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Heat exchanger performance modeling using ice slurry as secondary refrigerant

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ABSTRACT

Ice slurry is a biphasic secondary refrigerant that theoretically allows important energy savings in secondary refrigerant distribution loop compared to single phase refrigerants. However, an accurate evaluation of these energy savings requires the knowledge of the thermal and rheological performance of the refrigerant.

Based on the experimental model developed by the authors, a theoretical analysis of heat exchangers performance is presented in this work in order to calculate the potential energy savings associated to its use. The influence of ice concentration, mass flow rate, heat exchanger length and cooled fluid temperature over pumping power and heat transfer rate is studied. The ratio between heat transfer rate and pumping power is used as the evaluation parameter, which allows us to find the most favorable operation conditions for ice slurry flow.

Results for ice slurry are compared to those obtained for carrier fluid at same inlet temperature to assess the improvement obtained.

Modélisation de la performance des échangeurs de chaleur utilisant un coulis de glace comme frigoporteur

Mots clés : Coulis de glace ; Chute de pression ; Transfert de chaleur ; Echangeur de chaleur

1. Introduction

Ice slurry is considered as a very promising secondary refrigerant that, besides the reduction on the charge of primary refrigerant associated to any secondary refrigerant, allows a reduction in energy consumption compared to single phase secondary refrigeration systems as well as the possibility of thermal storage. This reduction in energy consumption has been extensively treated previously and is only outlined here. It is obtained in two different ways: firstly, the energy efficiency of an ice slurry plant is greater than that of a plant using a single phase secondary refrigerant (Rivet, 2007; Stamatiou and Kawaji, 2005); secondly, the energy consumption on the pumps used in the secondary refrigerant distribution system can be reduced compared to the energy consumption necessary to pump the traditional single phase secondary refrigerant (Kauffeld et al., 2005).

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Nomenclature

A	heat transfer area (m^2)
c_p	specific heat (J kg^{-1} K^{-1})
D	pipe diameter (m)
h	convective heat transfer coefficient (W m^{-2} K^{-1})
H_f	specific latent heat of fusion of ice (J kg^{-1})
HTR	heat transfer ratio ($HTR = \dot{q}_{is}/\dot{q}_{cf}$)
IR	improvement ratio ($IR = PR_{is}/PR_{cf}$)
k	thermal conductivity (W m^{-1} K^{-1})
L	tube length (m)
$\dot{m}$	mass flow rate (kg s^{-1})
P	pumping power (W)
PPR	pumping power ratio ($PPR = P_{is}/P_{cf}$)
PR	power ratio ($PR = \dot{q}/p$)
$\dot{q}$	heat transfer rate (W)
T	temperature (K)
ΔT_m	effective mean temperature difference (K)
U	overall heat transfer coefficient (W m^{-2} K^{-1})
v	flow velocity (m s^{-1})

Greek symbols

(ϕ)	ice mass fraction (–)
(h)	Darcy friction factor (–)

Subscripts

c	corrugated tube
cf	carrier fluid
in	tube inner wall
is	ice slurry
out	tube outer wall
pg	propylene glycol
s	smooth tube

The attention of this paper is focused on the energy savings obtained in the secondary refrigerant distribution system. An accurate assessment of these savings requires the knowledge of ice slurry thermal and rheological performances. Some of the most important works developed to predict heat transfer in ice slurry flow have been summarized by Egolf et al. (2005), whereas Doetsch et al. (2005) have summarized ice slurry rheology and Kitanovski et al. (2005) have summarized ice slurry pressure drop. Most recently, the authors of this work have experimentally developed a thermal and rheological model for the ice slurry produced using 9 wt% sodium chloride brine as base solution (Illán and Viedma, 2009a, 2009b), which has been experimentally validated in a commercial corrugated tube heat exchanger (Illán and Viedma, 2009c). According to that model, the Darcy friction factor and the Nusselt number for ice slurry flowing through horizontal pipe can be obtained as a function of Reynolds number, ice content and ice particle-pipe diameter ratio: $\lambda = f(Re, \phi, d/D)$; $Nu = f(Re, \phi, d/D)$. Based on this model, a theoretical analysis of smooth and corrugated tube heat exchangers performance is developed in this work in order to analyze the potential energy savings associated to the use of ice slurry. Pumping power and heat transfer rate have been numerically obtained for tube lengths between 0 and 10 m. Influence of ice content, mass flow rate and cooled fluid temperature have been analyzed for each tube length; the variation range of all these variables analyzed is given in Table 1.

According to Kozawa et al. (2005), two types of ice slurry thermal storage are distinguished: heterogeneous and homogeneous. When heterogeneous storage is employed, the ice slurry can be used in an indirect way. The chilled carrier fluid with no ice particles can be extracted from the bottom of the storage tank and used as conventional single phase secondary refrigerant, maintaining the high thermal storage capacity of ice slurry systems. On the other hand, when homogeneous storage is employed, ice slurry can be extracted from the storage tank and used in a direct way. In this case, some benefits of saving in pipe dimensions are expected.

Although the influence of mass flow rate, ice concentration, wall temperature or the distance from the heat exchanger inlet have been recently analyzed by several authors (Lee et al., 2006; Niezgoda-Zelasko, 2006; Ionescu et al., 2007; Kousksou et al., 2010) apart from that summarized by (Egolf et al. (2005), the present work analyzes jointly pressure drop and heat transfer in order to assess the improvement obtained by using ice slurry.

A power ratio, defined as the ratio between heat transfer rate and pumping power ($PR = \dot{q}/P$), has been used as comparison parameter. The ice slurry power ratio (PR_{is}) has been calculated for the case when ice slurry flows through the heat exchanger. Similarly, carrier fluid power ratio (PR_{cf}), has been calculated for the case when a heterogeneous storage is used and only carrier fluid flows through the heat exchanger.

An improvement ratio has been defined as the ratio between ice slurry and carrier fluid power ratios ($IR = PR_{is}/PR_{cf}$). Values of improvement ratio higher than 1 will represent those situations where the use of ice slurry improves heat exchanger performance; alternatively, values of improvement ratio lower than 1 imply that the use of ice slurry will not be recommended.

Heat transfer ratio ($HTR = \dot{q}_{is}/\dot{q}_{cf}$) and pumping power ratio ($PPR = P_{is}/P_{cf}$) have also been calculated and plotted in order to obtain additional information about ice slurry performance.

Table 1 – Variation range of all variables analyzed.

Tube type	Tube length (m)	Ice concentration (wt%)	Ice slurry mass flow rate (kg s^{-1})	Propylene glycol outlet temperature (°C)	Propylene glycol mass flow rate (kg s^{-1})
Smooth	0–10 ($\Delta L = 1$ mm)	5, 10, 15, 20, 25	825, 1225, 1625, 2025, 2425	0, 25, 50	650, 900, 1150, 1400, 1650
Corrugated	0–10 ($\Delta L = 1$ mm)	5, 10, 15, 20, 25	825, 1225, 1625, 2025, 2425	0, 25, 50	650, 900, 1150, 1400, 1650