TECHNICAL TRANSACTIONS 1/2018
MECHANICS
DOI: 10.4467/2353737XCT.18.016.7967
SUBMISSION OF THE FINAL VERSION: 20/12/2017

Lena Krawczyk
Marlena Sołek (marlena.solek@pk.edu.pl)
Institute of Thermal and Process Engineering, Faculty of Mechanical Engineering, Krakow University of Technology

Łukasz Mika
Department of Thermal and Fluid Flow Machines, Faculty of Energy and Fuels, AGH University of Science and Technology.

ICE SLURRY FLOW IN BALL VALVES

PRZEPŁYW ZAWIESINY LODOWEJ PRZEZ ZAWORY KULOWE

Abstract

This paper presents the results of experimental studies of the flow resistance of slurry ice flowing through ball valves. Loss coefficients in ball valves were determined from experimental investigations. The study focused on 1/2", 3/4" and 1" ball valves at two valve positions (20° and 30°). The ice mass fraction in the studied ice slurry ranged between 5% and 30%.

Keywords: ice slurry, ball valve, Bingham model, laminar flow

Streszczenie

W pracy przedstawiono wyniki badań doświadczalnych oporów przepływu zawiesiny lodowej w zaworach kulowych. Na podstawie wyników badań doświadczalnych wyznaczono wartości współczynników strat miejscowych w badanych zaworach. W badaniach wykorzystano przelotowe zawory kulowe o średnicach 1/2", 3/4" oraz 1" przy dwóch pozycjach zamknięcia (20° i 30°). Udziały masowe drobinek lodu w zawiesinie w badaniach wynosiły od 5 do 30%.

Słowa kluczowe: zawiesina lodowa, zawór kulowy, model Binghama, przepływ laminarny

1. Introduction

Ice slurry, also known as binary ice, is a mixture containing a liquid and small ice particles which are usually less than 0.5 mm in size. Water, which may contain a freezing-point depressant, is most often the base fluid. Frequently used freezing-point depressants include, for example, ethyl alcohol. Other possible additives include: methanol, ethylene glycol, propylene glycol and sodium chloride [1, 6, 10]. Ice slurry is mainly used as a refrigerant in intermediate refrigeration systems. It is also used in applications where its excellent 'cold' storage properties can be taken advantage of [1, 2].

The mass fraction of ice particles in ice slurries may vary – this determines their rheological properties [1, 2, 6, 10]. Most researchers believe that ice slurry with mass fraction of ice (by mass) of up to 15% exhibits the properties of a Newtonian fluid (similar to those of water), while at higher mass fractions of ice, its properties resemble those of a non-Newtonian fluid [6, 10]. One of several rheological models must be used to describe the rheological properties of ice slurries. The most frequently used models include those proposed by: Bingham [6, 10], Casson [4] and Ostwald-de Waele [3]. In this paper, Bingham's model will be used to describe the rheological properties of the ice slurry. This model has been selected because, taking into consideration an analysis of pipe flow curves, it best describes the rheological properties of ice slurry with an aquatic solution of ethyl alcohol as the base fluid [6, 10].

The authors of papers concerning this topic have presented results of experimental studies of ice slurry flow resistances in most basic pipeline elements, such as straight sections [11, 12], bends and elbows [10], expansion and contraction joints [7, 9] as well as poppet and ball valves (mainly in the turbulent flow range) [6, 8]. Paper [6] presents sample values of local loss coefficients for ice slurry with ice fractions ranging between 5% and 30% during its flow through a straight DN20 ball valve for aperture angles of 25° and 35°. In the turbulent flow area, the authors reported high levels of consistency between the calculated values of the local loss coefficients and the theoretical values given in [13]. However, the local loss coefficients in the valves referred to the velocity of the ice slurry in the pipeline downstream of the valve. Therefore, it is impossible to analyze any phenomena characteristic of ice slurry flow directly in the valve itself. Most experimental studies which focus on flow resistance in the ball valves described in [6] concern the turbulent flow range.

The main conclusion to be drawn from a review of the available literature on ice slurry flow in all pipeline fittings is the fact that the values of local loss coefficients for the turbulent flow area approximate the theoretical values given in literature for Newtonian fluids [6, 7, 9, 10]. In ball valves, local loss coefficients for the flow of ice slurry with different ice fractions in the turbulent range are consistent with the theoretical values given in [13] for Newtonian fluids with regard to most valve aperture angles. Another conclusion to be drawn from the analysis of literature is that the ice slurry flow resistance increases in a valve when the ice particles cumulate in the almost fully closed ball valve (right before the valve is fully closed). This is probably due to the presence of ice particles which might hamper ice slurry flow through the valve at high valve closure angles [9].

In literature, there are no reports on comprehensive studies of ice slurry resistances in ball valves in the laminar flow range of various ice fractions. Furthermore, the measured ice slurry flow resistances in valves have not referred to the actual velocity of ice slurry flow in the valve itself.

2. Experimental setup

In order to measure the flow resistance of the ice slurry in ball valves, an experimental stand was used which enabled the flow resistance of the mixture to be investigated in various pipeline fittings (e.g. Y-pipes, distributors, contractions, expansions and valves). The set-up was quite advanced. Only part of the entire experimental set-up was used to measure ice slurry flow resistances in a ball valve (Fig. 1). Pumps installed in the pipeline drive the flow of ice slurry through the system (1). Refrigerant is generated in the ice slurry generator (2) and collected in the buffer tank (3), from where it is pumped towards the investigated valve (8). The tank is fitted with mixers (3) which are designed to maintain a homogenous composition of the ice slurry. Before the ice slurry is generated, it is necessary to prepare the essential, exchangeable elements of the test stand, such as the investigated ball valve (8) and the necessary measurement equipment.

Among the measurement devices used in the experimental setup were PT100 temperature sensors (7) used to measure the temperature of the ice slurry flowing through the system. In order for the measurements to be accurate, the sensors were previously calibrated using a Beamex MC2 calibrator. The PT100 sensors were placed in thermometric sleeves. Other measurement devices used at the stand were Fuji Electric pressure difference sensors (9) with measurement ranges of 0-1 kPa, 0-6 kPa and 0-32 kPa. 4 mm pressure impulse nozzles were used in the studies due to the presence of ice particles. Non-insulated, transparent impulse ducts (10) were used for measurements using the nozzles. The transparent duct made it possible to verify that no air bubbles formed in the slurry – it is essential to detect any air bubbles to ensure that the measurement results are accurate, as the presence of air bubbles often causes measurement errors. The measurement of the mass flux of the ice slurry and its density was possible with the use of the MASSFLO MASS 6000 mass flow meter (5).

The ice slurry studied in the paper was produced using a 10.6% aquatic solution of ethyl alcohol.

When studying ice slurry flow, it is essential to determine the mass fraction of ice in the slurry. Several methods can be used to determine the content of ice particles, including calorimetric measurements, the use of the freezing curve of an aquatic solution of ethyl alcohol [5] and measurements of the density of the slurry using a mass flow meter [6, 10]. All three methods were used in this paper. The freezing curve and measurements of slurry density were used for continuous measurements, whereas the calorimetric method, which is more accurate but more problematic for continuous measurements, was used to verify the results of the primary method.

Ice slurry consists of a solid phase, with lower density, and a liquid phase. It is necessary to ensure that its composition is homogeneous. Due to the content of ice particles in the ice slurry, it is essential to keep stirring it. The stirring may, however, have the undesirable effect of aeration. As a result, a three-phase mixture is created – this may distort flow resistance measurement results. In order to avoid the aeration of the ice slurry, a special method was used whereby the surface of the liquid in the tank was stabilised using a large float. During the stirring process, the float was located on the surface of the ice slurry in the tank, stabilising it and thus minimising aeration. This method does not fully resolve the problem, hence the need to use rotating speed adjusters to control the speed of the mixers. The correct mixing speed was chosen by means of experimentation, whilst at the same time, controlling the content or air in the slurry on a continual basis. The use of the float and the adjustment of the rotation speed of the mixers made it possible to eliminate the aeration of the ice slurry [6, 10].

The problem of maintaining a homogenous composition of the ice slurry also applies to distribution pipelines. It is necessary to ensure that the flow velocity is never lower than the velocity necessary to ensure the homogeneity of slurry composition. The results presented in [2] suggest that – regardless of the mass fraction of ice – below the velocity of 0.15 m/s, the flow of the ice slurry corresponds to the structure of moving sludge.

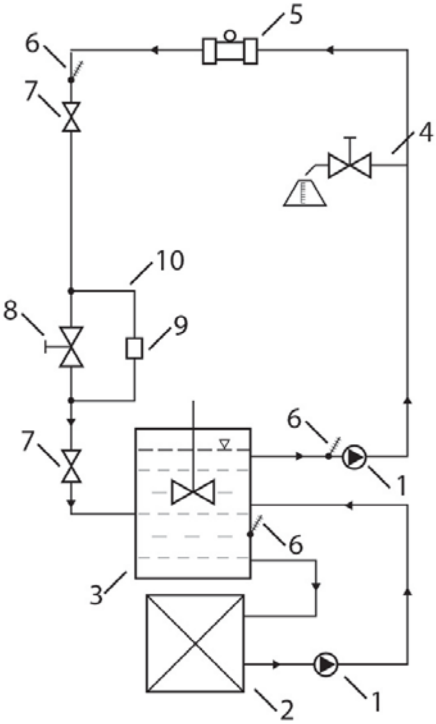

Fig. 1. Outline of the experimental setup 1 – pump, 2 – ice slurry generator, 3 – ice slurry buffer tank with mixers, 4 – ice fraction control, 5 – MASSFLO MASS 6000 mass flow meter, 6 – PT100 temperature sensor with a digital display, 7 – cut-off valve, 8 – the investigated ball value, 9 – Fuji pressure difference transducer, 10 – transparent impulse ducts

3. Results of experimental studies

The experimental studies on the ice slurry flow velocity relied on three ball valves with diameters of 1/2", 3/4" and 1", which were fitted in a copper pipeline with inner diameters of 16 mm, 20 mm and 26 mm, respectively. A series of measurements of flow resistances for ice slurry with the ice fractions of 5%, 10%, 15%, 20%, 25% and 30% were conducted for each ball valve at a closure angle of 20° and 30°. The actual opening position was controlled using a handle with an angle scale. The ball valve closure angles of 20° and 30° enabled the generation of laminar flows through the valve. Figure 2 shows the actual position of the ball against the valve body at a certain rotation angle adjustment.

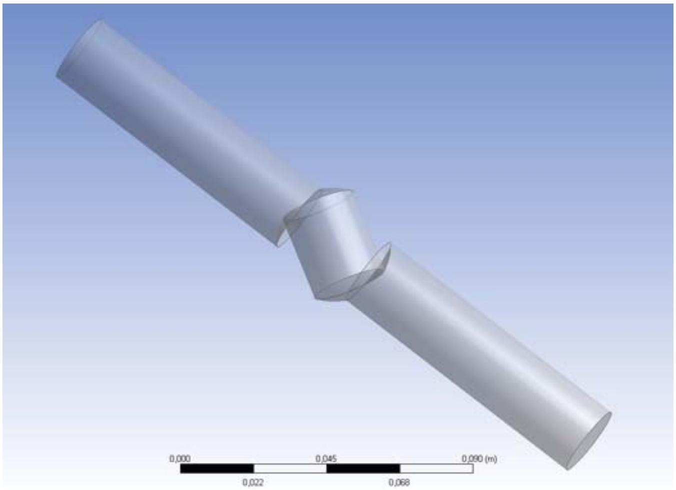

Fig. 2. Model of 1" ball valve at an angle of 30°

The experimental studies also focused on measuring the flow resistances in the ball valve Δp_{meas} as the sum of local resistances along with friction resistances in straight-line sections with distances L_1 and L_2 (downstream and upstream of the valve), as well as friction resistances Δp_L within a straight-line section with length L. Later, local resistances at the ball valve were determined on the basis of formula (1):

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

The local loss coefficients for ball valves for both valve closure angles were determined using equation (2):

$$k = \frac{2\Delta p}{\rho_{zl} w^2} \tag{2}$$

where w is the velocity of the ice slurry [m/s], and ρ_{zl} is the measured density of the slurry [kg/m^3].

The Reynolds number for Bingham fluids was used in the graphs to present the results of experimental studies and of the calculations of local loss coefficients for the ice slurry in the ball valves. It was represented with equation (3):

$$\mathrm{Re}_B = \frac{\rho_{zl} w D}{\mu_p} \tag{3}$$

The dynamic coefficient of plastic viscosity in equation (3) for an ice slurry prepared on the basis of a 10.6% solution of ethyl alcohol and mid-sized 0.125mm ice particles was determined experimentally on the basis of pipe flow curves and is represented with equation (4) [6, 10]:

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

where x_S represents the content of ice particles in the slurry [-].

The hydraulic diameter D in correlation (3) was determined for all three ball valves and two closure angles (20° and 30°) from equation (5), taking into consideration the curve of the free surface area of the flow of ice slurry through valve A [m^2] and the circumference of that surface *Circ* [m]:

$$D = \frac{4A}{Circ} \tag{5}$$

The dimensions of all the valve elements were represented in the Ansys software program – this made it possible to determine both values from equation (5) necessary to calculate the hydraulic diameter for the two valve positions. Table 1 presents the values of *A* and *Circ* for two valve closure angles (20° and 30°) for 1/2", 3/4" and 1" valves obtained from Ansys.

Table 1. Values of ***A*** and ***Circ*** for two closure angles of 1/2", 3/4" and 1" valves

Valve/position	A [m^2]	Circ [m]
1/2"/20°	$112.9\cdot10^{-6}$	$36.8\cdot10^{-3}$
1/2"/30°	$88.3\cdot10^{-6}$	$33.6\cdot10^{-3}$
3/4"/20°	$177.3\cdot10^{-6}$	$46.0\cdot10^{-3}$
3/4"/30°	$139.5\cdot10^{-6}$	$42.1\cdot10^{-3}$
1"/20°	$325.5\cdot10^{-6}$	$62.2\cdot10^{-3}$
1"/30°	$257.9\cdot10^{-6}$	$57.1\cdot10^{-3}$

Figs 3, 4, 7, 8, 11 and 12 present the relationship between the pressure drops in the 1/2", 3/4" and 1" ball valves (at closure angles of 20° and 30°) and the velocity in the valve of ice slurry with mass fractions of ice of 5%, 10%, 15%, 20%, 25% and 30%. Figs 5, 6, 9, 10, 13 and 14 present the relationship between local loss coefficients in the 1/2", 3/4" and 1" ball valves (at closure angles 20° and 30°) and the Reynolds number from the Bingham model for ice slurry with a mass fraction of ice of 5%, 10%, 15%, 20%, 25% and 30%. In the turbulent flow range, the local loss coefficients for the flow of ice slurry through the ball valves was compared to the values of those coefficients found in literature [13] for Newtonian fluids.

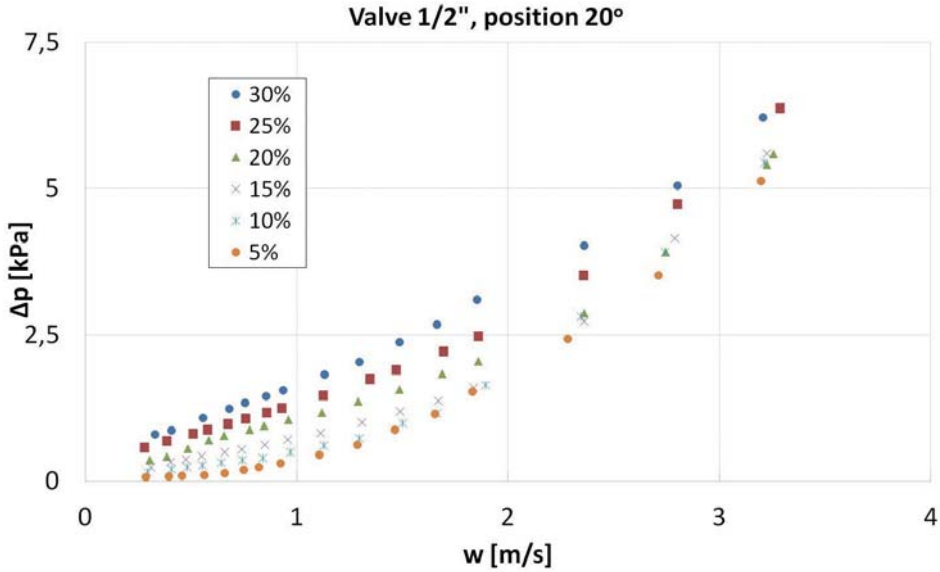

Fig. 3. Relationship between the pressure drop in the 1/2" valve at an angle of 20° and the velocity of the ice slurry in the valve for various ice fractions

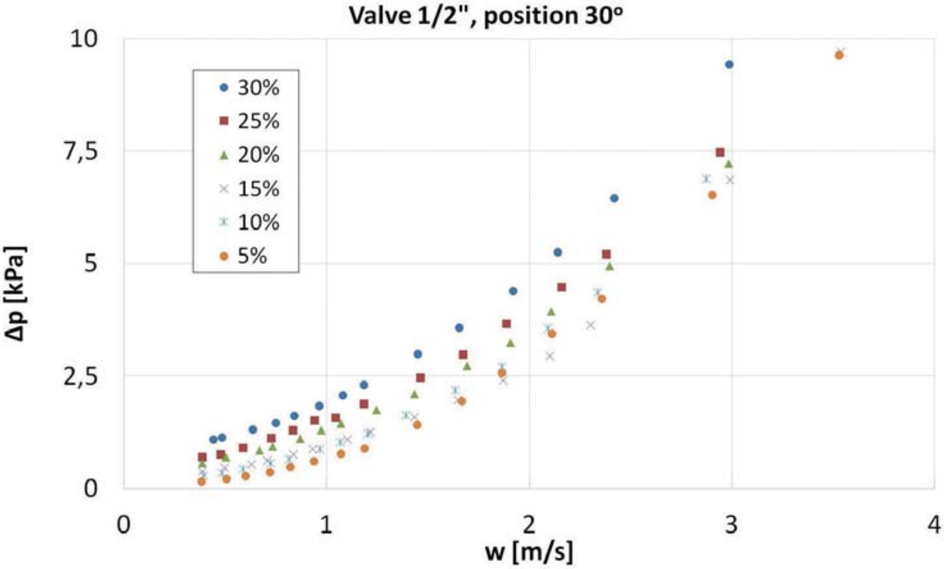

Fig. 4. Relationship between the pressure drop in the 1/2" valve at an angle of 30° and the velocity of the ice slurry in the valve for various ice fractions

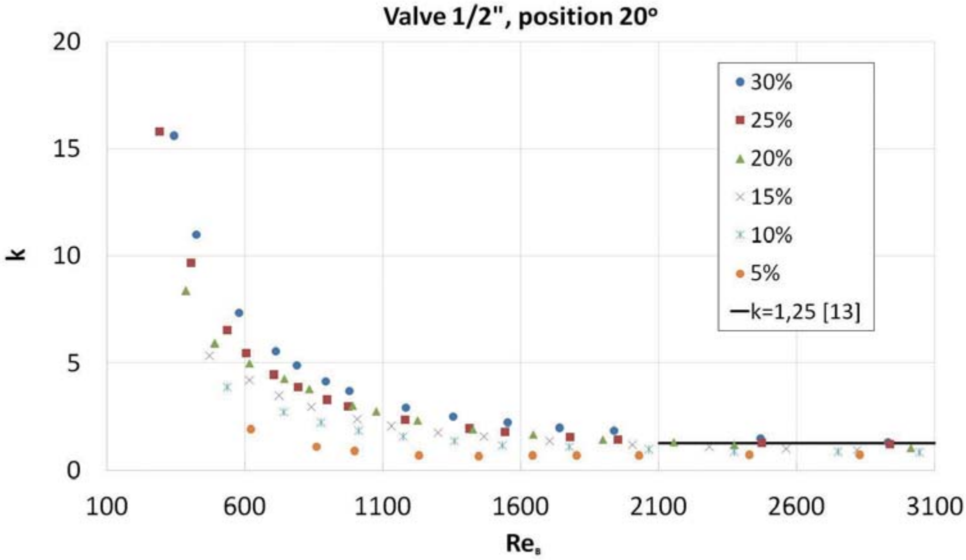

Fig. 5. Relationship between the local loss coefficients in the 1/2" valve at an angle of 20° and the Reynolds number from the Bingham model for various ice fractions

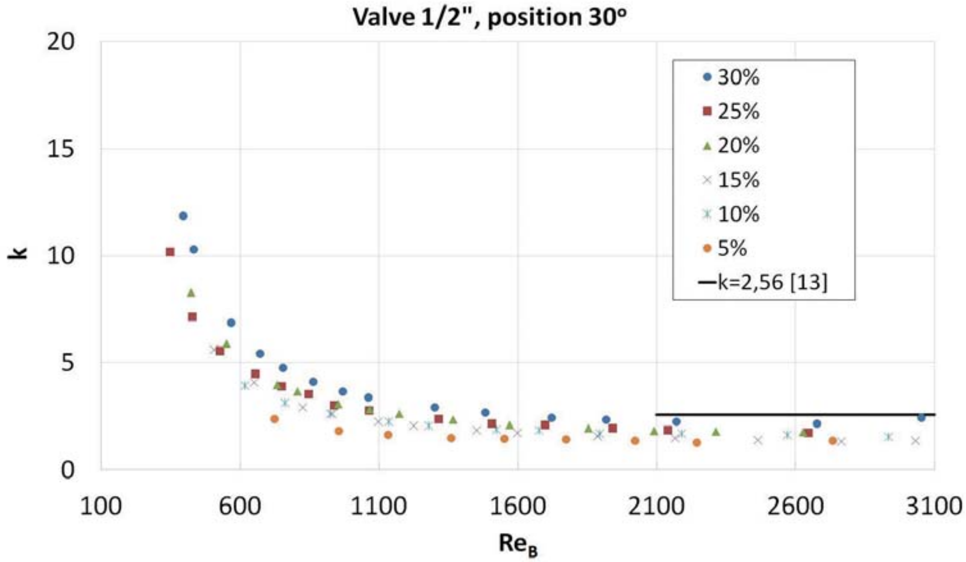

Fig. 6. Relationship between the local loss coefficients in the 1/2" valve at an angle of 30° and the Reynolds number from the Bingham model for various ice fractions

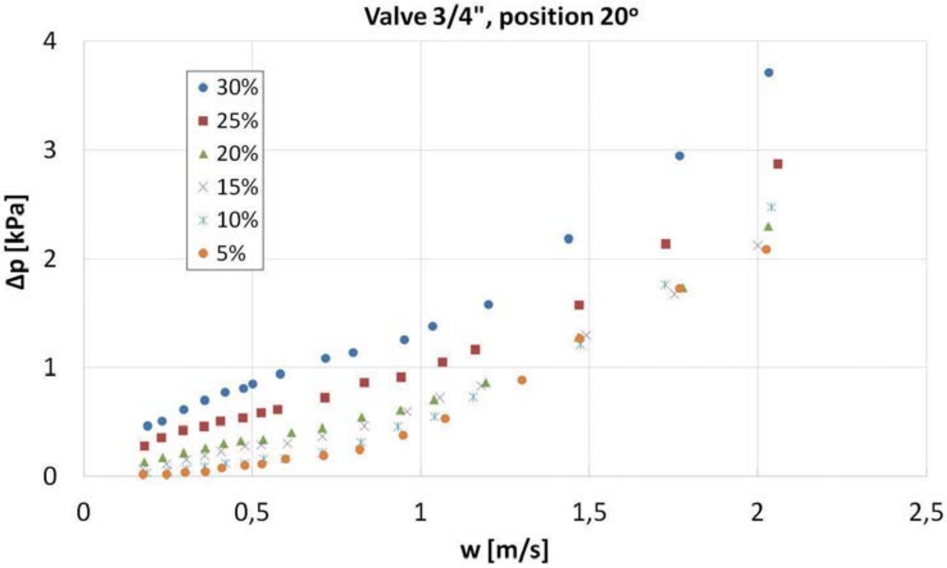

Fig. 7. Relationship between pressure drop in the 3/4" valve at an angle of 20° and the velocity of the ice slurry in the valve for various ice fractions

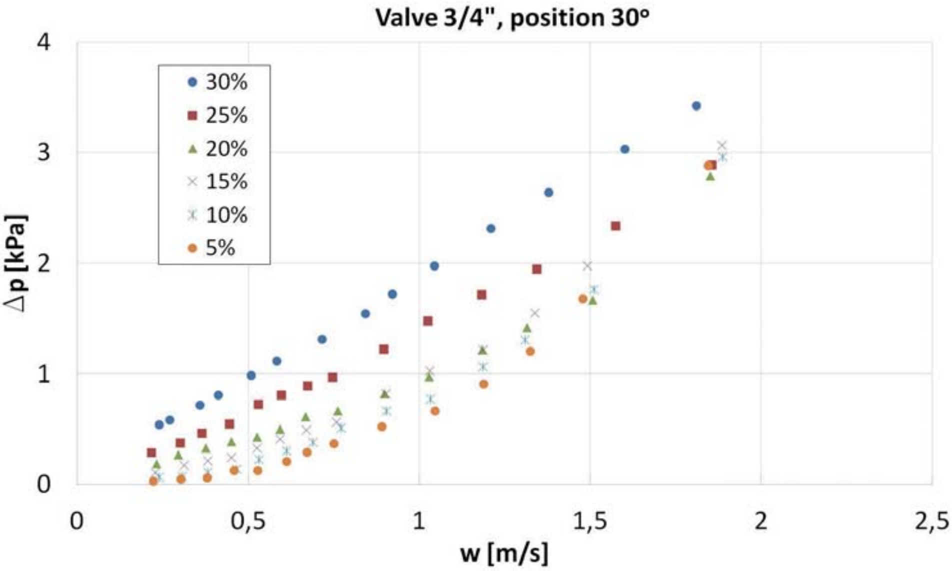

Fig. 8. Relationship between pressure drop in the 3/4" valve at an angle of 30° and the velocity of the ice slurry in the valve for various ice fractions

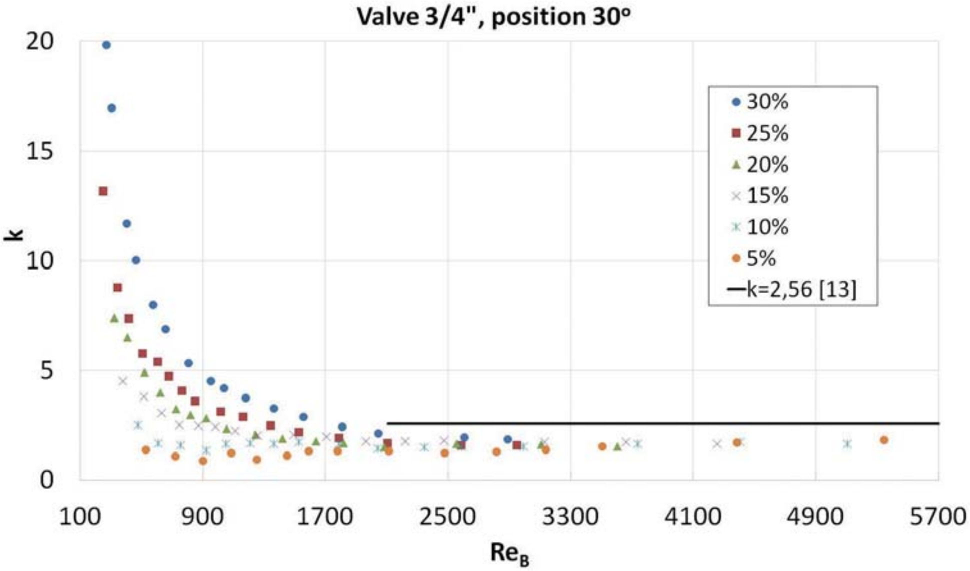

Fig. 9. Relationship between the local loss coefficient in the 3/4" valve at an angle of 20° and the Reynolds number from the Bingham model for various ice fractions

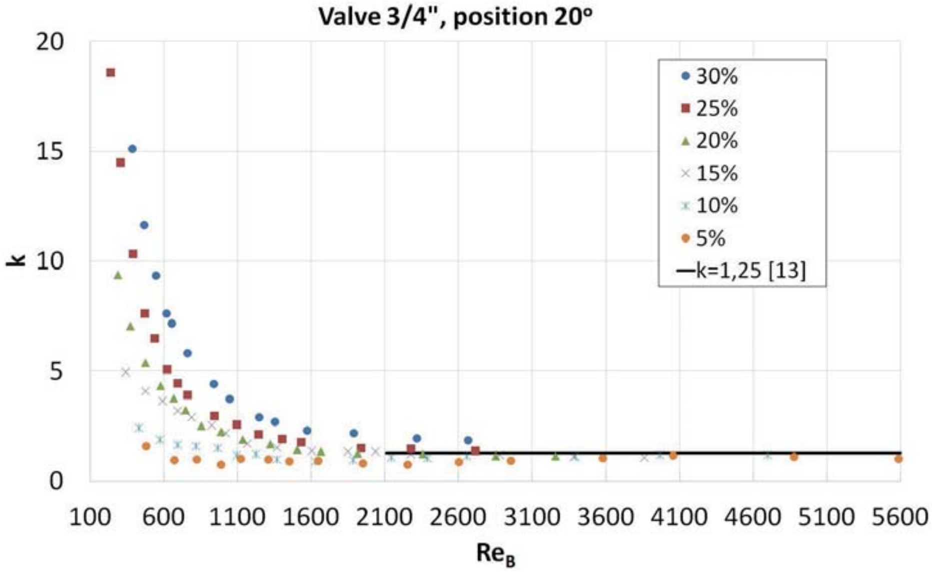

Fig. 10. Relationship between the local loss coefficient in the 3/4" valve at an angle of 30° and the Reynolds number from the Bingham model for various ice fractions

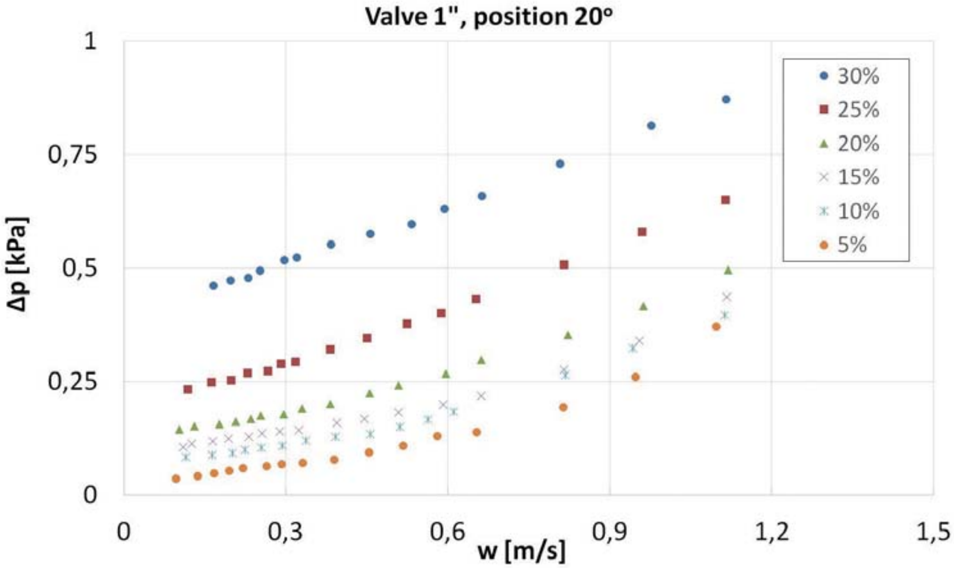

Fig. 11. Relationship between pressure drop in the 1” valve at an angle of 20° and the velocity of the ice slurry in the valve for various ice fractions

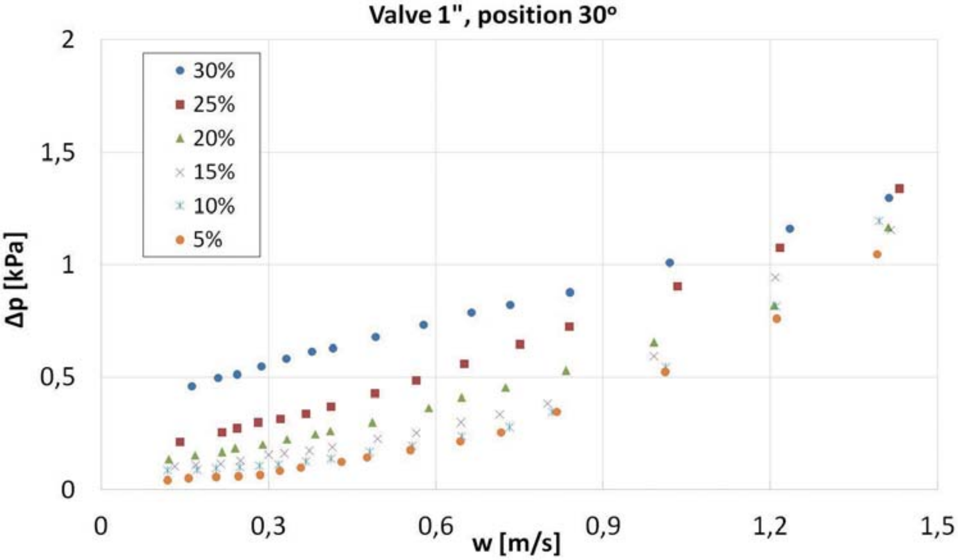

Fig. 12. Relationship between pressure drop in the 1” valve at an angle of 30° and the velocity of the ice slurry in the valve for various ice fractions

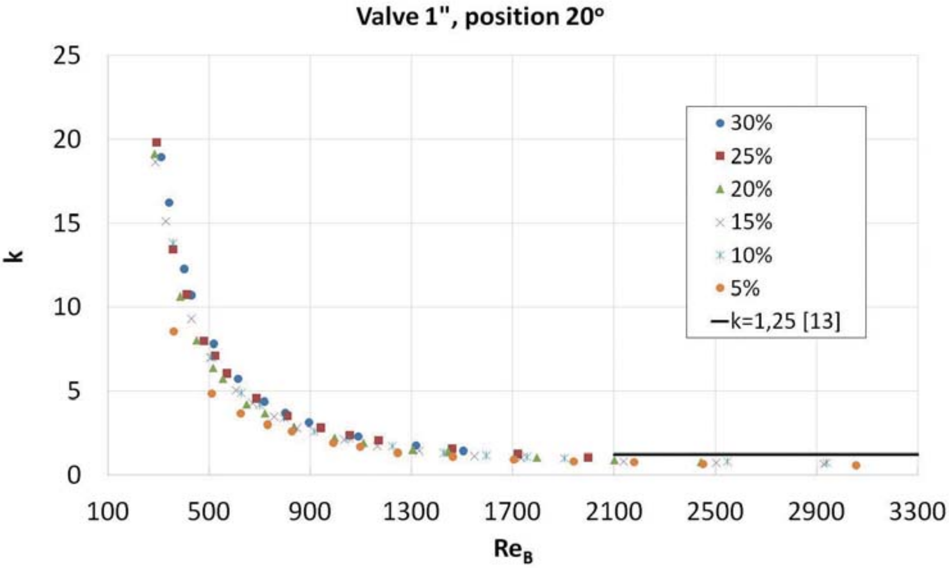

Fig. 13. Relationship between the local loss coefficient in the 1'' valve at an angle of 20° and the Reynolds number from the Bingham model for various ice fractions

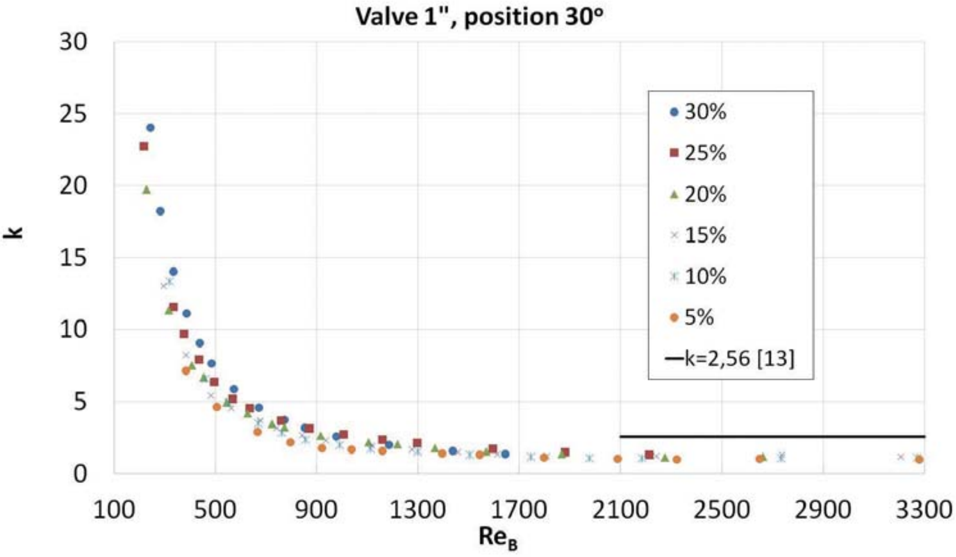

Fig. 14. Relationship between the local loss coefficient in the 1'' valve at an angle of 30° and the Reynolds number from the Bingham model for various ice fractions

4. Conclusions

The analysis of the relationship between pressure drops in the 1/2", 3/4" and 1" ball valves and the flow velocity in the valve for ice slurry with a mass fraction of ice of 5%, 10%, 15%, 20%, 25% and 30% presented in Figs 3, 4, 7, 8, 11 and 12 reveals a similar nature of the obtained measurement points for the three valves and the two positions (20° and 30°). In each graph, the highest pressure drops were detected for the ice slurry with the greatest proportion of ice particles (30%) and the lowest for the ice slurry with the smallest proportion of ice particles (5%). Moreover, in all cases, it is clear that the higher the pressure drop at the valve the higher the content of ice particles in the ice slurry. The relationships between the measurement points presented in Figs 3, 4, 7, 8, 11 and 12 are of a linear nature up to a certain boundary velocity, as the smaller ice mass fraction in the slurry the lower velocity of the studied mixture. Therefore, it is possible to claim that the presence of ice particles in the slurry influences the laminar nature of the flow. Once a certain boundary value of flow velocity (different for each valve and position of choking element) is exceeded, the course of pressure drops changes into a parabolic nature.

Analysis of Figs 5, 6, 9, 10, 13 and 14, which present the relationship between local loss coefficients in the 1/2", 3/4" and 1" ball valves (at closure angles 20° and 30°) and the Reynolds number from the Bingham model, reveals that in the turbulent flow range, the values of the coefficients are consistent with the values given in literature for Newtonian fluids. In the laminar flow range, the values of local loss coefficients are higher than in the turbulent flow range. The higher value of the local loss coefficient the greater content of ice particles and closure angle of the valve (30°). The greatest differences in the values of the local loss coefficients are seen in valves with smaller diameters, whereas in the 1" valve, the values are quite similar. This is probably related to the value of the quotient of the medium diameter of an ice particle and the hydraulic diameter, which is identified in literature as an important parameter which has a significant impact on the flow of ice slurries [6, 10].

References

[1] Egolf P.W., Kauffeld M., *From physical properties of ice slurries to industrial ice slurry applications*, International Journal of Refrigeration, 28, 2005, 4–12.

[2] Hansen T.M., Kauffeld M., *Viscosity of ice slurry,* Second Workshop on Ice-Slurries of the International Institute of Refrigeration, Paris, France 2000.

[3] Kawashima T., Sasaki M., Takahashi H., *Dynamics of snow – water flow in pipelines, slurry handing and pipeline transport,* Hydrotransport 12, 1993, 533–613.

[4] Kumano H., Yamanada Y., Makino Y., Asaoka T., *Effect of initial aqueous solution concentration on rheological behavior of ice slurry,* International Journal of Refrigeration, 68, 2016, 218–225.

[5] Melinder A., *Thermopysical properties of liquid secondary refrigerants. Tables and diagrams for the refrigerants industry*, IIF/IIR, Paris 1997.

[6] Mika Ł., *Opory przepływu zawiesiny lodowej w elementach instalacji chłodniczej*, Monografia No. 339, wyd. Politechniki Krakowskiej, Kraków 2011.

[7] Mika Ł., *Flow resist of the slurry ice in contractions*, Technical Transactions, 2-M/2012, 273–282.

[8] Mika Ł., Górski B., Kantor R., *Flow modelling of slurry ice in a control valve,* Technical Transactions, 1-M/2015, 59–66.

[9] Mika Ł., Zalewski W., *Local pressure loss coefficient during the flow of slurry ice trough sudden pipe expansions*, Technical Transactions, 1-M/2015, 67–74.

[10] Niezgoda-Żelasko B., *Wymiana ciepła i opory przepływu zawiesiny lodowej w przewodach*, Monografia No. 334, wyd. Politechniki Krakowskiej, Kraków 2006.

[11] Niezgoda-Żelasko B., Zalewski W., *Momentum transfer of ice slurry flows in tubes, experimental investigation*, International Journal of Refrigeration 29, 2006, 418–428.

[12] Niezgoda-Żelasko B., Zalewski W., *Momentum transfer of ice slurry flows in tubes, modeling*, International Journal of Refrigeration 29, 2006, 429–436.

[13] Polska Norma M-34034, Rurociągi. Zasady obliczeń strat ciśnienia, 1976.