International Journal of Thermal Sciences 126 (2018) 82–95

Contents lists available at ScienceDirect

International Journal of Thermal Sciences

journal homepage: www.elsevier.com/locate/ijts

Experimental and numerical investigation of isothermal ice slurry flow

Landa Onokoko[a], Michel Poirier[b], Nicolas Galanis[a,*], Sébastien Poncet[a]

[a] Génie mécanique, Université de Sherbrooke, Sherbrooke QC, Canada
[b] CanmetEnergy, Natural Resources Canada, Varennes QC, Canada

ARTICLE INFO

Keywords:
Horizontal pipe
Single-phase fluid
Pressure drop
Friction coefficient
Ice slurry

ABSTRACT

The characteristics of propylene glycol ice slurry flow through a long horizontal pipe (L/D ≈ 177) were investigated experimentally for flow rates between 1 and 38 kg/min and ice fractions of 5%–24% by mass. Pressure losses in the tube, inlet and outlet densities, temperatures and mass flowrates of the ice slurry were measured and analyzed. A 3D CFD model which treats the ice slurry as a Newtonian fluid with effective properties depending on the local ice fraction and includes the shear-induced migration as well as the hindered settling velocity is also presented. It has been validated for laminar and turbulent conditions with data from the literature. The calculated pressure drop is in good agreement with experimental data from the present and previous studies. The proposed model has therefore been used to establish some important ice slurry flow characteristics which have never been obtained experimentally. Notably, the calculated results illustrate the axial and circumferential variation of the friction coefficient and explain its angular variation by analyzing the predicted ice fraction and velocity fields. The effects of the inlet ice fraction on these fields are also illustrated and analyzed.

1. Introduction

Ice slurries are mixtures of small ice particles (typically 0.1–1 mm of diameter) and a carrier liquid (a mixture of water and an additive -such as glycol, alcohol or salt-which lowers the freezing temperature). They offer the possibility of enhanced energy transport density and energy storage due to the combined effects of sensible and latent heat. Applications include comfort cooling of buildings, food processing and the replacement of secondary refrigerants in ice rinks or supermarkets. According to the Handbook on Ice Slurries [1], their thermophysical properties can be derived from linear weighing of the corresponding properties of the ice (which are essentially determined by the temperature) and the carrier liquid (which vary with the temperature and the concentration of the additive).

The rheological behavior of ice slurries is complex. Kitanovski & Poredos [2] showed that for high average velocities and very low ice concentrations "the ice slurry viscosity is almost independent of velocity as for Newtonian fluids". On the other hand, ice slurries exhibit a non-Newtonian behavior for ice concentrations exceeding approximately 20% but this threshold value is influenced by parameters such as the size of the ice particles as well as the nature and concentration of the additive [1]. Furthermore, separation of the solid ice particles and the carrier liquid increases when the velocity decreases or when the size of the particles and the density of the liquid carrier increase. Under such conditions, ice particles concentrate in the upper side of the tube because their density is smaller than that of the aqueous solution. Thus, various patterns (homogeneous flow, heterogeneous flow, moving bed and stationary bed) are encountered in ice slurry pipe flow which affect the hydrodynamics of the flow and the mechanisms of heat transfer [3]. In view of this complex situation, research activities in this field are numerous, especially regarding the rheological behavior of ice slurries by pressure drop measurements. Recent published articles include the experimental study by Mellari [4] who assumed that the monopropylene glycol (MPG) ice slurry follows the Ostwald-de Waele law and obtained correlations for the consistency coefficient and the flow index in terms of the initial MPG concentration and the mass ice concentration. The results confirmed that ice slurries sometimes behave as Newtonian fluids and other times as non-Newtonian (with a flow index higher or lower than one). Friess et al. [5] investigated the effect of foreign particles of higher density than ice which can serve as ice forming nuclei. Ideally, this would lead to an increased density of the modified ice particles and would suppress the buoyancy force which leads to the aforementioned non-homogeneous concentration distributions. They reported that it was indeed possible to modify the density of ice particles but that the process was uncontrollable and resulted in sedimentation of the modified ice particles. They concluded that further research is needed in this field using different substances.

Zhang & Shi [6] investigated numerically the forced convective flow

* Corresponding author.
E-mail address: nicolas.galanis@usherbrooke.ca (N. Galanis).

https://doi.org/10.1016/j.ijthermalsci.2017.12.017
Received 1 May 2017; Received in revised form 21 November 2017; Accepted 16 December 2017

Nomenclature

a	Average ice particle radius (m)
D	Internal pipe diameter (m)
f	Friction coefficient (–)
h	Hindrance function (-)
K_c, K_μ	Constants (-)
k	Turbulence kinetic energy ($m^2\ s^{-2}$)
L	Length of pressure drop measurement section (m)
$\dot{m}$	Mass flowrate ($kg\ s^{-1}$)
P	Pressure (Pa)
Re	Reynolds number (–)
$S_{\dot{\gamma}}$	Source term in species equation
T	Temperature (°C)
u	Velocity ($m\ s^{-1}$)
w	Mass fraction (% by weight)
x_i	Cartesian coordinates
Z	Axial coordinate (m)

Greek letters

$\dot{\gamma}$	Shear rate (s^{-1})
Γ	Diffusive coefficient ($m^2\ s^{-1}$)
ε	Dissipation of turbulence kinetic energy ($m^2\ s^{-3}$)
μ	Dynamic viscosity (Pa s)
ρ	Density ($kg\ m^{-3}$)
τ	Shear stress tensor (Pa)
∅	Volume fraction (% by volume)
ω_o	Terminal velocity of a single ice particle in aqueous solution ($m\ s^{-1}$)

Subscripts

a	Additive
as	Aqueous solution
ic	Ice particle
is	Ice slurry
o	Inlet condition
∞	Refers to constant pressure drop for a fixed flowrate

of ice slurries in a horizontal pipe using a 3D Euler-Euler multiphase model based on the kinetic theory of granular flow. The model was validated with experimental data from the literature and used to investigate stratification in isothermal flow and melting of ice for constant wall heat flux. Their results for isothermal flow show that stratification was weakened by the turbulent dispersion force and that therefore the particle concentration was more uniform at higher inlet velocities. In the heated case the results show that the local heat transfer coefficient decreases rapidly in the entrance region as in all forced convection flows. It stays approximately constant in the thermally-developed region and starts increasing after the ice slurry is fully melted. Similar results for laminar and turbulent isothermal flows of ethylene-glycol ice slurries had been reported earlier by two of the present authors [7] using a simpler single-phase 3D model which treats the ice slurry as a Newtonian fluid with effective local properties depending on the local ice concentration. The predicted axial evolution of the ice concentration and velocity distributions clearly show that laminar results are essentially determined by ice particle movement due to buoyancy and diffusion while turbulence mixing is the controlling parameter for high average velocities. Niezgoda-Zelasko & Zalewski [8] performed CFD simulations of isothermal ice slurry flow using the single-phase model (Bingham fluid) and multi-phase models (mixture and Eulerian models). They showed that in the laminar region the Bingham and mixture models gave a correct description of momentum transfer. In the turbulent region the best agreement between experimental and numerical results (for the single-phase and the Eulerian models) was obtained with the RNG k-ε turbulence model and the enhanced wall treatment algorithm. The single-phase model overestimated pressure drops by less than 16%. In the case of the multiphase simulations the introduction of the particle size as a parameter led to agreement better than 10% between the simulations and experiments.

The pressure drop due to ice slurry flow is very important for engineering applications and has been investigated extensively, particularly for flow in horizontal tubes. According to Niezgoda-Zelasko & Zalewski [8], Hagg [9] and Grodzek et al. [10] the pressure drop increases with increasing ice fraction and velocity. On the other hand, Knodel et al. [11] and Liu et al. [12] reported a decrease in pressure drop with increasing ice fraction for low values of this parameter. These discrepancies suggest a different behavior of ice slurries for different ice fraction ranges.

In view of this situation the first objective of the present work is to study experimentally the characteristics of isothermal propylene glycol ice slurry flow through a horizontal circular tube. For this purpose the time evolution of measured temperature, density, and pressure drop as well as the corresponding ice mass fractions are presented and analyzed. Secondly we wish to further investigate the validity of the proposed single-phase CFD model for ice slurry flow. Hence, its numerical predictions of the velocity and/or ice mass fraction profiles as well as the pressure drop for different flowrates and ice mass fractions are compared to present and previous experimental results. Good agreement is obtained between these sets of data. The model is then used to investigate flow characteristics such as the axial and circumferential distribution of the friction coefficient as well as the effects of the inlet ice fraction on the axial evolution of the velocity and ice fraction fields. The complementarity of experimental and numerical results provides important insights into the flow of isothermal ice slurries.

2. Experimental study

2.1. Apparatus and procedure

The schematic diagram of the experimental apparatus (designed and built at the CanmetENERGY research center in Varennes, QC, Canada), is shown in Fig. 1. Its basic components are an 11 kW refrigeration capacity ice slurry generator (MuellerMaximICE®, Model ORE-3), a measurement loop including the test section and a data acquisition system. An 800 L ice slurry tank separates the ice generator and the measurement loop. It is equipped with a rotary mixer to ensure uniform distribution of the ice particles. The ice slurry is made by mixing water and Dowfrost 50/50 (a commercial product containing water, propylene glycol and corrosion inhibitors). Its measured freezing point is −1.29 °C. The corresponding initial mass fraction of the propylene glycol is 4.24% or 5.35% according to the correlations developed by Renaud-Boivin et al. [13] and Melinder [14] respectively; an in-house correlation between the freezing temperature and the propylene glycol mass fraction gives an intermediate value of 4.59%. The test section is a horizontal straight copper pipe with an inner diameter of 0.01692 m and a length of 3.188 m. It is equipped with two pressure taps at a distance of 2.997 m which are connected to a differential pressure transducer. Resistance temperature detectors (RTDs) are installed at the inlet and outlet of the tube and in the ice slurry tank. The mass flowrate and density of the ice slurry are measured before and after the tube with Coriolis flow and density meters. These quantities are measured every 15 s and stored in a monitoring system which also calculates the corresponding ice mass fractions from the in-house correlations. The range