TECHNICAL TRANSACTIONS | **CZASOPISMO TECHNICZNE**
MECHANICS | MECHANIKA

1-M/2015

ŁUKASZ MIKA*, WOJCIECH ZALEWSKI*

LOCAL PRESSURE LOSS COEFFICIENT DURING THE FLOW OF SLURRY ICE TROUGH SUDDEN PIPE EXPANSIONS

WSPÓŁCZYNNIK MIEJSCOWYCH STRAT CIŚNIENIA PRZY PRZEPŁYWIE ZAWIESINY LODOWEJ PRZEZ NAGŁE ROZSZERZENIA PRZEWODU

Abstract

The paper presents the results of experimental studies on ice slurry flow resistance in sudden pipe expansions. In the experimental studies, the mass fraction of solid particles in the slurry ranged from 5 to 30%. The pressure loss coefficients identified as a result of the experimental studies of the turbulent flow of the ice slurry are the same as the coefficients calculated for Newtonian liquids.

Keywords: *slurry ice*, *loss coefficient*, *pressure loss coefficient*, *sudden pipe expansion*

Streszczenie

W artykule przedstawiono wyniki badań współczynnika miejscowych strat ciśnienia przy przepływie zawiesiny lodowej przewodem o nagle zwiększającym się przekroju przepływu. Badania przeprowadzono dla zawiesiny lodowej o udziale masowym lodu od 5 do 30%. Otrzymane z badań wartości współczynników strat miejscowych w turbulentnym zakresie przepływu są zgodne z wartościami tych współczynników obliczonymi jak dla przepływu cieczy newtonowskiej.

Słowa kluczowe: *zawiesina lodowa*, *współczynnik miejscowych strat ciśnienia*, *nagłe rozszerzenie przekroju przepływu*

---

* Ph.D. Eng. Łukasz Mika, Prof. Ph.D. D.Sc. Eng. Wojciech Zalewski, Institute of Thermal and Process Engineering, Faculty of Mechanical Engineering, Cracow University of Technology.

1. Introduction

Ice slurry is a mixture of a base fluid and ice particles whose dimensions range from $1.0 \cdot 10^{-4}$ to 0.5 mm. Water or aquatic solutions of glycols, alcohols or salts are most often used as base fluids. The key properties of ice slurry include its high specific thermal efficiency, its high heat transfer coefficient values, and its environmental neutrality. Those properties make it possible for ice slurry to be used not only as a refrigerant, but also as a heat-accumulating agent.

Currently, ice slurry is used in air-conditioning installations for large buildings and mines. It is the chosen refrigerant for air-conditioning systems in supermarkets used to cool reach-in refrigerators, cold plate freezers and cold rooms where food is stored. Ice slurry is also used in the petrochemical and dairy industries, as well as in breweries, medicines and fire-fighting. The first ice slurry-fed systems were created in the early 1980s. They are now widespread in many countries of the world, including Japan, South Africa, South Korea, Germany, France, Colombia and Singapore. In Poland, this cooling technology is not used yet. A significant barrier to its application is the price of the ice slurry generators and the resulting investment costs, which exceed those necessary in the case of traditional refrigeration systems, as well as a lack of knowledge on the part of the investors and designers with respect to the specific properties of ice slurry and refrigeration systems based on heat accumulation in ice.

The specific properties of the ice slurry make it necessary to take account of them in design calculations performed for the planned installations. Besides thermal calculations, flow calculations are equally important, as they enable the determination of the flow resistance of the slurry in pipes and cooling installation fittings. The body of relevant literature includes publications on friction resistances during the flow of ice slurry through straight-line pipe sections, as well as bends and elbows. However, there is no data on local flow resistances in various pipe fittings such as ball valves, globe valves, control valves, pipe reducers, T-connectors and distributors. The results of the study of local flow resistances of ice slurry in sudden pipe expansions presented in this paper should contribute to a better understanding of the topic.

2. Experimental setup description

The experimental studies were carried out with an experimental stand, the setup of which is presented in Figure 1. Ice slurry with the required content of ice made in the ice generator (2) was collected in the accumulation tank (4). The measurement section consisted of the analysed fitting (1) installed between straight-axis pipe sections, each with a length of 4.9 m – this fulfilled the role of run-up sections. The mass flux of the slurry (flow velocity) in the measurement section was adjustable using either the by-pass (12) located directly downstream of the pump package, or the inverter (6) of the pump drive (5). The mass stream could be additionally adjusted using another by-pass, which may extend or reduce the flow path of the slurry.

Ice slurry temperature was measured using precise HART SCIENTIFIC Pt 100 resistance sensors located in thermometric sleeves (11).

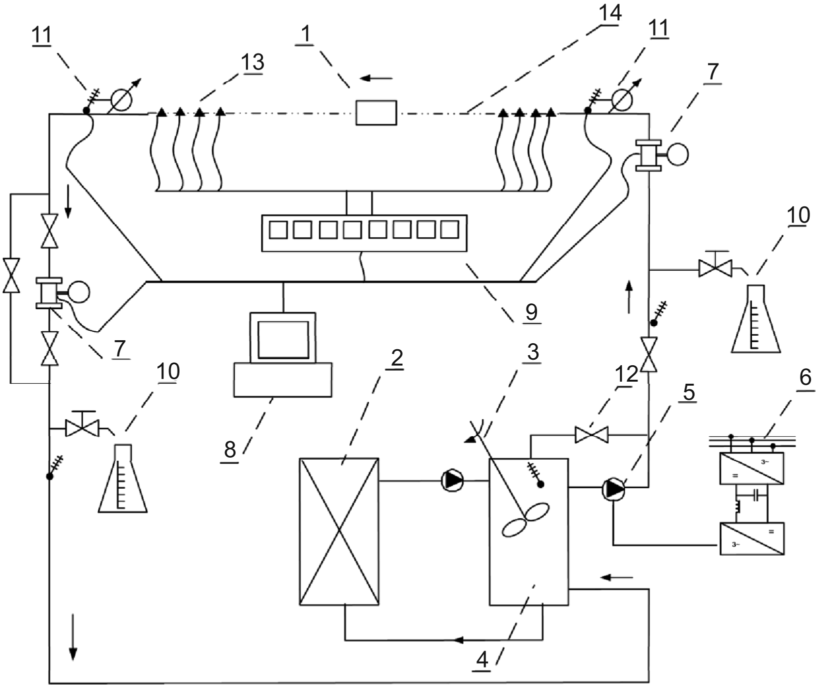

Fig. 1. Schematic diagram of the experimental test stand: 1 – expansion; 2 – ice slurry generator; 3 – mixer; 4 – storage tank; 5 – main pump; 6 – main pump inverter; 7 – mass flow-meter; 8 – data collecting; 9 – multipoint measurement of pressure; 10 – control of ice fraction; 11 − measurement of temperature and pressure; 12 – bypass; 13 – pressure measurement stub; 14 – removable section of the test stand

FUJI ELECTRIC meters with various measurement ranges were used to measure pressure and pressure differences. Due to the properties of the slurry ice, it was decided that pressure in the installation would be measured using 4mm impulse stub pipes (13) with non-insulated transparent impulse piping.

The mass flux of the ice slurry was measured using Danfoss (Siemens) MASSFLO mass flow meters (7), which also performed continuous measurements of the density of the flowing medium. Table 1 shows the key measurement devices used in the study.

The experimental study was conducted for ice slurries with a mass fraction of ice of 30%, 25%, 20%, 15%, 10% and 5%, made on the basis of a 10.6% aquatic solution of ethyl alcohol. In order to avoid heterogenic flow, it was necessary to ensure a minimum flow velocity of ice slurry in the measurement section between 0.15 m/s and 0.25 m/s, depending on pipe diameter and ice content [1, 3, 5, 7].

The mass flux of the ice slurry, its density and the mass fraction of ice were controlled both upstream and downstream of the investigated fitting in order to prevent ice crystals from remaining or melting in the measurement section of the stand. The measurement was conducted indirectly, using a computer data acquisition system (8) based on IDAM 7000 modules with an accuracy of 0.5%.

Table 1

List of key measurement devices

Device	Type	Measurement range	Accuracy (direct reading)
Pressure transmitters	FUJI ELECTRIC FKC(G)V series	0–1 [kPa] 0–6 [kPa] 0–32 [kPa]	0.07%
Temperature sensors	HART SCIENTIFIC Pt100	–100–100 [°C]	0.018 [°C]
Mass flow meter	SIEMENS MASSFLO 2100	0–52000 [kg/h] 0.1–2.9 [g/cm^3]	0.1% 0.0005 [g/cm^3]

The experimental study covered the flow of the ice slurry through 6 pipe expansions with the significance and dimensions listed in Table 2.

Table 2

Basic geometrical parameters of the investigated expansions

Expansion (symbol)	15/28	18/28	15/22	22/28	18/22	15/18
Smaller diameter [mm]	15	18	13	22	16	15
Bigger diameter [mm]	28	28	20	28	20	18

The mass fraction of ice was identified on the basis of simultaneous constant measurement of the temperature and density of the slurry. The measurement was deemed correct if the same ice slurry density value was obtained when measured with a flow meter and on the basis of temperature measurements. In order to determine the content of ice crystals using temperature measurements, Melinder's freezing curve of an aquatic solution of ethanol [4] was used. Throughout the study, the mass fraction of ice determined using both methods did not vary by more than 2%.

3. Study methods

As measurement of dynamic pressure is troublesome and causes flow disturbances, ice slurry flow resistances are calculated on the basis of static pressure measurements. Provided that static pressure losses are known, it is possible to calculate local loss coefficients on the basis of the Coriolis coefficients. Once the value of the said coefficients and the density of the ice slurry are determined, it is possible to calculate local flow resistances of the slurry for any flow velocity values.

In connection with the applied study method, flow resistances caused by friction were also determined for straight-line pipe sections with outer diameters of: ϕ15 mm, ϕ18 mm, ϕ22 mm and ϕ28 mm. The method applied to measure flow resistance values in pipe expansions involved measuring static pressure (and as a control measurement also the differences in static pressure at selected measurement points) along the flow of the ice slurry through the entire measurement section [2]. The measurement section consisted of the analysed fitting and run-up sections, this made it possible to obtain a fully developed velocity profile.

The method applied in the study consisted of extrapolating a fully developed pressure gradient to the place of installation of a particular fitting, on both its sides separately.

On the basis of the information collected in the trial measurement series, the static pressure measurement stubs were installed within the measurement section at distances of: 80D, 65D, 50D and 35D upstream of the studied fitting, and 95D, 80D, 65D and 50D downstream of the studied fitting.

The value of the local pressure loss coefficient was calculated using equation:

$$k = \frac{2\Delta p}{\rho V_1^2} + \alpha_1 - \alpha_2 \frac{V_2^2}{V_1^2} \tag{1}$$

where

Δp – pressure drop,
V – flow velocity,
α – Coriolis coefficient,
ρ – ice slurry density.

Indices 1 and 2 refer to the state of the ice slurry upstream and downstream of the expansion.

In order to determine the local loss coefficient in the fittings in which flow velocity changes, it is necessary to know the Coriolis coefficient for the laminar and turbulent flow range on both sides of the studied fitting.

In reference works, it is difficult to find verified equations for determining the Coriolis coefficient in the turbulent flow range for non-Newtonian fluids. However, papers by other authors indicate that in the said range, both the values of local loss coefficients and the velocity profiles of both non-Newtonian and Newtonian fluids are quite similar [2, 8]. Therefore, in order to calculate the value of the Coriolis coefficient for the turbulent flow of ice slurry in a tube, an empirical relationship may be used as for a Newtonian fluid.

The Strzelecka and Jeżowiecka-Kabsch equation [5] was used for Reynolds numbers within the range of Re = 2800 – 100000:

$$\alpha = 1 + 105 \cdot \left(\frac{10}{\ln^2 \mathrm{Re}}\right)^3 - 11.88 \cdot \left(\frac{10}{\ln^2 \mathrm{Re}}\right)^2 + 1.208 \cdot \left(\frac{10}{\ln^2 \mathrm{Re}}\right) \tag{2}$$

The value of the Coriolis coefficient in the laminar flow range for a Bingham fluid was determined in the paper using equation [6]:

$$\alpha = \frac{54 \cdot (47 \cdot \varepsilon_B^2 + 58 \cdot \varepsilon_B + 35)}{35 \cdot (\varepsilon_B^2 + 2 \cdot \varepsilon_B + 3)^3} \tag{3}$$

where

ε_B – Bingham's fluid active shear stress ratio.

The properties of the ice slurry were determined on the basis of the equations provided in [4–7].

4. Calculation of local pressure loss coefficients

Using the obtained results, it was possible to determine the slopes of the pressure gradient lines, as well as their intersection point with the static pressure axis on both sides of the expansion. The same calculations were conducted for all the measured values of pressure upstream and downstream of the expansion. The results of the calculations were used to determine the difference in static pressure for the ice slurry flowing through each of the studied expansions. The resulting values of the difference in static pressure at the expansions and the calculated values of the Coriolis coefficients were used to determine the local pressure loss coefficients. Figures 2, 3 and 4 show the values of local loss coefficients as a function of the Reynolds number (for a Bingham fluid) for the studied expansions and mass shares of ice in the slurry amounting to between 5% and 30%. At the points where laminar flow changes into turbulent flow, disturbances in the distribution of the measurement points (local minimums) are visible. The graphs show the results of calculations of the pressure loss coefficients within the turbulent flow range obtained using the formula concerning the flow of a Newtonian fluid:

$$k = \left(1 - \frac{V_1}{V_2}\right)^2 \tag{4}$$

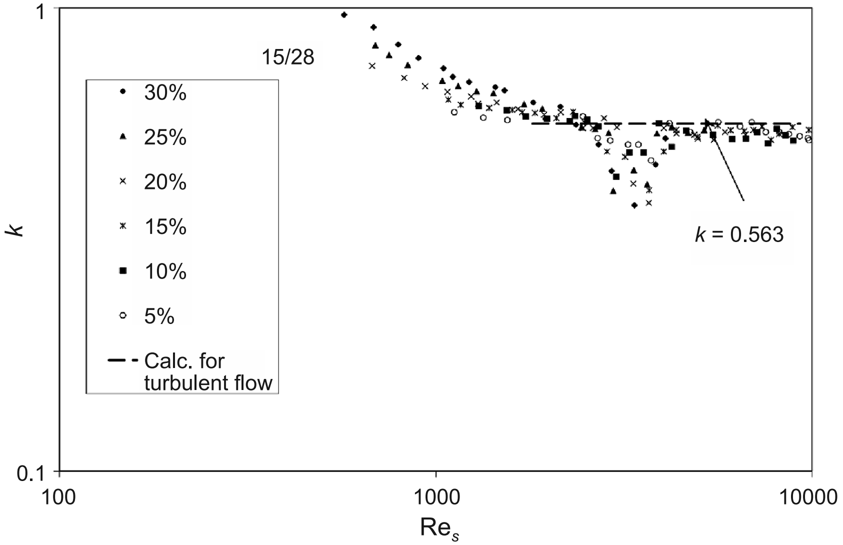

Fig. 2. Pressure loss coefficient for slurry ice (5%–30%) in correlation of the Reynolds number for a Bingham liquid in a 15/28 expansion

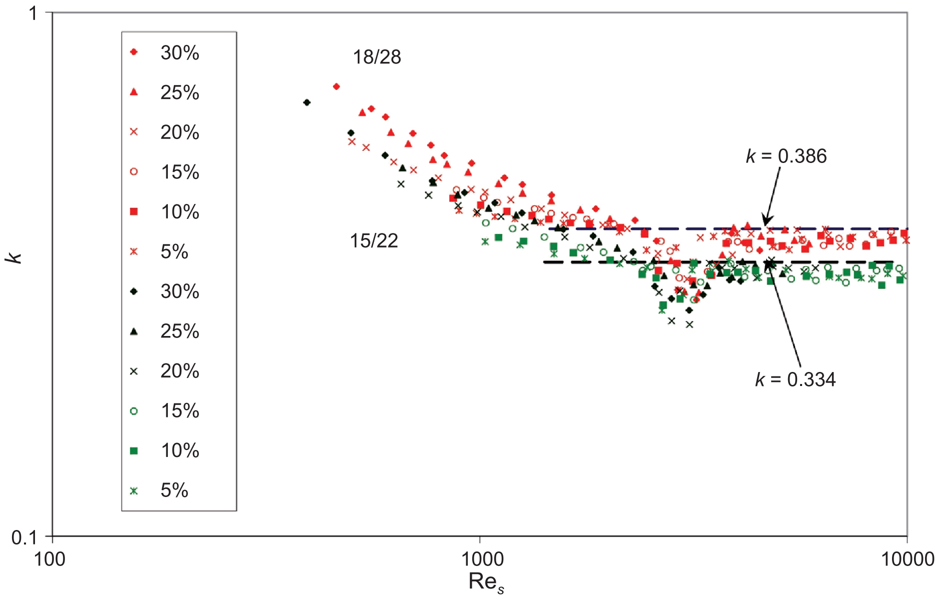

Fig. 3. Pressure loss coefficient for slurry ice (5%–30%) in correlation of the Reynolds number for a Bingham liquid in a 18/28 expansion and a 15/22 expansion

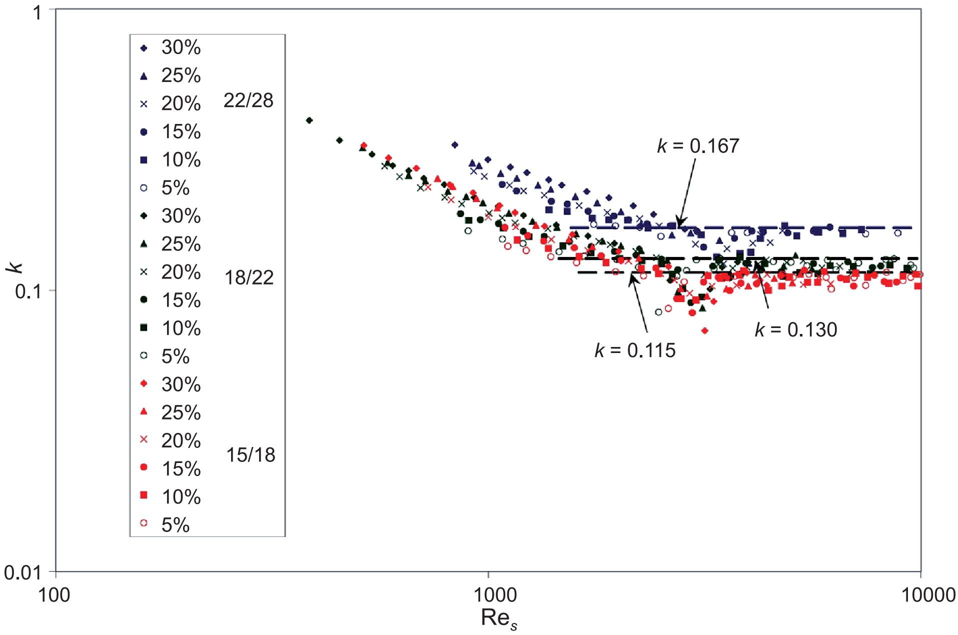

Fig. 4. Pressure loss coefficient for slurry ice (5%–30%) in correlation of the Reynolds number for a Bingham liquid in expansions 22/28, 18/22 and 15/18

5. Conclusions

As can be inferred from the graphs presented in Figures 2, 3 and 4, in the laminar flow range there exists a clear correlation between the values of the local loss coefficient and the Reynolds number of the slurry (Bingham fluid). As the value of the Reynolds number increases, the value of the said coefficient decreases. In the turbulent range, the value of the local loss coefficient is constant, independent of the Reynolds number, and close to the values calculated as for a Newtonian fluid. This is consistent with results obtained by other authors [1, 2, 8].

In both flow ranges, it is possible to observe the influence of the content of ice and the expansion's diameters ratio on the value of the local pressure loss coefficient. The higher the ice content of the slurry, the higher its viscosity, which directly translates into an increase of the value of the local loss coefficient and local flow resistances in the expansion. An increase of the ratio of the diameters of the pipe upstream and downstream of the expansion causes a decrease in the value of the local loss coefficient.

References

[1] Ayel V., Lottin O., Peerhossaini H., *Rhelogy flow behaviour and heat transfer of ice slurries: a review of the state of the art*, International Journal of Refrigeration, 26, 2003, 95-107.

[2] Fester V., Mbiya B., Slatter P., *Energy losses of non-Newtonian fluids in sudden pipe contractions*, The Chemical Engineering Journal, 145, 2008, 57-63.

[3] Kitanovski A., Vuarnoz A., Ata-Caesar D., Egolf P.W., Hansen T.M., Doetsch Ch., *The fluid dynamics of ice slurry*, International Journal of Refrigeration, 28, 2005, 37-55.

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

[5] Mika L., *Energy losses of ice slurry in pipe sudden contractions*, Experimental Thermal and Fluid Science, 35, 2011, 939-947.

[6] Mika Ł., *Opory przepływu zawiesiny lodowej w elementach instalacji chłodniczej*, Wydawnictwo Politechniki Krakowskiej, Kraków 2011.

[7] Niezgoda-Żelasko B., *Wymiana ciepła i opory przepływu zawiesiny lodowej w przewodach*, Wydawnictwo Politechniki Krakowskiej, Kraków 2006.

[8] Turian R.M., Ma T.W., Hsu F.L.G., Sung M.D.J., Plackmann G.W., *Flow of concentrated non--Newtonian slurries: 2 Friction losses in bends, fittings, valves and venturi meters*, International Journal Multiphase Flow, 24, 1998, 243-269.