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Ice slurry flow through gate valves – local pressure loss coefficient

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Abstract. The paper presents the calculation results of local pressure loss coefficient in three different models of a gate valve in their two opening positions. The study was carried out on ice slurry with the mass fraction of ice particles of 30%, 25%, 20%, 15%, 10% and 5%. The slurry is considered to be the Bingham Plastic liquid within this study and the local loss coefficient data were provided thanks to the obtained results of the local resistance calculations in the fittings tested in the experimental investigation. The transitional behavior of ice slurry has been detected. The value of the local pressure loss coefficient decreases firstly up until transition point then it remains constant in the turbulent flow regime. The ice crystals content directly determines its value, as the larger ice mass fraction in the mixture, the greater value of the loss coefficient. Declining opening position of the gate valves results in decreasing the value of the loss coefficient data in relation to the Reynolds number for Bingham liquid.

1. Introduction

Ice slurry is a homogenous mixture made up of carrier fluid and microscopic ice crystals smaller than 0.5 mm. Pure water is commonly offered as the carrier liquid, however it is indicated to add depressants such as ethanol, propylene and ethylene glycols or sodium chloride in order to obtain the decreased freezing point of refrigerant. Retaining agent's consistent low temperature while it is cooled results in releasing large latent heat of fusion making the ice slurry an accumulating coolant. Because of its environmental neutrality and high heat transfer coefficient due to the great heat transfer surface area of ice flecks, ice slurry can be applied either in indirect or direct systems.

Providing energy efficient comfort cooling at reduced costs in all investment and operating expenses, the ice slurry installations have been employed in air-conditioning systems for enormous facilities and gold mines. The ice slurry-based HVAC systems has been replacing chilled water ones for over 30 years particularly in East Asian countries like Japan and South Korea [2]. Ice slurry cooling is also a promising technology in brewing and dairy industries. As a direct cooling medium it is widely used in fishing industry, mainly in fish cooling, storage and transportation. Nowadays the greatest ice slurry manufacturers for fish processing are Japan, Iceland and Norway. The fast cooling rate allows medium to suddenly cool vital organs of a patient who is suffering cardiac arrest or expects a surgery that can cause brain damage. Delivering ice slurry to the lungs in order to cool blood maintains organs' safe low oxygen levels thereby leads into prolonging the time needed for medical treatment and preventing ischemic damage.

Nevertheless the ice slurry cooling technology has not been widespread in Poland yet. Lack of knowledge and high investment costs (related to the purchase of the special generator) in comparison with the conventional refrigerator system result in unpopularity of those systems in Poland.

The correct parameters of ice crystals allow ice slurry to achieve its full capability as a refrigerant. As the specific mass fraction of ice particles and the mass flow rate through the various ice slurry-based systems generate unique flow characteristics and flow resistance in straight-line pipes and fittings, it is required to run flow calculations. The ice slurry flow in horizontal pipes have been already described in detail in numerous publications [1, 5, 15, 19]. Bédécarrats et al. [1], Grozdek et al. [5], and Wang et al. [19] analyzed the pressure drop in of ice slurry made on the basis of approximately 10% aquatic solutions of ethyl alcohol. They noticed that the pressure drop depends on the ice particles mass fraction and the flow velocity of slurry. There are limited references to the local resistances and flow of ice slurry through pipeline elements, such as bends and elbows [1, 15, 16], pipe expansion and pipe contraction [11, 14, 16], liquid distributors [13], tees [13, 16], poppet valves [12] and ball valves [9]. Mika [11-14] investigated the influence of ice mass fraction on the local resistance coefficient. The ice content does not determine the value of local loss coefficient up to the certain opening position of poppet valves and ball valves. Exceeding that rotating angle results in dependence of coefficient k on the ice particles mass fraction.

Nevertheless there are no data referring to the ice slurry flow through a gate valve. The papers published so far pertain to the flow of other non-Newtonian liquids through butterfly valves [8], diaphragm valves [6, 7], gate valves [18] and globe valves [3, 4, 18].

The body of literature [1, 3, 11-16, 19] indicates that ice slurry evinces non-Newtonian behavior for mass fraction of ice higher than 10%. There are suggested several rheological models in order to evaluate the flow of ice slurry, however Mika [14] detected that ice slurry behavior in pipes is approximated by Bingham liquid.

The paper focuses on the analysis of calculation results of the local resistances in three models of gate valves (DN15, DN20, DN25). The study was carried out on ice slurry with the mass fraction of ice flecks of 5%, 10%, 15%, 20%, 25% and 30%.

2. Experimental investigation

The scheme of the experimental setup for studying ice slurry flow through the gate valve is shown in Figure 1.

Ice slurry precipitated in aquatic solution of ethyl alcohol in the ice generator, where water and the added depressant were cooled. Due to the evaporation of the circulating Freon, ice crystals were generated on the evaporator internal surface area (10) resulting in increasing the concentration of ethanol in slurry thereby decreasing the freezing point. The mixture pumped into the storage tank (8) was being stirred in order to maintain its homogenous character and to avoid ice clumping. The prepared ice slurry was then being transported by the main pump (9) towards the subject valve (1), which was inserted into the middle of a 4.9 meters long straight-axis pipe. The measurement section obtained two 0.5 meters long run-up segments with the fitting assembled between them. The ice slurry mass flow through the analysed gate valve was regulated by the main pump inverter (11) or by piping medium back into the tank through a bypass line (6).

The mass flow rate was measured with the Siemens MASS 2100 flow sensor (5), which in addition unceasingly delivered the density measurement of the flowing coolant, whereas the pressure in the installation and the pressure drop measurement was realised using the Fuji Electric FKC differential pressure transmitters (3). In order to detect air bubbles and to avoid measurement error, impulse pipes were transparent and non-isolated. Besides ice slurry density measurement and its temperature measurement were particularly significant as both of them determined the specific ice particles mass fraction since the six different mass fractions of ice flecks were taken into consideration during the experimental studies. The Hart Scientific Pt100 temperature sensor (4) was installed in the thermometric sleeve located at the inlet of the measurement section where it provided an accurate measurement of ice slurry with the ice mass fractions of 30%, 25%, 20%, 15%, 10% and 5%. Their content was prearranged thanks to the ethyl alcohol curve of freezing point evolved by Melinder [10].

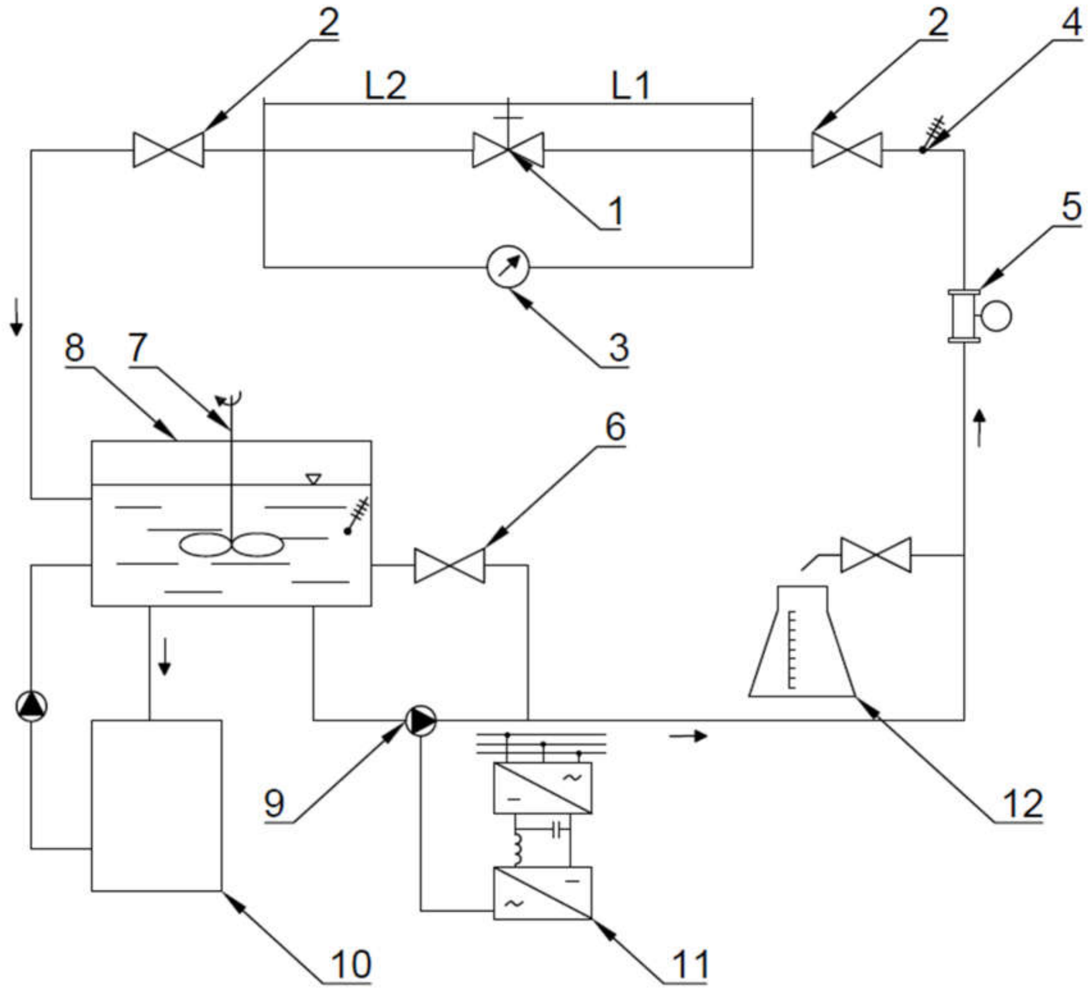

Figure 1. Experimental stand scheme: 1 – gate valve; 2 – control valve; 3 – measurement of pressure; 4 – measurement of temperature, 5 – mass flow meter; 6 – bypass; 7 – mixer; 8 – storage tank;9 – main pump; 10 – ice slurry generator; 11 – main pump inverter; 12 – control of ice share

Every scheduled change of ice mass fraction during performed study was preceded by generating ice slurry with a demanded fraction in the storage tank. Preventing ice lingering or melting in the measurement segment required supervising perpetually its mass fraction and the density of the coolant. Ice crystals were suspended within a 10.6% hydrous solution of ethanol and the slurry flow velocity exceeded 0.25 m/s in the measurement area due to providing homogenous flow of coolant through the investigated valve.

The experimental study of the ice slurry flow resistances was carried out on three different models of gate valves and their two opening positions. Those settings subtended the stem rotation angles of 360° and 720°. Adjusting the valves in those aperture angles and ensuring a minimum mass flow rate of ice slurry in the measurement section between 0,03 kg/s and 0,35 kg/s allowed to accomplish both the laminar and turbulent flow in the studied valves. The areas and circumferences of the individual positions of analysed fittings are presented in Table 1.

Table 1. Opening parameters of the investigated gate valves.

Gate valve	DN15		DN20		DN25	
Rotation angle	360°	720°	360°	720°	360°	720°
Valve position	1	2	1	2	1	2
Area [mm^2]	155,52	109,57	203,14	134,53	398,96	310,3
Circumference [mm]	46,69	45,6	57,98	55,72	74,34	73,05

Figure 2 shows the actual position of the disc against the body of the gate valve at a certain rotation angle adjustment.

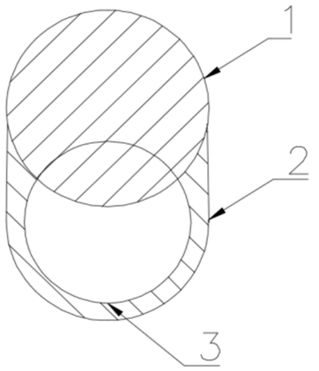

Figure 2. Cross-sectional diagram of the DN25 gate valve (720° angle adjustment): 1 – disc; 2 – body; 3 – flow cross section.

3. Study methods

The local resistances in the gate valves were determined by the measured values of the ice slurry flow resistances while flowing through the measurement section (Δp_{meas}) and the friction resistances in the run-up lengths with the distance L_1 and L_2 and in the entire measurement line of length L (Δp_L). The local resistances in the fitting are formulated as follows:

$$\Delta p_z = \Delta p_{meas} - \Delta p_L \frac{L_1 + L_2}{L} \tag{1}$$

The examined block was composed of one of the three available gate valve models described in Table 1 and the straight-line flow stabilization pipes (of combine length L) with internal diameters of ϕ16 mm, ϕ20 mm, ϕ26 mm. Those run-up pipes allowed ice slurry to obtain its fully developed path-velocity decomposition for both laminar and turbulent flow in the measurement area.

Achieving the laminar flow of the coolant through the pipe ahead of the analysed fitting and through the valve itself entailed either a fully open position of the regulating valve or its low rotation angle adjustments. Thereby the experimental studies were carried out for both one and two complete turns of the valve stem nut, while the ice slurry flow area compromised at least 50% of fully open gate valve. The values of the measurement lengths and the locations of the measure stub pipes were adopted from the studies conducted within [11, 14] concerning ice slurry flow resistance in sudden pipe expansions. In order to measure flow resistances of the ice slurry with a mass fraction of ice between 5% and 30% in the measurement section.

Determining the value of the pressure drop in the individual gate valves allowed to set down the local pressure loss coefficient in the fitting. That parameter was obtained with equation (2).

$$k = \frac{2 \cdot \Delta p_z}{pV^2} \tag{2}$$

where

Δp – local resistance in the gate valve, [Pa]

ρ – ice slurry density, $[\frac{kg}{m^3}]$

V – ice slurry flow velocity through the gate valve. $[\frac{m}{s}]$

In the body of literature, the value of the local pressure loss coefficient in any fitting is usually related to the Reynolds number. As ice slurry is considered to be the Bingham Plastic liquid within this study, the Reynolds number is defined as:

$$Re = \frac{\rho VD}{\mu_p} \tag{3}$$

where

D – hydraulic diameter, [m]

μ_p – ice slurry plastic dynamic viscosity. [Pa·s]

The dynamic viscosity of the fluid given in equation (3) is determined by formula (4) [11, 15]:

$$\mu_p = 0.0035 + 0.0644(x_s) - 0.7394(\,x_s)^2 + 5.6963(x_s)^3 - 19.759(x_s)^4 + 26.732(x_s)^5 \tag{4}$$

where

x_s – ice mass fraction. [-]

The equation (4) refers to ice slurry made on the base of 10.6% solution of ethanol and its ice particles with a diameter of 0.125 mm.

4. Calculation results

The obtained results of the local resistance calculations (Figure 3) provided the values of local pressure loss coefficients in the gate valves tested in the experimental investigation. The local resistance value depends on the ice particles content (the higher ice mass fraction, the higher their values). Figure 4 - 6 presents the transitional behavior of ice slurry with the ice mass fractions of 30%, 25%, 20%, 15%, 10% and 5% in the partially open DN15, DN20 and DN25 valve in comparison with the one calculated for water (based on [17]) and obtained for laterite and gypsums suspensions in a fully open DN25 gate valve [18]. The comparison to the current calculation results obtained for DN15 and DN20 gate valves are not attached, as the experimental studies performed within the body of literature were not carried out on such small valves [3, 4, 6, 8].

Figures 4 – 6 present the fully-developed turbulent flow of water through the individual gate valves in either of their two positions. Position 1 applies to the valve's stem rotation angle of 360° and in an analogical manner position 2 pertains to the angle of 720°.

The transitional behavior of ice slurry has been detected on all of the studied models of the gate valves and variability course of the local loss coefficient coincides with the conclusions presented in the body of literature involving the determining the loss coefficient in any fitting inserted in the non-Newtonian liquid-based installation [3, 4, 6, 7, 8, 11, 13, 14, 16, 18]. The value of the loss coefficient drops while the Reynolds number increases within the laminar flow range. Their values in the area of laminar flow are dependent on the ice flecks content - the larger ice mass fraction in the mixture, the greater value of the loss coefficient. The transition from laminar to turbulent flow proceeds in region, where the loss coefficient curves deviate from the tendency of falling and the studied parameter takes a low constant value. The values of the ice slurry local loss coefficient in turbulent region are approximated to the ones of Newtonian liquid. Declining opening position of the gate valves results in decreasing the value of the loss coefficient data in relation to the Reynolds number.

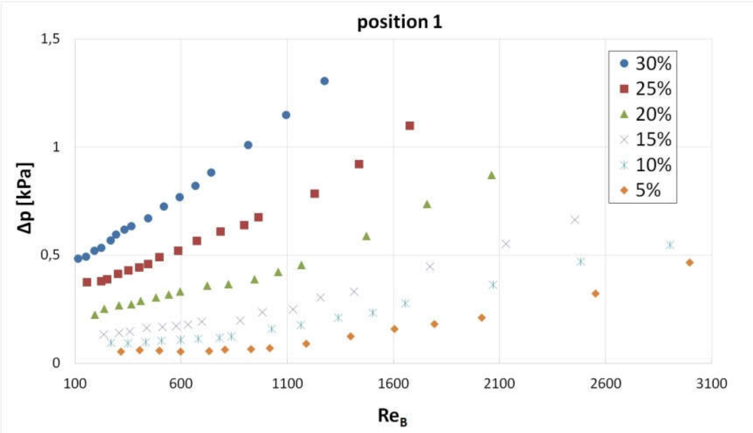

Figure 3. Comparison of the local resistance in DN25 gate valve and the Reynolds number for Bingham liquid.

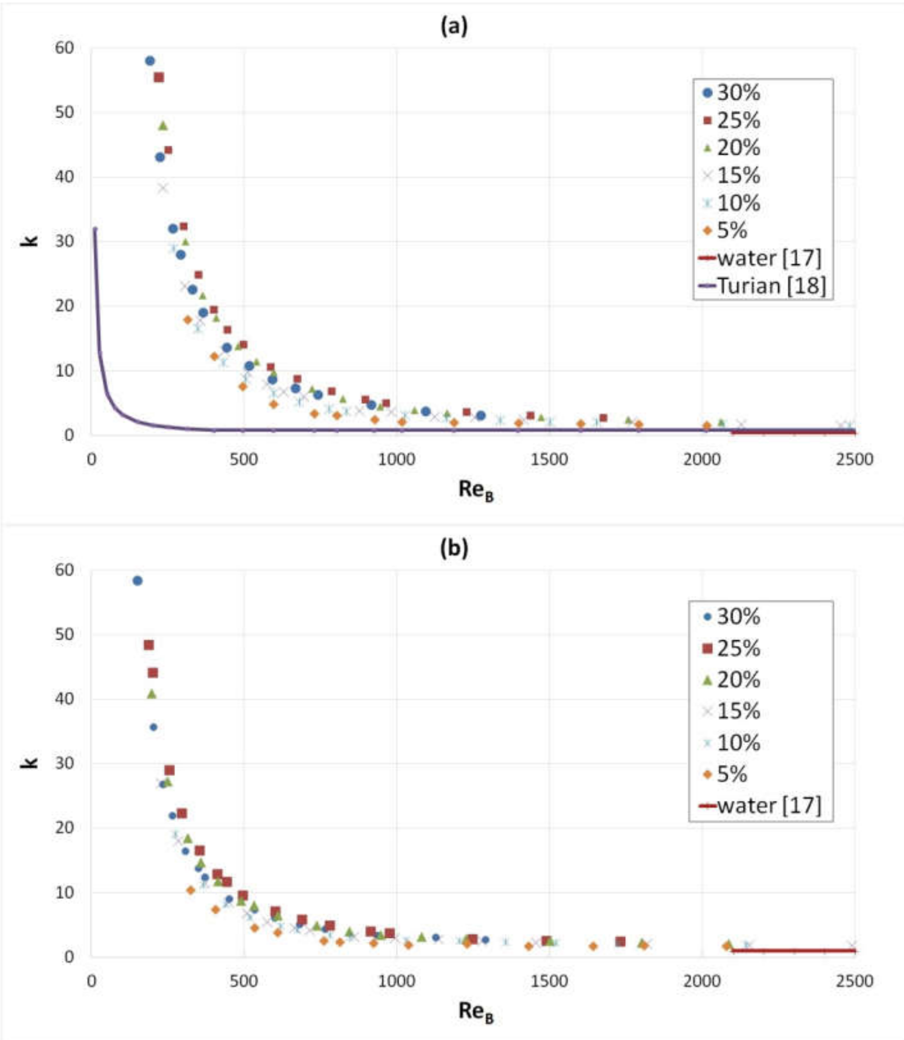

Figure 4. Experimental results of the loss coefficient obtained for DN25 gate valve in: (a) position 1, (b) position 2

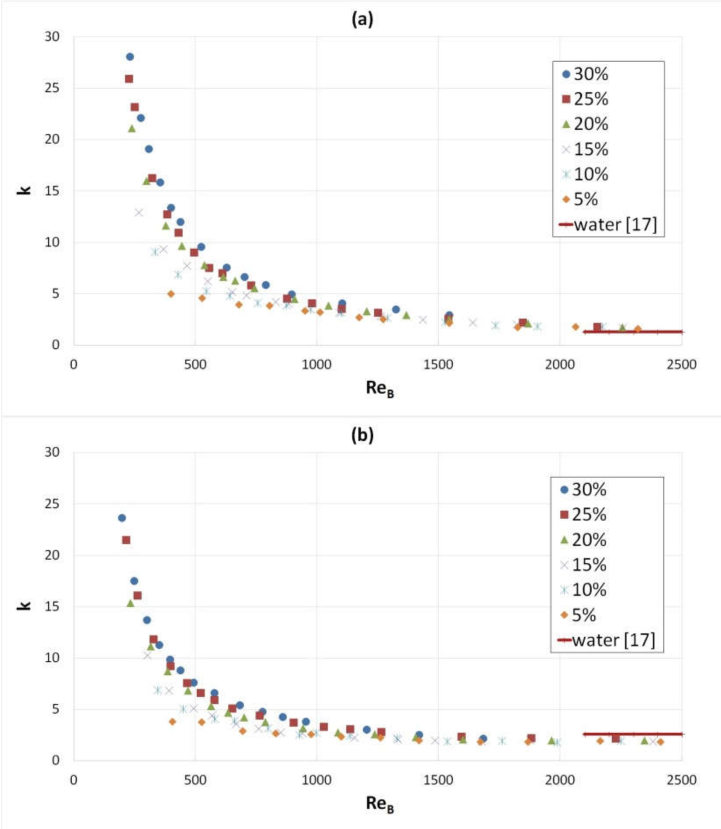

Figure 5. Experimental results of the loss coefficient obtained for DN20 gate valve in:
(a) position 1,
(b) position 2

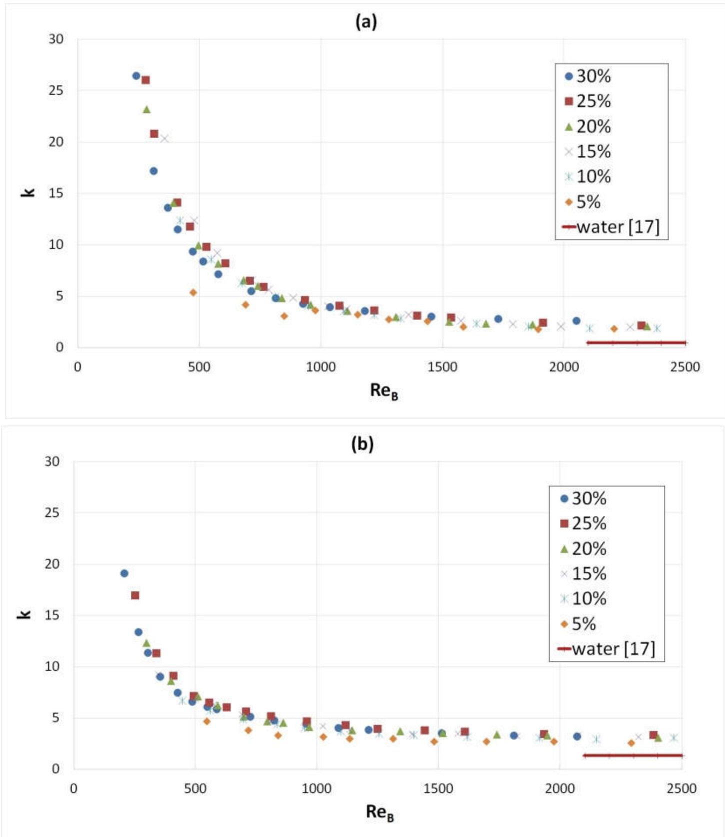

Figure 6. Experimental results of the loss coefficient obtained for DN15 gate valve in:
(a) position 1,
(b) position 2

5. Conclusions

On the basis of the results of experimental studies it was evaluated that up to the Reynolds number of ca. 500 the value of the local loss coefficient obtained for position 1 are definitely higher than for position 2. Ice slurry with 5% content of ice particles is an exception as it is characterized by the smallest variability of the coefficient in the area of the laminar flow. The local loss coefficient for the remaining content of ice particles achieve overwhelmingly larger values in the laminar region than in the turbulent one. The chosen method of calculation and the minimal Reynolds number adopted in the work result in obtaining larger values of this coefficient in the laminar flow for the DN25 valve than for smaller ones. The variability course of the local loss coefficient in turbulent range coincides with the one obtained for Newtonian liquid. The dependency of loss coefficient on ice content in the area of laminar flow result from the ice slurry viscosity, which grows with refrigerant's ice crystals content.

The functions provided in literature do not delineate closely the results obtained within this paper though. Carrying out the experimental investigation on slurries with different viscosities flowing through the gate valve in its fully open position, other researchers adopted Ostwald De Waele rheological model, used the Metzner-Reed generalized Reynolds number and related it to the velocity ahead of the studied fitting. In view of the above, those discrepancies led to the departing their experimental results from ours.

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