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Advanced numerical modeling of turbulent ice slurry flows in a straight pipe

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ABSTRACT

The present work aims at developing and assessing an advanced numerical model in order to investigate the dynamic behavior of ice slurry flows under isothermal conditions. The transport equation proposed by Phillips et al. [1] for solid suspension flows is used to describe the evolution of the particle volume fraction within the flow. For turbulent flows, an original term is introduced to account for the turbulent dispersion of the particles. The model has first been favorably compared to experimental data available in the literature for three types of solid-fluid suspensions. It is also shown that it provides more accurate predictions than more complex two-phase models. The numerical model has then been used confidently to investigate ice slurry flows. Four turbulence closures have been compared in a numerical benchmark. The results obtained by the $k-\omega$ SST model have then been compared for discussion to the analytical model of Kitanovski and Poredǒs [2] for eight sets of inlet flow conditions. The present model is able to capture more complex flow features, especially the secondary flow and the near-wall boundary layers.

1. Introduction

Ice slurries are a complex mixture of liquid water, ice particles and a given additive used to lower the freezing point temperature of the mixture. Progressively, they become a competitive alternative to conventional secondary refrigeration systems due to the recent improvements in ice slurry generator technology. Companies can now manufacture generators able to produce highly concentrated ice slurries without ice agglomeration, especially using seawater (see the recent review of Melinder and Ignatowicz [3]). As other phase changing media, ice slurry allows to store and transport a very large amount of "cold energy". Egolf and Kauffeld [4] observed that the heat capacity of ice slurries is eight times higher than the heat capacity of traditional single-phase secondary refrigerants. For a given amount of transported energy, the pumping energy consumption is then drastically reduced compared to other secondary refrigerants and smaller equipment can be used. The reduced freezing point temperature of the mixture enables to improve the quality of the produced cold and to obtain a cooling process with almost no temperature change. Ice slurries contain a very small quantity of non-polluting additives, which makes them an efficient refrigeration technology with a low environmental impact. They have therefore been widely applied in various industrial applications going from building cooling to food conditioning, or even in medical protective cooling applications. The reader can refer to some review papers [4–7] for more details.

More surprisingly, their local and/or time-dependent hydrodynamic behavior still remains not fully understood. The thermal insulation of the heat exchangers and the opacity of ice slurries, among other parameters, make the measurements of local velocity, temperature or ice concentration difficult. During the last two decades, experiments concerned mainly global measurements: pressure loss, mass flowrate, wall temperatures or density among other things, both at the inlet and the outlet of heat exchangers. Various operating conditions were considered in terms of flowrate, initial concentration of the additive and of the ice particles, type of additive, geometrical configuration, thermal boundary conditions … As examples, Renaud-Boivin et al. [8] performed experiments in a shell and tube heat exchanger with an ethylene glycol ice slurry flowing in the tubes and hot water in the shell and Kumano et al. [9] investigated the flow and heat transfer characteristics of ethanol ice slurry in the transition region. From experimental measurements of the flowrate and the pressure loss, other authors deduced rheological laws for ice slurry flowing in pipes [10] or more complex geometries [11]. Reviews on the thermophysical properties of ice slurry may be found in Refs. [4,12].

The lack of reliable local experimental data has slowed down the development of innovative and dedicated numerical models. Ice slurry flows are very challenging for numerical methods: multiphase flows, non-Newtonian behavior, thermal imbalance between the different

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Nomenclature

C_f	friction coefficient, −
D	particle diameter, m
D	pipe diameter, m
K	turbulence kinetic energy, $m^2.\ s^{-2}$
L	pipe length, m
P	pressure, Pa
(r, θ, z)	radial, tangential and axial coordinates
Re_b	bulk Reynolds number, −
S	stratification index, −
T	temperature, K
$u'_i u'_j$	Reynolds stress tensor components, $m^2.\ s^{-2}$
U_{in}	inlet mean velocity, $m.\ s^{-1}$
u	local mean axial velocity, $m.\ s^{-1}$
w_s	terminal particle settling velocity, $m.\ s^{-1}$
δ	Kronecker symbol, −
ΔP	pressure drop, Pa
ε	dissipation rate of turbulence kinetic energy, $m^2.\ s^{-3}$
$\dot{\gamma}$	shear rate, s^{-1}
μ	dynamic viscosity, $Pa.\ s$
ν	kinematic viscosity, $m^2.\ s^{-1}$
ϕ	particle volume fraction, $m^{-3}.\ m^{-3}$
Φ_{in}	inlet particle volume fraction, $m^{-3}.\ m^{-3}$
ρ	density, $kg.\ m^{-3}$
τ	shear stress, Pa
ω	specific turbulence dissipation rate, s^{-1}
i, j	indices
in	quantity evaluated at the pipe inlet
m	mixture
max	maximum value
min	minimum value
l	liquid phase, aqueous solution
s	solid phase, particles
w	wall

phases, phase change … For all these reasons, numerical methods are seldom applied to the research carried out on ice slurry flows. Mellari et al. [10] used an in-house solver to investigate unsteady laminar ice slurry flows in a horizontal pipe under isothermal conditions. The flow was supposed axisymmetric and the slurry treated as a single-phase mixture. The rheology of the ice slurry composed of monopropylene glycol was taken into account through a power law, while no transport equation for the ice concentration was considered. Their simulations exhibited discrepancies up to 100% compared to the measured pressure drop at high inlet velocities. Niezgoda-Zelasko and Zalewski [13] analyzed laminar and turbulent ice slurry flows using a RNG $k-\varepsilon$ model. Ice slurry was considered as a complex mixture exhibiting the properties of a Bingham fluid. Their numerical modeling was validated in terms of normalized pressure drops for ice fractions up to 30% and bulk Reynolds numbers $Re_b = U_{in}D/\nu_m$ up to 6430. The mixture and Eulerian models were found to provide very similar results for the mean velocity field, while the Eulerian model underestimates the pressure drop. The authors finally recommended the use of the Eulerian model, together with the Syamlal-O'Brien model for the interphase interaction and the RNG $k-\varepsilon$ turbulence model to get an accuracy better than 10%. Wang et al. [14] investigated isothermal turbulent ice slurry flows in different elbow pipes using an Euler-Euler model based on the kinetic theory of granular flow. A $k-\varepsilon$ model with standard wall functions was used as turbulence closure. The numerical results remained within ± 20% the experimental values for the pressure drop. Such a model has been later successfully applied to the forced convective flow and heat transfer of ice slurry in horizontal pipes by Zhang and Shi [15]. Mika [16] performed numerical calculations of Newtonian ice slurry flows in a poppet-type flow control valve using the mixture model and a RNG $k-\varepsilon$ model with standard wall functions. A good agreement with the measurements was obtained for the local loss coefficient. Wang et al. [17] applied the mixture model together with a standard $k-\varepsilon$ model to characterize heterogeneous ice slurry flows in horizontal pipes under isothermal conditions. It compared fairly well in terms of ice concentration profiles, while it underestimated the pressure drop by about 15%. Onokoko and Galanis [18] studied isothermal turbulent ice slurry flows in a horizontal tube using the Phillips et al.'s model [1] (with different features compared to the present model) and a realizable $k-\varepsilon$ turbulence closure. The near-wall treatment was not specified and the model was validated in the case of a laminar forced convection of water in a pipe. They took into account some rheological characteristics of ice slurries through a piecewise rheological law.

Numerical developments are still required to develop simple but accurate and reliable numerical models to describe the flow dynamics and the structure of ice slurry even in simple geometries like straight pipes. The objective of the present paper is three-fold: (1) to properly apply and validate the model proposed by Phillips et al.'s [1] for turbulent solid-liquid suspension flows. Three experimental database will be used for comparisons; (2) to improve the predictions of the $k-\omega$ SST model by adding a new term derived from stochastic Lagrangian models [19] and accounting for the turbulent dispersion of the solid particles; (3) to extend the new model to isothermal ice slurry flows and propose a deep insight into their dynamics for eight different operating conditions with an emphasis on the stratification phenomenon. The analytical model of Kitanovski and Poredoš [2] will be used to enrich the discussion.

The present paper is then organized as follows: the numerical modeling and its validation are presented in Sections 2 and 3 respectively. The validation is achieved by comparisons to experimental results published in the literature for three types of solid-liquid suspension flows. The influence of the inlet axial velocity and the inlet particle concentration on the hydrodynamic and concentration fields are then discussed in details in Section 4 for isothermal ice slurry flows in a tube. The pertinence of the new model is compared to the analytical model of Kitanovski and Poredoš [2]. Finally, Section 5 summarizes concluding remarks and future views.

2. Numerical modeling

Three-dimensional steady calculations are performed using a finite-volume solver under isothermal conditions. The model proposed by Phillips et al.'s [1] is used for the transport equation of the particle volume fraction. An additional term in the transport equation of the ice concentration accounts for the turbulent dispersion of the particles.

2.1. Geometrical modeling

One will consider in the following the isothermal turbulent flows of ice slurries in a cylindrical tube under steady-state conditions (Fig. 1). The results will be later compared for discussion to the analytical model of Kitanovski and Poredoš [2].

Table 1 summarizes the main geometrical and flow parameters for the configuration considered by Kitanovski and Poredǒs [2]. These authors considered ice slurries flowing through a cylindrical pipe of length $L = 1.68$ m and diameter $D = 0.0272$ m. Ice slurry is composed of liquid water with 10 wt% ethanol additive and ice particles having a diameter equal to $d = 0.001$ m. The two varying parameters are the inlet axial velocity U_{in} and the inlet particle concentration Φ_{in}.

The operating conditions (U_{in}, Φ_{in}) are reported on the safety diagram provided by Snoek (Fig. 2a). They cover the three regions within