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Thermal and flow behavior of ice slurries in a vertical rectangular channel. Part I: Local distribution measurements in adiabatic flow

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Abstract

Local measurements of the axial mixture velocity and ice fraction profiles were conducted for the vertically, upward adiabatic ice slurry flow in a 0.305-m (W) × 0.61-m (L) × 0.025-m (gap) rectangular channel using a hot film anemometer (HFA) and an on-line ice slurry sampling/calorimetry technique. Experiments were performed at area-averaged ice fractions and mean velocities up to 16 vol% and 0.15 m s^{-1}, respectively. The ice fraction distributions systematically displayed slight peaking near the adiabatic walls for average ice fractions less than 8%; however, at higher ice fractions, the ice fraction distributions became flatter. For average ice fractions greater than 2%, the velocity distributions displayed flatter profiles than in single-phase flow, which indicates the non-Newtonian flow characteristics of ice slurries.

Keywords: Adiabatic ice slurry flow; Hot-film anemometry; Ice fraction local distributions; Velocity distributions; Non-newtonian flow characteristics

1. Introduction

Recently, there has been an increasing interest in the use of ice slurries as a phase change material for many cooling applications due to several thermo-physical and transport advantages as well as the environmentally friendly nature that ice slurries offer. Although other alternatives such as slurries of polymeric phase change materials (PCMs) and block or crushed ice have been recently developed for cooling applications (e.g., [1–3]), ice slurries are superior in many aspects due to the large latent heat and surface area density of ice crystals, as well as the dynamic behavior of ice slurry. This growing interest towards ice slurries has been demonstrated in recent years through five international workshops that have brought a large number of researchers involved in the ice slurry generation, rheology, flow and heat transfer research and some other aspects of this potential new secondary refrigerant. However, many issues are still unresolved.

Ice slurry or "slush ice" is a mixture of fine ice crystals, water and an additive such as glycol, salt or alcohol, which functions to lower the freezing point of the solution and limit the crystal size. The ice crystal sizes typically range from 0.01 mm to 1 mm in diameter depending upon the additive type and concentration

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Nomenclature

A	area, m^2
C_p	heat capacity, $J\,kg^{-1}\,K^{-1}$
D	diameter, m
H	channel gap, m
$\dot{H}$	heat input, W
L	length, m
$\dot{m}$	mass flow, $kg\,s^{-1}$
M	number of samples
N	number of samples
n	power law index for pseudoplastic fluids
p	power index for Newtonian fluids
Q	volumetric flow rate, $m^3\,s^{-1}$
Re	Reynolds number
T	temperature, K
t	time, s
u	velocity or axial velocity, $m\,s^{-1}$
U_o	sampling velocity, $m\,s^{-1}$
$\langle u \rangle$	flow rate average velocity, $m\,s^{-1}$
V	integrated average velocity, $m\,s^{-1}$
W	channel width, m
X	mass fraction of solids, –
X_s	ice fraction, –
x	axial distance from inlet nozzle, m
y	transverse distance from a brass plate, m
y'	transverse distance from pipe axis, m
z	lateral distance, m

Greek symbols

α^*	aspect ratio (=channel height/width)
Δ	change in parameter
λ	latent heat of ice (=333.6 $kJ\,kg^{-1}$)
μ	kinematic viscosity, Pa s
ρ	density, $kg\,m^{-3}$
Φ	ice volume fraction, vol%

Subscripts

a	antifreeze agent
b	brine or bulk
c	cross sectional
cal	calorimeter
cf	carrier fluid
crit	critical
f	final
fp	freezing (or melting) point
h	hydraulic
hy	hydrodynamic
j	instantaneous measurement
in	inlet
L	local
m	mean or average
o	sampling
out	outlet
RMS	root mean square
s	mass fraction
sl	ice slurry or solid–liquid
T	turbine
v	volume fraction
w	water

Superscripts

′	instantaneous component
·	rate

[4,5] as well as the ice slurry generation method. When a freezing point depressant is not employed, ice slurry crystals larger than 1-mm in diameter are normally produced (e.g., [6]).

For the case of an adiabatic ice slurry flow, the momentum and continuity equations clearly reveal that the velocity and ice fraction distributions are coupled and interdependent [7–9]. However, often in horizontal ice slurry flows it has been observed that the ice crystals tend to accumulate near the top of the horizontal pipe at high ice fractions and low mean velocities, resulting in a considerable distortion of the velocity profile [10,11]. Alternatively, any significant change in the ice slurry velocity may alter the ice fraction distribution across the pipeline of interest.

Despite the relatively high importance of the velocity and ice fraction distributions in ice slurry flows, there has not been any known study that has attempted to quantify these distributions, which are needed to infer the form of constitutive relationships for modeling purposes. Some of the previous velocity and ice fraction distribution measurements [12–16] made in horizontal pipes or channels and in vertical ducts revealed the plug flow behavior of the ice slurries in laminar flow. However, these investigations were of preliminary nature and did not provide a systematic set of data.

Slurries of fine particle sizes are also known to exhibit non-Newtonian flow characteristics [3] due to the particle agglomeration and formation of structures. Previous investigations on the rheology of ice slurries summarized by Ayel et al. [4] have suggested that ice slurries behave as Newtonian slurries for weight ice fractions between 0 and 0.15. On the other hand, a study performed by Kitanovski and Poredos [17] suggested that the non-Newtonian flow characteristics of ice slurries not only depend on the average ice fraction but also on the mean velocity, pipe diameter and ice crystal sizes. Other factors that could also influence the rheological behavior of ice