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

1-M/2015

BEATA NIEZGODA-ŻELASKO*, JERZY ŻELASKO*

HEAT TRANSFER OF ICE SLURRY FLOWING IN RECTANGULAR AND SLIT CHANELS

WYMIANA CIEPŁA ZAWIESINY LODOWEJ PODCZAS PRZEPŁYWU W KANAŁACH PROSTOKĄTNYCH I SZCZELINOWYCH

Abstract

This paper presents the results of experimental investigations into heat transfer between the wall and ice slurry during its flow through channels of rectangular and slit cross-sections. Ice slurry flow is treated as a generalized flow of a non-Newtonian fluid. The influence of solid particles, the flow character, as well as the cross-section of the channel on the heat transfer coefficient are discussed. As the final result, the dimensionless dependences for the calculation of the Nusselt number value in the range of laminar and turbulent flows are presented.

Keywords: *ice slurry*, *heat transfer*, *melting*, *generalized non-Newtonian fluid flow*

Streszczenie

W artykule przedstawiono wyniki badań eksperymentalnych wymiany ciepła ścianka-zawiesina lodowa podczas przepływu w kanałach o przekrojach prostokątnym oraz szczelinowym. Przepływ zawiesiny lodowej traktowany jest jako uogólniony przepływ cieczy nienewtonowskiej. Omówiono wpływ udziału cząstek stałych, charakteru ruchu, przekroju poprzecznego na zmiany współczynnika przejmowania ciepła. Końcowym efektem pracy są zależności kryterialne służące do wyznaczania liczb Nusselta w obszarze przepływu laminarnego i burzliwego.

Słowa kluczowe: *zawiesina lodowa*, *wymiana ciepła*, *topnienie*, *uogólniony przepływ cieczy nie-Newtonowskiej*

* Ph.D. D.Sc. Eng. Beata Niezgoda-Żelasko, Ph.D. Eng. Jerzy Żelasko, Faculty of Mechanic Engineering, Cracow University of Technology.

Nomenclature

c_{pB}	–	mean value of specific heat of ice slurry [(J/(kg·K)]
d	–	diameter [m]
d_h	–	hydraulic diameter [m]
K_F	–	phase change number $K_F = r/(c_{pB} \cdot \Delta T)$
K^*	–	consistency index, [Ns^n/m^2]
L	–	tube length [m]
L_{Heat}	–	length of heat measurement section [m]
n^*	–	characteristic flow-behaviour index $n = d(\ln\tau_w)/d(\ln\Gamma)$
$\dot{q}_m$	–	mean heat flux density [W/m^2]
r	–	ice melting capacity [J/kg]
T	–	temperature [K]
T_f	–	mass mean temperature [K]
T_w	–	wall temperature [K]
w	–	flow velocity [m/s]
x_a	–	carrying fluid concentration [%]
x_s	–	mass fraction of ice [%]
α	–	heat transfer coefficient [W/(m^2·K)]
Δx_s	–	change of mass fraction of ice [%]
λ	–	heat conductivity [W/(m·K)]
μ_p	–	plastic viscosity [Pa·s]
$\lambda_{B,w}$	–	heat conductivity of ice slurry at flow velocity $w \neq 0$ [W/(m·K)]
$\lambda_{B,w=0}$	–	heat conductivity of ice slurry at flow velocity $w = 0$ [W/(m·K)]
ρ	–	density [kg/m^3]
Gz_K	–	Graetz number, $\mathrm{Gz}_K = \mathrm{Pr}_B \mathrm{Re}_K d_h / L_{\text{Heat}}$
Nu	–	Nusselt number, $\mathrm{Nu} = \alpha d_h / \lambda_{B,w=0}$
Pe_K	–	Peclet number for ice slurry, $\mathrm{Pe}_K = \mathrm{Re}_K \cdot \mathrm{Pr}_B$
Pr_B	–	Prandtl number for ice slurry, $\mathrm{Pr}_B = \mu_p c_{pB} / \lambda_{B,w=0}$
Re_B	–	Reynolds number for ice slurry, $\mathrm{Re}_B = w d_h \rho_B / \mu_p$
Re_K	–	Reynolds number according to Kozicki, $\mathrm{Re}_K = \rho_B w_m^{2-n^*} d_h^{n^*} / (8^{n^*-1} K^*)$

1. Introduction

Ice slurry is a mixture of either water ice crystals and water, or water with a content of a substance which lowers the freezing point (salt, glycol, alcohol). Ice slurry is a non-Newtonian fluid. This medium is treated as a rheologically stable liquid. Rheological models most frequently assigned to this fluid are: the Ostwald de Waele power law model [5]; the Bingham model [1, 4, 6, 11]; the Casson model [7].

Experimental studies regarding the heat transfer processes in ice slurry flows refer to various flow geometries. The largest number of all published works concerns ice slurry flows through tubes [6, 7, 9, 13]. Paper [12] includes a thermal study of ice slurry in a plate heat exchanger. Stamatiou and Kawaii [14] present the results of thermal studies of ice slurry made up of a 6.2% water salt solution in vertical tubes of a rectangular cross-section. A detailed list of references concerning heat transfer processes with ice slurry is available in paper [1].

The objective of this paper is to present the phenomena accompanying the heat transfer process in ice slurry during its flow through horizontal straight tubes of rectangular and slit cross-sections

2. Experimental studies

The test program included measurements of flow and thermal parameters of ice slurry flow through:
– a rectangular tube with the following dimensions: 0.0078 × 0.0265 × 3.0 [m];
– a tube of a rectangular (slit) cross-section, with the following dimensions: 0.03 × 0.0358 × 2.0 [m].

Tests concerning ice slurry heat transfer were conducted at a constant heat flux density. The selected thermal measurement lengths guaranteed a hydrodynamically and thermally formed ice slurry flow in turbulent regions. For laminar flow inside tubes, the measurements were taken in the take-off run length, in which the flow was hydrodynamically formed and practically thermally formed. The values of L_{heat}/d_h included in the present study are significantly higher than the ones commonly found in thermal studies of ice slurry flow in pipes (L_{heat}/d_h < 80) [2, 4]. In the case of thermal studies of ice slurry flow through rectangular tubes, Stamatiou and Kawaji [14] conducted research for tubes with hydraulic diameters of d_h = 0.023 and 0.047 m and with the values of L_{heat}/d_h = 11 and 22.

Paper [10] describes in detail the measurement stand and the adopted heat transfer measurement method.

Thermal studies included measurements for:
– mean flow velocities $0{,}1 \leq w_m \leq 4.5$ [m/s];
– heat flux density of $\dot{q}_m = 2000; 5000; 8000\ [\text{W/m}^2]$;
– mass fraction of ice $0 \leq x_s \leq 30\%$;
– average size of ice crystals (width/length) d_s = 0.1/0.15 [m] [10].

Figure 1 presents experimental values of heat transfer coefficients determined for the cross-sections: rectangular ($a \times b$ = 0.0078 × 0.0265 [m]); slit ($a \times b$ = 0.003 × 0.0358 [m]). A detailed description of the results of the experimental research on heat transfer during flow through the pipes is presented in [10]. In the case of the flow through the rectangular tubes, similar to flow in the pipes, it is possible to observe an increase in the heat transfer coefficient of the ice slurry in comparison to the heat transfer coefficient of the carrying liquid. The influence of solid particles on the increase of the ice slurry's heat transfer coefficient depends of the hydraulic diameter of the channel. The smaller hydraulic diameter causes the smaller increase of the heat transfer coefficient of the ice slurry in comparison to the heat transfer coefficient of ethanol. In laminar flow regions, this ratio equals 3.2–4.8 for a cross--section of a/b = 0.29; d_h = 0.012 [m], as well as 1.9–3.4 for the cross-section of a/b = 0.084; d_h = 0.0055 [m]. A similar trend could be observed in the case of the pipe flow [11].

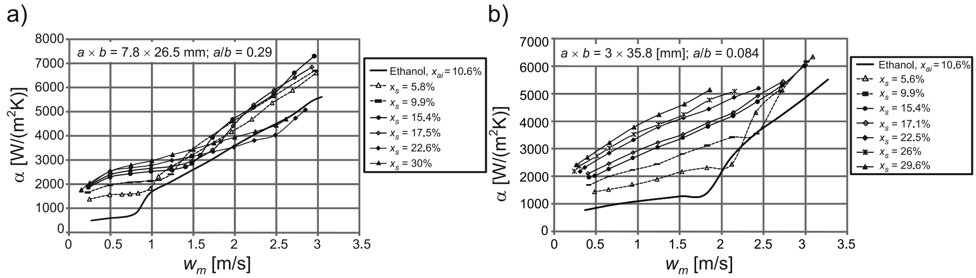

Fig. 1. Experimental values of heat transfer coefficients for different cross--sections: a) Rectangular channel $a \times b = 0.0078 \times 0.0265$ [m]; b) Slit channel $a \times b = 0.003 \times 0.0358$ [m]

The above mentioned relationships show that the values of the heat transfer coefficients of ice slurry are influenced by two opposing phenomena. One of these is the microconvection effect of solid particles, which causes increases in the effective value of the slurry's thermal conductivity. The smaller the hydraulic diameter of the channel, the greater the shear rate and the value of the effective thermal conductivity. Hence, the greater value of the heat transfer coefficient of the slurry. On the other hand, however, the smaller the pipe diameter, the lower the values of the Reynolds numbers corresponding to the same mean velocities and the greater the thickness of the near-wall layer. In addition, in the case of slurry, the shift of the critical Reynolds number towards greater values for greater ice fractions results in the fact that for various pipe diameters, the disruption of the laminar sub-layer caused by flow turbulization will occur later (for greater velocities) in the case of pipes with smaller diameters. In turbulent flow regions, the heat transfer coefficient of the ice slurry is much less dependent on the content of solid particles. The observable increase in the heat transfer coefficient of the slurry in comparison to ethanol amounted to 20–30%.

3. Calculating the heat transfer coefficient for ice slurry

In study analyzed the effect of generalised Reynolds number according to Kozicki Re_K [8], the phase-change number K_F, the influence of solid particles and the temperatur gradient in the transversal cross-section of the flow on the Nusselt number. This enabled the formulation of the dimensionless form of the equation used to determine heat transfer coefficients for rectangular and slit channels. Figure 2 shows the dependence of the Nusselt number ($\mathrm{Nu} = \alpha\, d_h/\lambda_B$) on the generalized Reynolds number according to Kozicki for the flow through a slit and a rectangular channel, respectively.

Figure 3 presents the influence of phase change, which accompanies the heat transfer process, on the Nusselt number values, in the form of a relationship of the Nusselt number and the expression $\Delta x_s K_F/100$. Figures 2 and 3 show that for different flow cross-sections, the change tendencies of the Nusselt numbers are similar.

The influence of solid particles on the Nusselt number (which occurs due to the microconvection effect and the reaction with the near-wall layer) has been taken into account by introducing an additional factor to Formula (1): $(d_s/d_h)^p$. Figure 4 presents the general tendency of changes in the Nusselt number from the expression d_s/d_h.

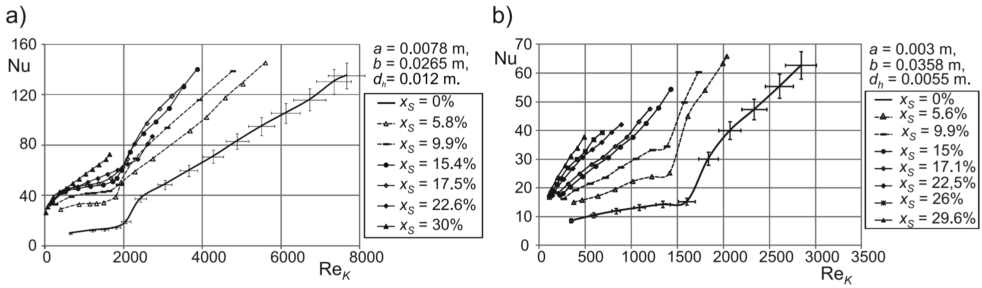

Fig. 2. The Nusselt number as a function of a generalized Reynolds number: a) rectangular channel $a \times b = 0.0078 \times 0.0265$ [m], b) slit channel $a \times b = 0.003 \times 0.0358$ [m]

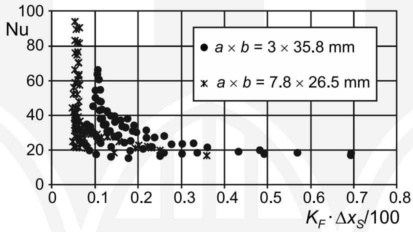

Fig. 3. A relationship of the Nusselt number and the expression $\Delta x_s K_F/100$

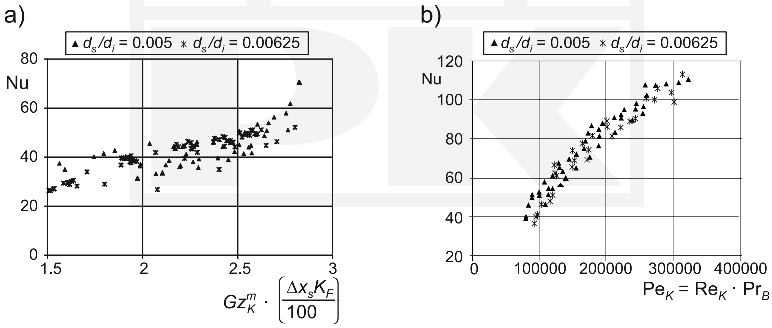

Fig. 4. Tendency of the changes in the Nusselt number from expression d_s/d_h: a) Laminar flow, b) Turbulent flow

Heat transfer between the fluid and the tube wall depend on the thickness of the near-wall layer and on the heat transfer coefficient of the liquid. In moving slurry, it is possible to observe an increase in heat conductivity (λ_{Bw}) in comparison to the heat conductivity of static slurry ($\lambda_{Bw=0}$).

Quantitatively, the result of the increase in the heat conductivity of a moving slurry is described by the Charunyakorn formula [3]. According to this equation, larger solid particles lead to greater heat conductivity. This is the cause of the increase in heat transfer coefficients of the slurry in comparison to the heat transfer coefficient of the carrying liquids. The above presented remarks concern types of slurry in which neither the melting process nor any related changes in the solid particle fraction take place. In laminar regimes, small mass fluxes make the amount of received heat sufficient to completely melt the ice particles within the near-wall layer. As a consequence, a structure with properties corresponding to the features of the carrying liquid was created near the wall. In this case, the heat transfer from the wall to the core of the fluid, where solid particles were present, was hindered. It should be kept in mind that in the analyzed case, the intensity of the heat transfer process also depends on the heat transfer process which takes place between the carrying liquid and the solid particles. The greater the contact surface between the solid particles and the carrying liquid (more particles with a smaller diameter d_s), the greater the intensity of heat transfer between the wall, the carrying liquid and the solid particles. As far as turbulent flow is concerned, greater mass fluxes and an intensive mixing process impede the complete melting of ice near the walls, and the influence of solid particles on the heat transfer process of ice slurry resembles a corresponding process in the case of the types of slurry which do not undergo phase change. Thus, graphs included in Figure 4 demonstrate a slightly different influence of the d_s/d_h parameter on the heat transfer process in the laminar and turbulent regimes.

Greater temperature gradients ($\Delta T = T_w - T_f$) in transversal cross-section and a more intensive melting process of solid particles (which accompany laminar flow) near the tube wall cause a visible change in the rheological properties of the liquid in a transversal cross--section. The influence on the heat transfer process of the heterogeneity of the rheological properties of slurry in a transversal flow cross-section has been taken into account. The following element was introduced to formula (1): $(K^*_{Tf} / K^*_{Tw})^y$. In turbulent flow regimes, this effect is not so visible and the accuracy of calculating the $(K^*_{Tf} / K^*_{Tw})^y$ quotient is outweighed by the measurement accuracy of the temperature difference ΔT.

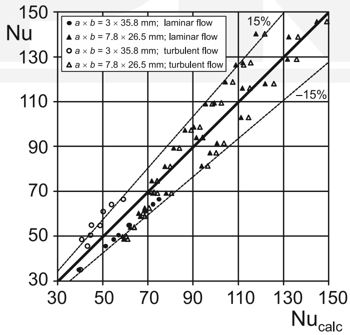

Fig. 5. Comparision of the measured and calculated Nusselt numbers for laminar flow (expression 1), and turbulent flow (expression 2)

Formulas (1) and (2) express the equations finally adopted for calculating the Nusselt number in laminar and turbulent regimes.

$$\mathrm{Nu} = 3.66 \cdot (\mathrm{Gz}_K)^{0.16} \cdot \left(\frac{\Delta x_s \cdot K_F}{100}\right)^{-0.28} \left(\frac{d_s}{d_h}\right)^{-0.12} \left(\frac{K_{Tf}^*}{K_{Tw}^*}\right)^{0.16}, \tag{1}$$

$$\mathrm{Nu} = 0.0032 \cdot (\mathrm{Pe}_K)^{0.86}. \tag{2}$$

Formula (2) takes into account the fact that in turbulent flow regimes, the temperature profile of the fluid was thermally developed and the influence of the thermal entry length on the heat transfer process was overlooked.

Figure 5 presents a comparison of the measured and calculated Nusselt numbers by means of formulas (1) and (2) for all analyzed cross-sections.

4. Conclusions

An analysis of the experimental studies allows for the following conclusions to be drawn:

- for ice slurry with a mass fraction of ice of $x_s > 20\%$, there are velocities at which the ice slurry heat transfer coefficients are smaller than the heat transfer coefficients of the carrying liquid. The phenomenon of intersecting the heat transfer coefficient curve of the carrying liquid by the curves of heat transfer coefficients of ice slurry can be explained by the fact that the physical properties of slurry change along with the mass fraction of ice, which causes a change in the type of movement of the ice slurry. For greater mass fractions of ice, the change in the type of motion occurs at higher Reynolds numbers. The presence of solid particles in a homogenous slurry flow makes ice crystals absorb a part of the kinetic energy of the turbulence from the carrying liquid. The slurry flow laminarization process starts and the loss of laminar flow stability is 'delayed',
- irrespective of the transversal cross-section of the flow, it was possible to observe a stronger influence of the mass fraction of solid particles on the heat transfer coefficients in the laminar rather than in the turbulent range. This phenomenon might be explained by the significant influence of heat conduction in the near-wall region on the heat transfer process for laminar flow. On the other hand, the presence of ice crystals causes the heat conductivity coefficient to increase, by bringing on an additional microconvection effect. In the case of a turbulent flow, the microconvection process caused by solid particles is outweighed by the turbulence of the carrying liquid,
- in laminar flow regimes for over 80%, and in turbulent regime for over 88% of measurement points, the divergence between the heat transfer coefficient values calculated on the basis of their own criterial relations and those obtained through measurement is smaller than 15%. According to Kozicki, making the Nusselt number dependent on the generalized Reynolds number, as long as other similarity conditions are fulfilled, allows for the application of the suggested formula to non-Bingham fluids.

References

[1] Niezgoda-Żelasko B., *Heat transfer and pressure drop of ice slurries flow in tube*, Monografia 334, Wyd. PK, Kraków 2006.

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

[3] Charunkyakorn P., Sengupta S., Roy S.K., *Forced convective heat transfer in microencapsulated phase change material slurries: flow in circular ducts*, International Journal of Heat Mass Transfer, 34, 1991, 819-833.

[4] Egolf P.W., Kitanovski A., Ata-Caesar D., Stamatiou E., Kawaji M., Bedecarrats J.P., Strub F., *Thermodynamics and heat transfer of ice slurries*, International Journal of Refrigeration, 28, 2005, p. 51-59.

[5] Guilpart J., *Experimental study and calculation method of transport characteristics of ice slurries*, First Workshop on Ice Slurries of the International Institute of Refrigeration, Yverdon--Les-Bains, Schwitzerland 1999, p. 74-82.

[6] Jensen E., Christensen K., Hansen T., Schneider P., Kauffeld M., *Pressure drop and heat transfer with ice slurry*, Purdue University, IIF/IIR 2000, p. 521-529.

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

[8] Kozicki W., Chou C.H., Tiu C., *Non-Newtonian flow in ducts of arbitrary cross-sectional shape*, Chemical Engineering Science, 21, 1966, 665-679.

[9] Meewisse J.W., Infante Ferreira C.A., *Optimal properties of ice slurries in secondary cooling systems*, Purdue University IIR-IIF, 2000, 513-520.

[10] Niezgoda-Żelasko B., *Heat transfer of ice slurries flows in tubes*, International Journal of Refrigeration, 29, 2006, 437-450.

[11] Niezgoda-Żelasko B., Żelasko J., *Generalized non-Newtonian flow of ice-slurry*, Chemical Engineering and Processing, 46, 2007, p. 895-904.

[12] Nørgaard E., Sørensen T.A., Hansen T.M., Kauffeld M., *Perfomance of components of ice slurry systems: pumps, plate heat exchangers and fittings*, International Journal of Refrigeration, 28, 2005, 83-91.

[13] Snoek C., Bellamy J., *Heat transfer measurements of ice slurry in tube flow*, Exp. Heat Transfer Fluid Mech. Thermo, 1997, 1993-1997.

[14] Stamatiou E., Kawaji M., *Thermal and flow behavior of ice slurries in a vertical rectangular channel. Part I: Local distribution measurements in adiabatic flow*, International Journal of Heat and Mass Transfer 48, 2005, 3527-3543.