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Experimental investigation of ice slurry heat transfer in horizontal tube

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ABSTRACT

Heat transfer of ice slurry flow based on ethanol–water mixture in a circular horizontal tube has been experimentally investigated. The secondary fluid was prepared by mixing ethanol and water to obtain initial alcohol concentration of 10.3% (initial freezing temperature -4.4 °C). The heat transfer tests were conducted to cover laminar and slightly turbulent flow with ice mass fraction varying from 0% to 22% depending on test performed. Measured heat transfer coefficients of ice slurry are found to be higher than those for single phase fluid, especially for laminar flow conditions and high ice mass fractions where the heat transfer is increased with a factor 2 in comparison to the single phase flow. In addition, experimentally determined heat transfer coefficients of ice slurry flow were compared to the analytical results, based on the correlation by Sieder and Tate for laminar single phase regime, by Dittus–Boelter for turbulent single phase regime and empirical correlation by Christensen and Kauffeld derived for laminar/turbulent ice slurry flow in circular horizontal tubes. It was found that the classical correlation proposed by Sieder and Tate for laminar forced convection in smooth straight circular ducts cannot be used for heat transfer prediction of ice slurry flow since it strongly underestimates measured values, while, for the turbulent flow regime the simple Dittus–Boelter relation predicts the heat transfer coefficient of ice slurry flow with high accuracy but only up to an ice mass fraction of 10% and $Re_{cf} > 2300$ regardless of imposed heat flux. For higher ice mass fractions and regardless of the flow regime, the correlation proposed by Christensen and Kauffeld gives good agreement with experimental results.

Etude expérimentale sur le transfert de chaleur d'un coulis de glace à l'intérieur d'un tube horizontal

Mots clés : Accumulation thermique ; Coulis de glace ; Expérimentation ; Transfert de chaleur ; Tube horizontal

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Nomenclature

c	concentration (–)
c_A	initial additive concentration (–)
d	pipe inner diameter (m)
Gz	Graetz number (–)
L	length (m)
Re	Reynolds number (–)
Pr	Prandtl number (–)
$\dot{q}$	heat flux (W m^{-2})
w	velocity (m s^{-1})
z	axial tube distance (m)

Greek symbols

α	heat transfer coefficient (W m^{-2} K^{-1})
ρ	density (kg m^{-3})
ϑ	temperature (°C)
η	dynamic viscosity (Pas)
λ	thermal conductivity (W m^{-1} K^{-1})

Subscripts

b	bulk
cf	carrier fluid
cs	cross section
i	ice
in	inlet
is	ice slurry
m	mean
t	thermal
h	hydraulic
w	tube wall
x	axial distance

1. Introduction

Ice slurry as an advanced two-phase secondary fluid presents a promising substitute for cold energy transport and storage compared to the single phase fluids, mainly due to benefit from the latent heat of the ice phase change. If ice slurry is used for cold energy storage it is possible to shift electric load to off-peak hours, which significantly lowers the energy demand charges and can lead to reduction in total energy usage. Besides lower operating costs it can substantially cut capital investment through reduced installed refrigeration (and electrical) power. Furthermore, with single phase secondary fluid in the traditional indirect system the refrigerant charge (HFC) and related emissions are greatly reduced compared to a complete direct expansion system.

Today, cold energy storages installed as a part of refrigeration and air conditioning systems in industry and commercial buildings are mainly designed as ice-bank systems with ice formed around tube bundles. Only a small percentage of cold storage systems in the world are built on ice slurry technology despite their obvious advantages such as highly improved heat transport capability (to and from the storage and in heat exchangers), high heat capacity at any level below 0 °C and their temperature stability (Kauffeld et al., 2005). However, for an optimum design of cold energy storage systems with ice slurry, knowledge of flow and heat transfer behaviour of two-phase slurry is of high importance.

This paper reports on an experimental investigation of heat transfer behaviour of ice slurry based on ethanol–water mixture in straight tubes for cooling applications.

In the last ten years much research has been made in the field of ice slurry technology but with varying outputs and conclusions. Heat transfer measurements performed on ice slurries inside horizontal circular pipes were reported by many (Ayel et al., 2003; Egolf et al., 2005; Kauffeld et al., 2005). Christensen and Kauffeld (1997), Guilpart et al. (1999), Kauffeld et al. (1999), Jensen et. al (2000), Sari et al. (2000), Hägg (2005) and Zelasko (2006) reported increase of the heat transfer coefficient with increasing ice fraction and velocity but rather small or no influence on the heat transfer coefficient with increasing heat flux.

Knodel et al. (2000) reported decreased heat transfer coefficients with increased ice fraction up to a fraction of about 4%. At higher ice fractions, the Nusselt number was more or less constant. The experiments were done with ice water slurry in 24 mm horizontal pipe and velocity between 2.8 and 5 m/s.

Only Snoek and Bellamy (1997) observed a decrease in Nusselt number with increasing ice fraction. In their experiments they used ethylene glycol with initial concentration of 8–10%, with ice concentration, i.e. ice mass fraction, up to 33%.

A number of experiments have thus been performed to investigate local and average heat transfer coefficients but the results differ from one report to another. The most possible reason for differences in the reported heat transfer behaviour is the size and shape of the ice slurry particles. In the early age of ice slurry research the ice particles were large. The influence of the ice generation method and the time influence on the geometrical characteristics of the ice crystals were not known. Consequently, large ice particles lead to superheating phenomena which may significantly influence the heat transfer results. Hansen et al. (2002) reported on an investigation on ice agglomeration during storage, i.e. on ice crystal growth mechanisms during ice generation and its dependency on time during storage, while Pronk et al. (2004) reported on the influence of the ice crystal size on ice slurry heat transfer and superheating phenomenon.

With present-day ice generation methods, the ice particles have much finer crystalline form which, it seems, has an impact on the thermal boundary and in turn on heat transfer.

In this study, a series of heat transfer experiments have been conducted in order to investigate heat transfer of ice slurry in horizontal tubes with the intention to contribute to the clarification of the contradicting results published up to now.

2. Experimental details

2.1. Experimental apparatus

The experimental set-up designed and manufactured at the Division of Applied Thermodynamics and Refrigeration of the