = 2.2$ kg/s, 5 — $G = 3$ kg/s, 6 — $G = 4$ kg/s

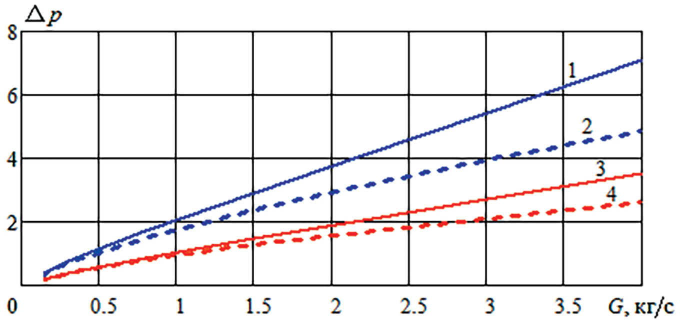

Figure 4. Dependence of the dimensionless pressure drop on RSM mass flow rate at 13 °C, $U = 2.06$ kg/kg and two diameter values: 1 and 2 — $D = 55$ mm, 3 and 4 — $D = 68$ mm; 1, 3 — calculation taking into consideration the dependence of RSM density and rheological parameters on excessive pressure ($\Delta p_{1)}$; 2, 4 — not taking into consideration (Δp_0)

The proposed method for calculating pressure drop during pipeline transportation of minced meat is significantly more complicated than the traditional hydraulic calculation method, because it involves the numerical solution of differential equation (9). The feasibility of its application is evaluated in reference to the pressure drop calculation error value, ignoring the dependence of RSM density and rheological parameters on excessive pressure. The results of calculating this error using formula (10) with varying values of individual factors are presented in the Figures 5 and 6.

In all cases, increasing RSM mass flow rate increases the simplified calculation error. This is caused by increase in dynamic pressure due to G increase. Changing the internal diameter of the pipeline significantly affects the calculation results. Increasing D reduces the dynamic pressure and decreases the simplified calculation error. In the Figure 5, for $G = 4$ kg/s and $D = 55$ mm, the simplified calculation error is 52 %, while for a diameter of 80 mm, it decreases down to 17 %.

Increasing temperature leads to a decrease in RSM viscosity, which leads to a decrease in the specific pressure loss calculated with the formula (8). As a result, the error in the simplified calculation decreases, but not as much as with increasing diameter. In Figure 6, at $G = 4$ kg/s and a temperature of 3 °C, it is 45.6 %, while at 23 °C, it decreases to 33.8 %.

As the moisture content increases, the viscosity of RSM decreases. This also reduces the specific pressure loss and the simplified calculation error. For example, at $G = 4$ kg/s and $U = 1.86$ kg/kg, this error amounts to 49.4 %, at $U = 2.06$ kg/kg, it decreases down to 45.6 %, and at $U = 2.70$ it decreases to 34.7 %.

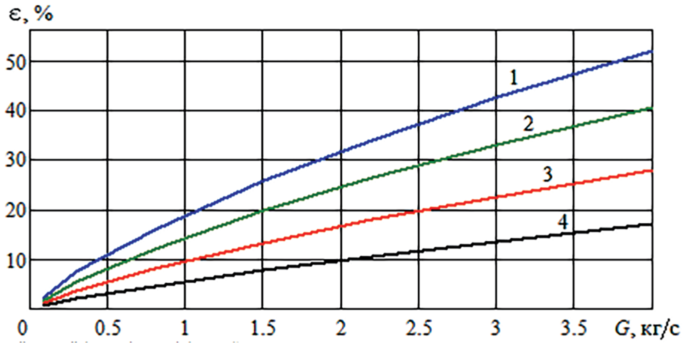

Figure 5. Dependence of the error of the simplified calculation of the pressure drop on RSM mass flow rate at 13 °C, $U = 2.06$ kg/kg and for 4 diameters of pipe: 1 — $D = 55$ mm, 2 — 60 mm, 3 — 68 mm, 4 — 80 mm

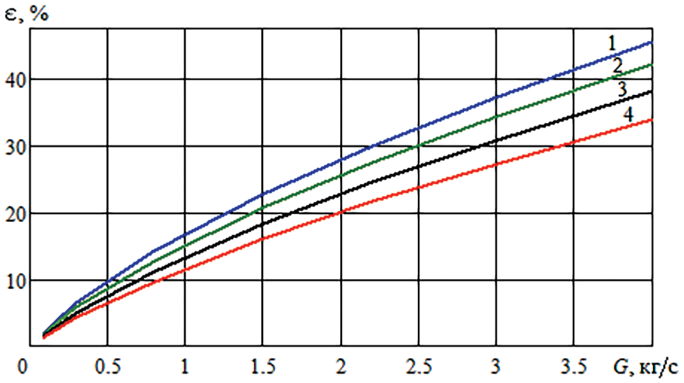

Figure 6. Dependence of the simplified calculation error on RSM mass flow rate at $D = 60$ mm, $U = 2.06$ kg/kg and for 4 temperatures: 1 — 3 °C, 2 — 10 °C, 3 — 17 °C, 4 — 23 °C

Figure 7 shows how the error calculated using formula (11) depends on the mass flow rate of RSM. The conditions used are the same as in Figure 5. It can be seen that assuming RSM density as constant, equal to its value at atmospheric pressure, leads to overestimation of the pressure loss. This is because, in the model used, mince density decrease directly leads only to an increase in RSM flow velocity within the pipeline. As a result, hydraulic losses increase. However, this increase does not exceed 4 % over the entire range of parameters studied.

Note that the error in the simplified calculation ε increases with increasing values of the factors that lead to increased hydraulic losses. To analyze this phenomenon it is necessary to plot another graph.

Δp_0 was chosen as the argument, calculated without taking into account the dependence of RSM density and rheological parameters on excessive pressure. The groups of points are numbered. Each group includes 6 points, which were obtained at six values of RSM mass flow rate from 0.3 to 4 kg/s. Groups of points 1–4 were calculated by varying the pipeline diameter, and 5–8 — by varying the temperature. It is evident that all of the indicated points practically lie on the same line. In the range $\Delta p_0 = 0–4$, the dependence in Figure 8 is close to a directly proportional dependence: $\varepsilon = 10\Delta p_0$. Only at $\Delta p_0 > 4$ does the indicated line deviate slightly downwards from the straight line.

According to the Figure 8, if the pressure loss according to the simplified calculation is $\Delta p_0 > 1$, then the simplified calculation error is $\varepsilon > 10\,\%$; if $\Delta p_0 > 6$, then $\varepsilon > 50\,\%$. This error is unacceptable for engineering calculations. The conducted assessment allows us to conclude that the third objective of the study has been fulfilled.

The Figure 8 enables estimation for how much greater the hydraulic losses are in the extended calculation than in the simplified one. With putting $\varepsilon = 10\Delta p_0$ into formula (10), the approximate estimation of the required dimensionless pumping pressure is obtained:

$$\Delta p_1 \approx \Delta p_0 \cdot \left(1 + 0{,}1 \cdot \Delta p_0\right). \qquad (12)$$

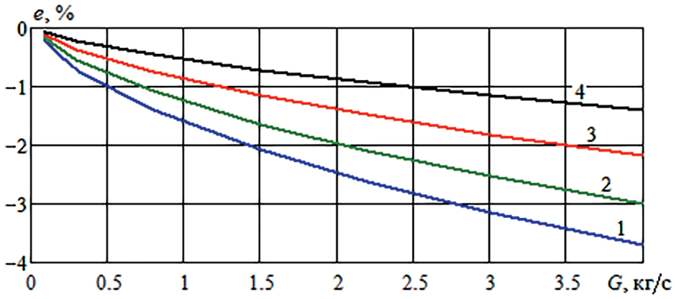

Fig. 7. Dependence of the simplified calculation error e on RSM mass flow rate at 13 °C, $U = 2.06$ kg/kg and for 4 diameters of pipe: 1 — $D = 55$ mm, 2 — 60 mm, 3 — 68 mm, 4 — 80 mm

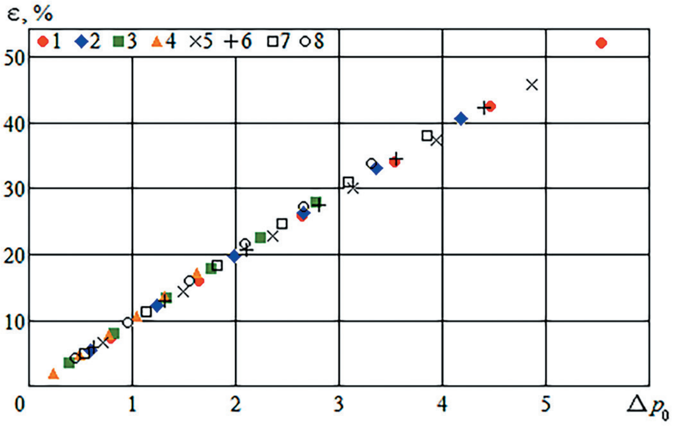

Figure 8. Dependence of the simplified calculation error on the dimensionless value of the pressure drop, calculated without taking into consideration the dependence of RSM density and rheological parameters on the excessive pressure at $U = 2.06$ kg/kg: 1, 2, 3, 4 — $t = 13$ °C; 1 — $D = 55$ mm, 2 — 60 mm, 3 — 68 mm, 4–80 mm; 5, 6, 7, 8 — $D = 60$ mm; 5 — $t = 3$ °C, 6 — $t = 10$ °C, 7 — $t = 17$ °C, 8 — $t = 23$ °C

The practical application of the Figure 8 and formula (12) is as follows. Under the assumption that while feeding the RSM the value $\Delta p_0 = I_0 \cdot L = 3$ (0.3 MPa) is obtained, where the value of I_0 is calculated via simplified method, according to formula (8), without taking into consideration the dependence of RSM density and rheological parameters on excessive pressure. Then, taking into consideration the dependence of RSM density and rheological parameters on excessive pressure, the hydraulic losses will be approximately 30 % greater, $\Delta p_1 \approx 3.9$ (0.39 MPa). It is this pumping pressure that should be taken into account when selecting the appropriate pumping equipment.

It should be noted that the Figure 8 was obtained for the representation of dependence of RSM density and rheological parameters on pressure. For the other types of minced meat the correlation between Δp_0 and ε (and therefore between Δp_0 and Δp_1) may quantitatively differ.

Conclusion

Thus, the purpose set out in the article has been achieved, and all research tasks have been solved. The developed method for calculating hydraulic losses in a pipeline, taking into consideration the dependence of minced meat density and rheological parameters on pressure, includes the following main steps:

1. Determination of the analytical dependence of minced meat density and rheological parameters (flow index m and liquid texture index K) on pressure according to the results of experimental studies — the formulas (3)–(5) should be referred to.
2. Derivation of the formula for specific pressure losses caused by friction along the length of the pipeline being researched (designed), taking into consideration the dependence of m and K on pressure — the formula (8) should be referred to.
3. Mathematical formulation of the Cauchy problem, including a differential equation for dimensionless excessive pressure and its preset value at the pipeline outlet.
4. Solving the Cauchy problem and determining the dimensionless excessive pressure at the pipeline inlet. This value is the required pumping pressure, which (along with the specified flow rate) is referred to in order to select the relevant pump.

The analysis showed that the results of previously conducted and published studies on the relationship between density and rheological parameters of "Russian" sausage mince (RSM) are sufficient to solve the tasks of this article. However, a full calculation for other mince systems will require similar experimental studies.

The error in the full calculation of hydraulic losses (dimensionless pressure losses $\Delta p_{1)}$ using the Cauchy problem (9) is determined by the accuracy of the used approximations and does not exceed 4–5 %. However, the error in the simplified calculation ($\Delta p_{0,}$ ignoring the dependence of density and rheological parameters on pressure) can reach 50 % under certain conditions. This error is unacceptable for design engineering calculations. Therefore, it is necessary to use the calculation method developed in this article. This method is significantly more labor-consuming than the traditional hydraulic calculations, because it requires numerical solving the Cauchy problem. Therefore, an approximate estimate of hydraulic losses increase due to the effect of pressure on the minced meat parameters was proposed.

On the example of minced meat produced for the "Russian" sausages, the influence of temperature, humidity, mass flow rate, and pipeline diameter on the calculation results was studied. In all cases increasing in hydraulic losses leads to increasing the correction required for the calculated pumping pressure. The dependence of ε on the pumping pressure was calculated using a simplified method, which ignores the dependence of the minced meat density and rheological parameters on pressure. In this context ε value represents a correction to the result of the simplified calculation of the pumping pressure, and it can be used for approximate assessment. The percentage by which the pumping pressure calculated with the dependence of the minced meat properties on pressure exceeds the value calculated without taking this dependence into consideration was determined. Formula (12) enables an approximate estimating of Δp_1 by Δp_0 without solving differential equation (9).

It should be noted that the numerical values of corrections obtained in this article are valid for the minced meat used in "Russian" sausages. For other minced meat systems those values may significantly differ. Moreover, it is necessary to take into consideration the hydraulic losses due to local spots of resistance, primarily at the pipeline bends.

REFERENCES

1. Gorbatov, A.V. (1979). Appendix 1. In a book: Rheology of meat and dairy products. Moscow: Food Industry. 384 p. (In Russian)
2. Donya, D.V., Makhacheva, E.V. (2014). Rheological parameters of combined minced meat. *Bulletin of KSAU*, 4(91), 249–253. (In Russian)
3. Bashkirova, T.V., Trofimova, T.P. (2021). *Reasearch of the rheological characteristics of minced meat with vegetative additives.* Current issues of inproving agricultural production and processing technologies. Conference materials collection. Yoshkar-Ola: Mari State University Press. 2021. (In Russian)
4. Cevik, M, Icier, F. (2020). Characterization of viscoelastic properties of minced beef meat thawed by ohmic and conventional methods. *Food Science and Technology International*, 26(4), 277–290. https://doi.org/10.1177/1082013219888300
5. Tsaregorodtseva, E.V. (2021). An effect of the recipe composition on minced meat properties. *Theory and Practice of Meat Processing*, 6(2), 174–182. https://doi.org/10.21323/2414-438X-2021-6-2-174-182
6. Cao, M., Zhang, X., Zhu, Y., Liu, Y., Ma, L., Chen, X. et al. (2022). Enhancing the physicochemical performance of myofibrillar gels using Pickering emulsion fillers: Rheology, microstructure and stability. *Food Hydrocolloids,* 128(5), Article 107606. https://doi.org/10.1016/j.foodhyd.2022.107606
7. Ghafouri-Oskuei, H., Javadi, A., Saeidi-Asl, M.R., Azadmard-Damirchi, S., Armin, M., Riazi, F. et al. (2022). Mechanical attributes, colloidal interactions, and microstructure of meat batter influenced by flaxseed flour and tomato powder. *Meat Science,* 187, Article 108750. https://doi.org/10.1016/j.meatsci.2022.108750
8. Li, K., Wang, L.-M., Cui, B.-B., Chen, B., Zhao, D.B., Bai, Y.H. (2024). Effect of vegetable oils on the thermal gel properties of PSE-like chicken breast meat protein isolate-based emulsion gels. *Food Chemistry,* 447, Article 138904. https://doi.org/10.1016/j.foodchem.2024.138904
9. Wang, X.-x., Wang, L.-y., Li, S.-m., Zhou, Z.-k. (2024). Amelioration of tiger nut insoluble dietary fiber as a partial substitute for fat in meat emulsions: Techno-functional properties and in vitro protein digestibility. *Food Research International,* 197(Part 1), Article 115167. https://doi.org/10.1016/j.foodres.2024.115167
10. Wang, H, Yang, Z., Yang, H., Xue, J., Li, Y., Wang, S. et al. (2022). Comparative study on the rheological properties of myofibrillar proteins from different kinds of meat. *LWT,* 153, Article 112458. https://doi.org/10.1016/j.lwt.2021.112458
11. Zheng, C., Cai, N., Huang, C., Huang, Y., Zou, J., Zhang, G. et al. (2023). Evaluation of amidated pectin as fat substitutes for minced chicken breast: Physicochemical properties and edible quality. *Food Research International,* 173(Part 2), Article 113371. https://doi.org/10.1016/j.foodres.2023.113371
12. Akimova, D., Suychinov, A., Kakimov, A., Kabdylzhar, B., Zharykbasov, Y., Yessimbekov, Z. (2023). Effect of chicken by-products on the physicochemical properties of forcemeat formulations. *Future Foods*, 7, Article 100238. https://doi.org/10.1016/j.fufo.2023.100238
13. Kang, Z.-L., Yao, P.-L., Zhao, S.-M., Hou, Q., Xu, J.-G., Ma, H.-J. (2024). Effect of temperature and sodium bicarbonate combined on aggregation, rheology and conformation of low-salt chicken myofibrillar protein. *LWT,* 204, Article 116417. https://doi.org/10.1016/j.lwt.2024.116417
14. Wang, Y., Liu, N.-n., Li, K., Chen, B., Wang, J.-l., Li, J.-g. et al. (2025). Assessing how the partial substitution of phosphate by modified chickpea protein affects the technofunctional, rheological, and structural characteristics of pork meat emulsions. *Meat Science,* 225, Article 109812. https://doi.org/10.1016/j.meatsci.2025.109812
15. Houška, M., Šesták, J., Jeschke, J., Adam, M., Přidal, J. (1988). *Rheology of minced meat transportation in pipes.* Conference: Progress and Trends in Rheology II. Heidelberg: Steinkopff, 1988. https://doi.org/10.1007/978-3-642-49337-9_163
16. Kogan, V.V., Semenova, L.E. (2019). Engineering rheology in food industry. *Vestnik of Astrakhan State Technical University. Series: Fishing Industry*, 4, 147–156. (In Russian)
17. Okonkwo, V.C., Mba, O.I., Kwofie, E.M., Ngadi M. O. (2021). Rheological properties of meat sauces as influenced by temperature. *Food Bioprocess Technology*, 14, 2146–2160. https://doi.org/10.1007/s11947-021-02709-9
18. Naumov, V.A. (2024). Calculation of pipeline transportation of minced meat depending on the lobe pump performance characteristics. *Vsyo o Myase*, 6, 29–32. https://doi.org/10.21323/2071-2499-2024-6-29-32 (In Russian)
19. Golovanets, V.A., Sachko, N.V., Prokhorenko, V.V. (2005). Study of rheological characteristics of fish raw materials used for the production of fishmeal and oil. *Bulletin of Kamchatka State Technical University*, 4, 253–255. (In Russian)
20. Gorbatov, A.V. (1979). Compression characteristics and density of meat and dairy products. Chapter in a book: Rheology of meat and dairy products. Moscow: Food Industry, 1979. (In Russian)
21. Gorbatov, A.V. (1979). Shear properties of meat and dairy products. Chapter in a book: Rheology of meat and dairy products. Moscow: Food Industry, 1979. (In Russian)
22. Naumov, V.A. (2024). Productivity and energy efficiency of the lobe pump for minced meat pumping. *Vsyo o Myase*, 4, 44–48. https://doi.org/10.21323/2071-2499-2024-4-44-48 (In Russian)
23. Levicheva, O.I. (2025). The analytical model improvement of the food lobe pumps load characteristics. *Journal of Science and Education of North-West Russia*, 11(1), 18–27. (In Russian)
24. Bibok, M., Csizmadia, P., Till, S. (2020). Experimental and numerical investigation of the loss index of a 90° pipe bend for power-law fluid. *Periodica Polytechnica Chemical Engineering*, 64(4), 469–478. https://doi.org/10.3311/PPch.14346

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Completely prepared the manuscript and is responsible for plagiarism.

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