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The fluid dynamics of ice slurry

Andrej Kitanovski[a,*], Didier Vuarnoz[a], Derrick Ata-Caesar[a], Peter W. Egolf[a], Torben M. Hansen[b], Christian Doetsch[c]

[a]*University of Applied Sciences of Western Switzerland (UASWS)*
[b]*Danish Technological Institute (DTI), Denmark*
[c]*Fraunhofer UMSICHT Institut*

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Abstract

A review of research work of fluid dynamics of fine-crystalline ice slurry is presented. Different rheological models which are applied are presented. Numerous models for the friction factor, obtained by empirical and semi-empirical approximation, are discussed. An overview of existing pressure drop experiments is given and problematic issues of respective measurements and experimental results are outlined. Because ice slurry is a two-phase fluid that is considered to be homogeneous, only in some cases work on stratified suspension flows is cited. Finally a variety of experimental results and some theoretical calculations of ice slurry flow patterns are shown.

Keywords: Two-phase secondary refrigerant; Ice slurry; Survey; Research; Physical property; Rheological property

Coulis de glace: dynamique des fluides

Mots clés: Frigoporteur diphasique; Coulis de glace; Enquête; Recherche; Propriété physique; Propriété rhéologique

1. Introduction

For several years researchers have been making efforts to describe the physical properties of ice slurry, its fluid dynamics and its heat transfer characteristics. Because various kinds of antifreeze depressants exist and can be used for producing ice slurry, published properties of ice slurries are always specific to a certain freeze depressing additive. Attention needs to be given to the inhibitors, which are commonly used in secondary refrigerants, and which affect basic properties like the freezing temperature. The method of producing and storing ice slurry also has a strong impact on the occurring ice slurry properties. This is particularly, because the size distribution of the ice particles varies for different production methods (e.g. vacuum generators, scraped-surface generators, generators based on supercooling of water, etc.) The mean particle size increases with the duration of storage and mixing. A variety of flow patterns are observed in ice slurry flows. They depend on the piping system, the operation parameters and the aforementioned physical properties. If a safe operation of a system is required, the flow pattern should correspond to homogeneous flow, which implies a constant ice concentration field as a function of the cross-sectional area of the tube.

* Corresponding author. Tel.: +41-24-557-61-54; fax: +41-24-426-44-77.
E-mail address: andrej.kitanovski@eivd.ch (A. Kitanovski).

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Nomenclature

Standard

A	area (m^2)
C	local concentration, concentration
Ca	Casson number
C_D	drag coefficient
D	pipe diameter (m)
d	ice particle diameter (m)
E_S	mass diffusion coefficient (m^2/s)
F	Fanning friction factor
He	Hedstrom number
L	length (m)
n	hindred settling parameter
p	pressure (Pa)
R	radial coordinate, specific pressure drop (Pa/m)
Re	Reynolds number
s, S	density ratio between solid and liquid
t	time (s)
T	temperature (°C)
V, v	velocity (m/s)
w	terminal settling velocity (m/s)
x	axial coordinate
y	radial coordinate

Greek

ϕ	angle of internal friction
ρ	density (kg/m^3)
σ	dispersive stress (Pa)
η	viscosity (Pa s)
ν	kinematic viscosity (m^2/s)
τ_{w0}	yield stress (Pa)
τ_w	wall stress (Pa)
τ	yield stress (Pa)
λ	Darcy's friction factor, thermal conductivity (W/mK)

Subscripts

app	apparent
B	Bingham
C	Casson
crit	critical
d	delivered
eff	effective
i	internal
f	fluid
is	ice slurry
K	arbitrary constant
l, *L*	liquid
max	maximum
n	power index
p	particle
r	in-situ
S,s	solid
v	volume, in-situ
0	limiting viscosity at zero shear rate

2. Rheology

Homogeneous suspensions are frequently described as single-phase, isotropic fluids with modified rheological behaviour. Instead of the viscosity of the liquid, η_L, a modified so called 'effective viscosity' of the suspension, η_{eff}, is commonly introduced. Many different models have been proposed for the viscosity of suspensions. Most of them essentially extend the work of Einstein ($C<0.01$) [1]:

$$\eta_{eff} = \eta_L(1 + 2.5C) \tag{1}$$

In this equation C is the concentration of the solid phase in a solid-liquid mixture. Eq. (1) does not take the sizes or positions of the particles into account, and the theory neglects the effects of particle interaction. Several models for the viscosity of Newtonian suspensions have been developed, as presented, e.g. in Ref. [2]. One of the most frequently applied equation for the viscosity of suspensions, which takes not only the concentration of the solid phase, but also the interaction between the solid particles into consideration, was given by Thomas [3]:

$$\eta_{eff} = \eta_L(1 + 2.5C + 10.05C^2 + 0.00273\exp(16.6C)) \tag{2}$$

The model is valid for particle concentrations up to 62.5% and particle sizes ranging from 0.1 to 435 μm. It considers that the flow is homogeneous. Eq. (2) has been widely recognized by researchers studying ice slurries. However, as has been shown by Hansen [4], this equation over predicts the viscosity of ice slurry at ice concentrations beyond 15%. He introduced Jeffrey's [2] equation with a constant $A=4.5$ to get the best fit with experimental results. At the same time Frei and Egolf [5] observed a time-dependent behaviour of ice slurry, which results in an altering size of the ice particles and consequently in also altering viscosities. Later, Hansen et al. [6] reported on the ice particle size distribution of ice slurry. They observed an increase of the mean diameter of the particles at constant ice concentration. As a consequence the number of ice particles decreases.

Various experiments have been performed to determine the effective viscosity of ice slurries. Different experimental methods and different storage tank sizes led to significant deviations between the obtained results (see Fig. 1). Eqs. (1) and (2) describe the viscosity of Newtonian suspensions, for which the shear stress is described by:

$$\tau = \eta_{eff}\frac{dv}{dy} \tag{3}$$

If the concentration of solid particles in a suspension is high,