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Erratum

Erratum to "Validation of the use of heat transfer models in liquid/solid fluidized beds for ice slurry generation" [International Journal of Heat and Mass Transfer 46 (2003) 3683–3695]

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Abstract

In the concerned paper, tube dimensions have been taken from the experimental set-up drawings. Recently, during Wilson plot calibration tests, after extension of the operating range of the set-up, came to light that the tube sizes used were slightly different from what was stated in the drawings. Consequently, published experimental fluidized bed heat transfer coefficients are up to 40% too low and some conclusions had to be adapted. The new, correct experimental heat transfer results show a much better agreement with heat transfer models in literature. The authors of the subjected paper deeply regret the errors. Corrected versions of Sections 4 and 5 of the paper are presented here.

Keywords: Fluidized beds; Heat transfer; Phase change

4. Results and discussion

4.1. Operating range of fluidized bed ice crystal generator

Ice slurry generation in a fluidized bed heat exchanger can only be stable within a certain range of operating conditions. The solid particles need to impact on the heat exchanging surfaces frequently enough to keep them free of ice. Several factors may prevent this:

1. If the temperature driving force is too high, ice crystal growth will be too fast and a solid ice layer will build-up regardless of the impact of solid particles.
2. A too low liquid phase velocity, encountered at low bed voidage, will not give the solid particles enough momentum. The particles can then not impact hard enough on walls to keep ice from sticking to the walls. Ice will also stick to walls if particles are too light or too small.
3. An aggregate fluidization regime or a too high bed voidage might cause parts of the heat exchanging walls to be without particle impacts for too long, allowing for build-up of an ice layer.

Heat transfer rates decrease if there is a solid (growing) layer of ice sticking to the heat exchanging surface.

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Also the fluidized bed will expand and flow out of the tube, because there is less volume available for the fluidized bed. The fluidized bed operation becomes unstable and it will eventually be completely blocked by ice.

The factors mentioned above are not independent: For each set of operating conditions there appears to be a maximum temperature difference above which ice will stick to walls.

A few parameters are essential to control the generation of ice slurry: The temperature driving force for crystallization, the bed voidage and the superficial velocity. Also fluid properties, bed and particle dimensions impose limits on the operating range of the fluidized bed ice generator, as these determine the fluidization regime. In experiments it was found that at a bed voidage of 0.75 or lower there was no stable ice slurry generation possible. Also at a bed voidage of 0.88 ice slurry could only be produced at very low temperature differences. Higher bed voidages may be possible at small temperature differences but were not tested. Optimum heat transfer coefficients have been predicted around a bed voidage of 0.73 by Jamialahmadi et al. [10]. This optimum bed voidage is probably hard to obtain during ice slurry generation. The limits on the operating range complicate determination of an accurate heat transfer model, as some parameters cannot be altered over a wide range.

The maximum allowable wall-to-bed temperature difference strongly depends on the mass concentration of freezing point depressant. At low freezing point depressant mass concentrations ice crystals are more likely to attach to walls and the allowable temperature difference is low. In Fig. 3 wall-to-bed temperature differences are given versus the freezing point depressant concentration for all experiments with sodium chloride at 0.80 bed voidage. The line between stable and unstable ice slurry generation conditions gives the maximum allowable wall-to-bed temperature difference. The limit depends almost linearly on the sodium chloride concentration. It was found that at a higher bed voidage the maximum allowable wall-to-bed temperature difference was smaller than in the experiments of Fig. 3. If ethylene glycol was used as freezing point depressant instead of sodium chloride, the stable operating range was larger. At equal freezing points, approximately 24% larger temperature differences could be applied with ethylene glycol. The limit again depended linearly on the concentration.

4.2. Thermophysical properties

The thermophysical property models for ice slurries of Section 2.2 combine properties of liquid solution, ice, and their interactions. It is, however, not known if there are interaction effects during ice formation in the fluidized beds. If heat is transferred primarily from walls to the liquid phase of the slurry and ice crystallization occurs in the bulk of the bed, only properties of the liquid phase are required for heat transfer calculations. Otherwise, if the ice slurry behaves as a single fluid, property models of the ice slurry including the solid ice phase need to be used.

In Fig. 4 heat transfer results of a typical production run are displayed for an ice slurry based on sodium chloride. Also the ice fraction at the outlet of the fluidized bed heat exchanger is displayed in Fig. 4. In this experiment the inlet temperature of the secondary refrigerant was kept constant. At higher ice fractions the temperature of the ice slurry decreases as the freezing point is further depressed, therefore the overall temperature difference slightly decreases. In other experiments the primary cooling fluid temperature was adjusted to obtain a constant overall temperature difference. The experiment was stopped at an ice mass fraction of approximately 0.17. The heat transfer coefficient is practically constant. The average heat transfer coefficient is calculated for comparison with other experiments.

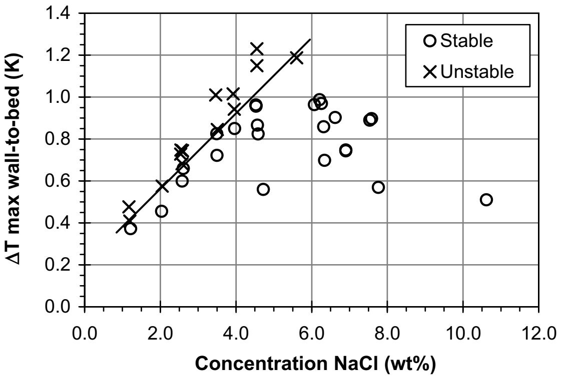

Fig. 3. Maximum wall-to-bed temperature difference for NaCl based ice slurry. Bed voidage of 0.80, 4 mm cylindrical steel particles in 55 mm diameter fluidized bed set-up.

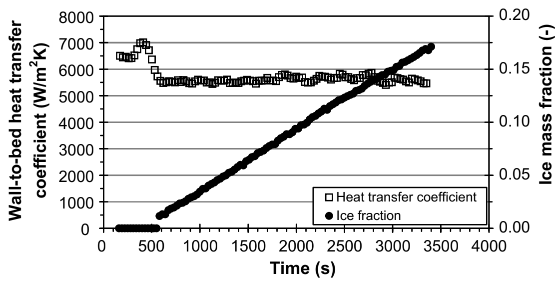

Fig. 4. Wall-to-bed heat transfer and ice fraction for NaCl ice slurry production run in 55 mm diameter fluidized bed with 4 mm particles and 0.80 bed voidage. NaCl concentration: 6.6 wt%, −4.1 °C initial freezing point. Ice crystallization starts at $t = 500$ s.

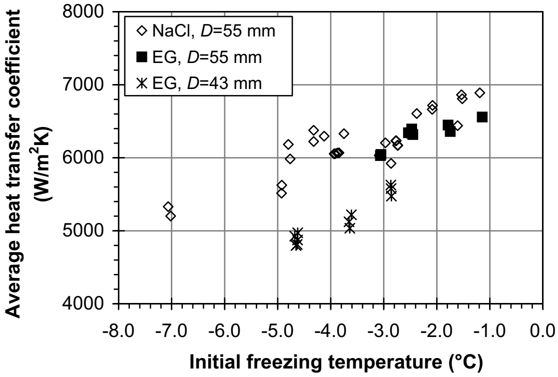

Fig. 5. Overview of the average heat transfer coefficients versus the initial ice slurry freezing temperature. Experiments with ice slurries based on NaCl and on ethylene glycol in the 55 mm diameter fluidized bed with 4 mm particles and with ice slurries based on ethylene glycol in the 43 mm diameter fluidized bed with 3 mm particles.

In Fig. 5 the range of the average heat transfer coefficient is given for the experiments with NaCl in the 55 mm diameter tube and for the experiments with ethylene glycol in both the 43 mm and the 55 mm tube. Heat transfer coefficients appear higher at higher freezing temperatures, but effects of other significant parameters, such as bed voidage and superficial velocity, are not shown in Fig. 5. The heat transfer coefficients are plotted versus the superficial velocity in Fig. 6 for the same experiments as in Fig. 5. The heat transfer coefficients predicted with the Dittus–Boelter model [18] for fluids with similar thermophysical properties but in single-phase flow without fluidized bed, are also shown in Fig. 6. The heat transfer coefficients are significantly higher with the fluidized bed present, which is consistent with earlier work on fluidized bed heat transfer [7]. It should be noted that it is not possible to produce ice slurry without the fluidized bed.

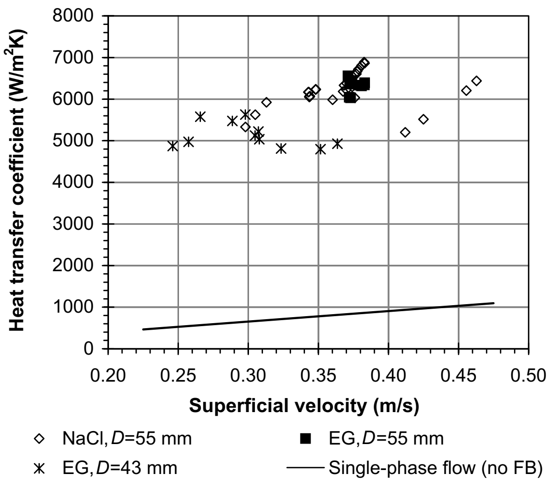

Fig. 6. Overview of the average heat transfer coefficients vs. the superficial velocity in the fluidized bed. Results of the same experiments as displayed in Fig. 5, with heat transfer coefficients under equal conditions without fluidized bed.

In the experiment of Fig. 4 the heater in the ice storage tank was not used, so effects of an increasing ice fraction could be observed. The heat transfer coefficient remained at a practically constant level at increasing ice fraction. As temperature differences and ice fractions only change very gradually, the system was assumed near steady-state for heat transfer calculations. To obtain a true steady state however, the heater is required to melt the ice crystals produced. A number of experiments have been performed under constant ice fraction conditions.

The general model of Eq. (7) was used to initially examine heat transfer trends at increasing ice fractions. This generalized model was considered suitable as an initial model to test effects of different thermophysical properties, as it was obtained from researches under a wide range of conditions. If the apparent heat capacity including the latent heat effect is used in this model to calculate the Prandtl number, a step change up to more than double the heat transfer coefficient would be seen after the start of ice formation. In the experimental data however no such step could be identified, as can be seen in Fig. 4. Instead a step down is observed, which is caused by the different temperature of the ice slurry as the supercooling substantially decreases after the start of ice formation. The Prandtl number at the start of ice formation calculated with apparent heat capacity in this experiment is 309, which predicts a heat transfer coefficient of 4.0×10^4 W/m^2 K, using Eq. (7). Such a large heat transfer coefficient was not observed in the experiments. The Prandtl number calculated with the sensible heat capacity only is 14.5, which predicts a heat transfer coefficient of 6.05×10^3 W/m^2 K, which is more consistent with the measured heat transfer coefficient of 5.60×10^3 W/m^2 K. The latent heat effect of the phase change was therefore disregarded and only sensible heat of the liquid phase and the sensible heat of the ice are relevant for heat transfer calculations.

Viscosity of ice slurries is higher when the ice fraction increases, according to Eq. (5). If the model of Eq. (7) is used, this would imply a decreasing heat transfer coefficient at higher ice fractions, as viscosity has a sum of exponents of −0.12. Thermal conductivity increases at higher ice fractions according to Eq. (2), which would give higher heat transfer coefficients because of a total exponent of 0.37. These two effects cancel each other at low ice fractions. At higher ice fractions the viscosity effect is dominant and heat transfer coefficients are predicted to decrease. The density and the sensible heat capacity only slightly change at higher ice fractions and are less influential in heat transfer models. In Fig. 7 the relative change of properties at increasing ice fraction is given for ice slurry with NaCl as the freezing point depressant, with initial concentration of 10 wt%, and an initial freezing point of −6.6 °C.

In Fig. 8 heat transfer coefficients calculated with Eq. (7) for the experimental conditions of Fig. 4 are displayed. Also heat transfer coefficients calculated with thermophysical properties of only the liquid phase of the ice slurries are displayed, which would be valid if ice crystals would not affect heat transfer. Both curves are very similar; relative difference between the curves is smaller than 2%. The curves do not provide enough detail to be certain about the type of thermophysical property models that need to be used. At low ice fractions, the influence of ice crystals appears to be relatively unimportant for the heat transfer coefficients in the fluidized bed ice slurry generator. Thermophysical property models of the ice slurry as a single fluid, including the solid ice properties, are used in the next section to obtain an accurate heat transfer model. These predict a more constant heat transfer coefficient than if only the properties of the liquid phase were used. This is more consistent with the experimental results.

At higher ice mass fractions both curves predict a slightly decreasing heat transfer coefficient. In the experiments however this was not observed. Instead, heat transfer coefficients increased slightly at higher ice fractions, as can be seen in Fig. 4. The ice particles themselves might have a positive effect on heat transfer, similar to those of the inert steel particles. The effect is small and could also be caused by the slightly different temperature levels at higher ice fractions. Furthermore,

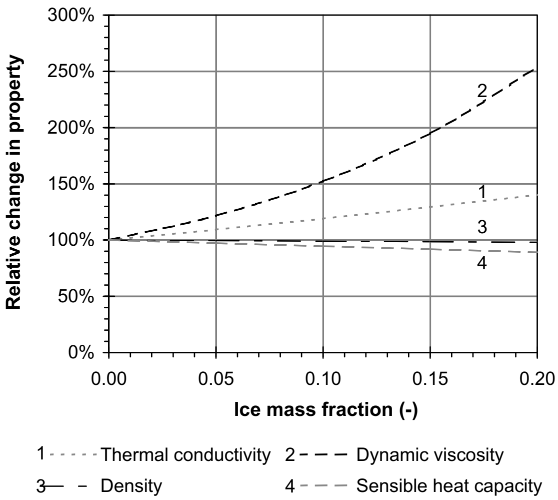

Fig. 7. Relative change of ice slurry properties at increasing ice fraction. For ice slurries based on 10 wt% NaCl, initial freezing temperature −6.6 °C.

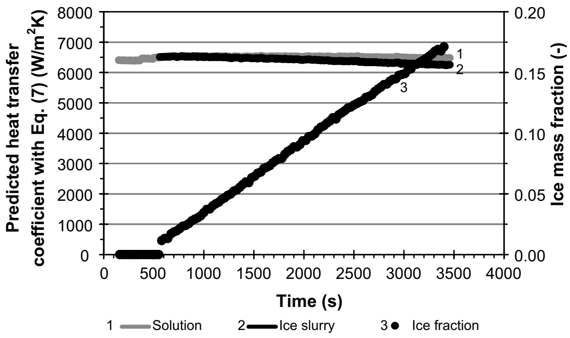

Fig. 8. Estimated heat transfer coefficients with Eq. (7) using thermophysical properties of ice slurry and of liquid solution at increasing ice fraction. Conditions as in Fig. 4.

this slightly increasing trend was not obvious in all experiments.

4.3. Heat transfer model

Because of the practical limits of ice slurry generation in the fluidized beds, discussed in Section 4.1, the bed voidage and the ice slurry temperatures were altered over a relatively small range. Some parameters concerning system dimensions were not varied. For example the ratio between the particle diameter and the column diameter was hardly varied in experiments, as in the smaller diameter fluidized bed also smaller steel particles were used. In Table 1 an overview of the range of operating parameters is given.

The heat transfer data obtained were compared with predictions of literature models of Eqs. (6), (7) and (10) and with some literature models that were used to obtain the generalized correlations [17,22–24]. The results given in Table 2 show that some literature models predict higher, while other predict lower heat transfer coefficients than have been measured during ice generation. The comparison shows that the heat transfer models proposed by Haid [9], Haid et al. [7], and Kollbach [24] give the best accordance with measured heat transfer coefficients. Among these models, Kollbach's model shows the smallest average absolute error. However, this model was not proposed for accurate determination of heat transfer coefficients, but as a design calculation tool to estimate a lower limit of the heat transfer coefficient. Therefore the second-best model proposed by Haid [9], which is based on a large collection of experimental data points, is assumed to be the most reliable model to predict heat transfer coefficients during ice slurry generation.

A comparison between experimental Nusselt numbers and Nusselt numbers predicted by Haid's model from Eq. (7) for all the experiments with stable ice slurry production is displayed in Fig. 9. A corresponding

Table 1
Range of operating parameters

Parameter	Min.	Max.
Re_p (–)	192	1096
Pr (–)	13	29
ε (–)	0.77	0.88
d_p (m)	3.4×10^{-3}	4.6×10^{-3}
D_h (m)	42.7×10^{-3}	54.8×10^{-3}
u_s (m/s)	0.25	0.46
T (°C)	−7.1	−0.7
m_{fpd} (wt%)	1.2	13.2
w_i (–)	0	0.19
μ_{is} (Pa s)	1.7×10^{-3}	4.5×10^{-3}
λ_{is} (W/m K)	0.53	0.69
ρ_{is} (kg/m^3)	995	1080
c_{p_is} (kJ/kg K)	3.63	4.16
Nu_p (–)	24	61
α (W/m^2 K)	3870	7110

comparison for heat transfer coefficients is shown in Fig. 10. Both figures clearly show that Haid's model overestimates heat transfer coefficients during ice generation. If the proportional factor, c_1 in Haid's model of Eq. (7) is adjusted to $c_1 = 0.0656$, then the accuracy of the model is improved resulting in an average error of −2.2% and a standard deviation of 15.1%.

The original model proposed by Haid [9] overestimates heat transfer coefficients during ice generation. A likely cause for this difference is the interference of ice crystals or interference of the ice crystallization process. As was shown in Fig. 4, heat transfer coefficients during ice generation appear to be slightly lower than heat transfer coefficients just before the start of ice crystallization at $t = 500$ s. These lower heat transfer coefficients might be explained by the existence of small ice nuclei at the heat exchanger walls causing a microscopic insulation layer of a few to 20 μm.

Another reason for the differences with Haid's model might be the temperature levels close to the freezing point of the solutions. Viscosity of solutions is relatively high close to the freezing point and a high viscosity is a likely cause for modified behavior, as was reported by Bremford et al. [19]. Temperature levels of the various

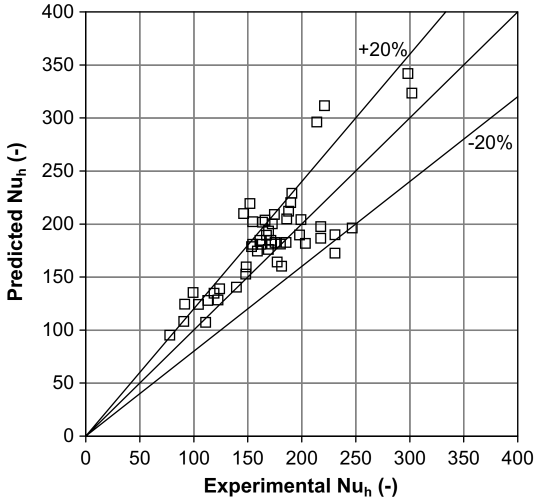

Fig. 9. Comparison of experimental and predicted values of hydraulic Nusselt number with Eq. (7) and the +20% and −20% margins.

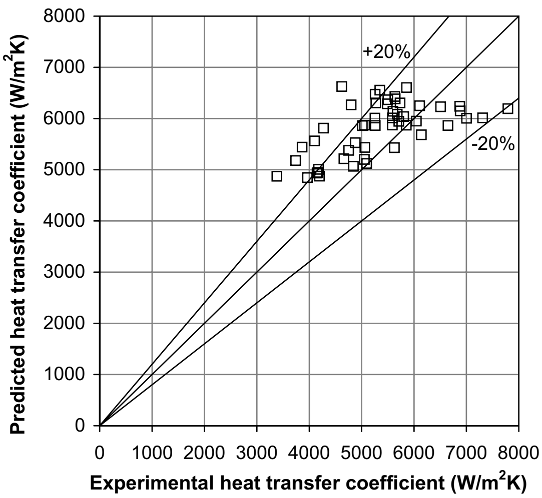

Fig. 10. Comparison of experimental and predicted values of heat transfer coefficient with Eq. (7) and the +20% and −20% margins.

Table 2
Comparison of literature heat transfer models of Eqs. (6), (7) and (10) applied to all experimental data for ice slurry generation

Model	Parameters							Rel. avg. error (%)	St. dev. rel. error (%)
	c_1	c_2	c_3	c_4	c_5	c_6	c_7		
Haid [9] (Eq. (7))	0.0734	0.75	0.63	–	–	–	–	+9.4	16.9
Haid et al. [7] (Eq. (6))	0.1493	0.72	0.52	0.19	−1.41	0.17	0.03	+11.8	17.1
Kim et al. [20] (Eq. (10))	0.0722	0.25	0.5	0.25	0.25	–	–	−22.4	12.3
Ruckenstein et al. [17] (Eq. (10))	0.067	−0.237	0.33	0.522	–	–	–	+14.1	20.3
Kang et al. [22] (Eq. (6))	0.191	0.69	0.33	0.31	−1	–	–	−26.0	11.7
Muroyama et al. [23] (Eq. (6))	0.137	0.729	0.33	0.271	−1	–	–	−27.5	11.8
Kollbach [24] (Eq. (6))	0.118	0.7	0.5	0.2	−1	–	–	−4.2	15.9

Table 3
Comparison of heat transfer coefficients at steady state with Haid's model of Eq. (7) in 1.0–25.0 °C temperature range

Exp.	Average temp slurry (no ice) (°C)	Experimental heat transfer (W/m^2 K)	Predicted heat transfer (W/m^2 K)	Relative difference (%)
1	25.0	7803	7136	−8.5
2	20.0	7530	6992	−7.1
3	15.0	6970	6813	−2.3
4	10.0	6584	6647	+1.0
5	5.0	6315	6464	+2.4
6	1.0	5789	6276	+8.4

researches were typically above 300 K, which is 28–34 K higher than in the current research. An experiment measuring heat transfer coefficients of water at temperatures between 1 and 25 °C was conducted to compare heat transfer coefficients at conditions more similar to the various literature researches. Table 3 shows that Haid's model overestimated heat transfer coefficients at temperatures between 1.0 and 10.0 °C similar to the ice generation experiments, but underestimated heat transfer coefficients at higher temperature levels.

In the models of Eqs. (6) and (7), both column diameter and particle diameter influence the heat transfer only indirectly, as these parameters co-determine superficial velocity and bed voidage. It is likely that parameters such as column diameter and particle diameter also have a significant impact and can also partially explain differences.

5. Conclusions

The formation of ice crystals did not have a large effect on heat transfer coefficients in the fluidized bed ice slurry generator. If at a given set of operating conditions stable ice slurry production was possible, heat transfer coefficients were similar to those in fluidized beds before start of ice crystal formation. Heat transfer coefficients measured using the fluidized beds were significantly higher than those predicted for single-phase flow.

A range of temperature differences was determined in which stable ice slurry generation was possible. The limit of this range depended linearly on the concentration of freezing point depressant.

Thermophysical property models reported for ice slurries in literature could be applied in models to predict wall-to-bed heat transfer coefficients. The heat capacity without the latent heat term should be used for this purpose. An empirical heat transfer model by Haid [7] was proposed to predict heat transfer coefficients in a fluidized bed ice slurry generator. This heat transfer model overestimated heat transfer coefficients during ice generation with an average error of 9.4%. Relatively low temperature levels during ice slurry production were the most likely cause for the differences, as only a small influence of ice crystals was observed.