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Experimental study on pressure drop and heat transfer in pipelines for brine based ice slurry Part II: Dimensional analysis and rheological model

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ABSTRACT

The rheological behaviour of the ice slurry made from 9% NaCl brine has been experimentally studied in this work. Starting from the dimensional analysis of pressure drop and heat transfer processes, the minimum numbers of non-dimensional parameters present in these processes have been determined. Rheological behaviour has been adjusted to the experimental data on ice slurry pressure drop. Two different behaviours were observed depending on the shear rate values, with a clear yield stress recognizable in the low shear rate region and a shear thickening behaviour for high shear rate values. A modified Herschel–Bulkley rheological model has been proposed, which is able to predict ice slurry behaviour in both, low and high shear rate region. The influence of the parameters involved has been determined and an analytical equation for the Darcy friction factor has been obtained from the model proposed and compared to experimental results. The comparison showed a very good agreement between these data.

Etude expérimentale sur la chute de pression et le transfert de chaleur dans les tuyauteries des systèmes aux coulis de glace à base de saumure. Partie II : analyse dimensionnelle et modèle rhéologique

Mots clés : Coulis de glace ; Frigoporteur ; Chlorure de sodium ; Expérimentation ; Chute de pression ; Transfert de chaleur ; Tube horizontal ; Calcul ; Rhéologie

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Nomenclature

c_p	specific heat ($J\,kg^{-1}\,K^{-1}$)
d	particle average diameter (m)
D	pipe diameter (m)
g	gravity acceleration ($m\,s^{-2}$)
h	heat transfer coefficient ($W\,m^{-2}\,K^{-1}$)
H_f	specific latent heat of fusion of ice ($J\,kg^{-1}$)
k	thermal conductivity ($W\,m^{-1}\,K^{-1}$)
K	consistency coefficient (-)
l_p	length of the pressure drop test section (m)
p	flow index (-)
ΔP	pressure drop across the test section ($N\,m^{-2}$)
q''	heat flux ($W\,m^{-2}$)
R	pipe radius (m)
t	temperature (K)
U	average flow velocity ($m\,s^{-1}$)
$\dot{V}$	volumetric flow rate ($m^3\,s^{-1}$)

Greek symbols

β	thermal dilatation coefficient (K^{-1})
δ	carrier fluid concentration (-)
ε	pipe relative roughness (-)
γ	shear rate (s^{-1})
φ	ice mass fraction (-)
λ	friction factor (-)
μ	dynamic viscosity (Pa s)
ρ	density ($kg\,m^{-3}$)
τ	shear stress (Pa)
τ_y	Herschel–Burkley yield stress (Pa)

Dimensionless groups

He	Hedström number ($D^2\rho\tau/\mu^2$)
Nu	Nusselt number (hD/k)
Re	Reynolds number ($\rho UD/\mu$)

Subscripts

cf	carrier fluid
i	ice
ref	reference state (0 °C, no ice present)
w	pipe wall

1. Introduction

The adequate design and operation of an ice slurry industrial facility requires detailed knowledge of the ice slurry physical properties, its heat transfer and its fluid dynamics properties. Many works studying ice slurry behaviour have been developed over the last few years. However, according to Kitanovski et al. (2005), even in recent experiment on pressure drop determination and despite that the suspension was produced in identical types of ice slurry generators, very large differences in the results are observed. According to Egolf et al. (2005), a large diversity of results on heat transfer, which were presented by scientists of different laboratories, is observed. Therefore, in most published works, certain conclusions are drawn only for a restricted range and the results obtained do not provide a full explanation for the discussed phenomena (Niezgoda-Żelasko and Zalewski, 2006).

Pressure drop and heat transfer processes characteristics are both affected by ice slurry rheological behaviour. Therefore, without a thorough understanding of process hydrodynamics, the design of any ice slurry system becomes inaccurate and specific to the particular application (Kauffeld et al., 2005).

It is widely accepted that ice slurry behaves as a Newtonian fluid at low ice concentrations and as a non-Newtonian fluid at high concentrations, being its non-Newtonian behaviour more marked as ice concentration increases. Although some authors treat ice slurry as a power law fluid, rheological models with a yield shear stress are the most frequently applied to describe ice slurry behaviour, including Bingham, Casson and Papanastasiou models.

Extensive reviews of rheological models applied to ice slurry were made by Kauffeld et al. (2005) and Kitanovski et al. (2005) or Ayel et al. (2003), but along the reviewed works the different authors do not agree on the behaviour of ice slurries with ice fraction. According to Kitanovski et al. (2005), the effect of different particle shapes and sizes, and the effect of heat transfer on pressure drop and flow patterns must be further investigated.

Based on the dimensional analysis of pressure drop process, this work aims to establish which non-dimensional parameters have a strong influence on ice slurry rheological behaviour. Using these parameters as tests variables, an experimental study of ice slurry pressure drop will allow to characterize ice slurry behaviour and to obtain the most appropriate rheological model. Expressions for the ice slurry Darcy friction factor can be deduced from the rheological model proposed.

Additionally, dimensional analysis of heat transfer process is presented in order to determine the minimum number of non-dimensional parameters present in heat transfer process.

2. Dimensional analysis

In order to define test conditions, a dimensional analysis of the pressure drop and heat transfer processes has been made, allowing to establish the minimum numbers of non-dimensional parameters present in these processes (Illán et al., 2005).

Firstly, it is clear that the antifreeze agent used has a strong influence in the carrier fluid properties and the ice concentration. Therefore it must be the first parameter considered.

Dimensional analysis allows obtaining the following relationship between all the non-dimensional parameters involved in the pressure drop process for ice slurry flowing through horizontal pipes, which also is influenced by the specific antifreeze depressant used:

$$\frac{\Delta P/l_p}{\frac{1}{2}\rho_{cf}U^2/D} = f\left(\frac{\mu_{cf}}{\rho_{cf}U\cdot D}, \varphi, \frac{d}{D}, \delta, \frac{\rho_i}{\rho_{cf}}, \varepsilon, \frac{g\cdot\Delta\rho\cdot D}{\rho_{cf}U^2}\right) \quad (1)$$