INTERNATIONAL JOURNAL OF REFRIGERATION 48 (2014) 221–232

Available online at www.sciencedirect.com

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Analysis of heat transfer phenomena during ice slurry production in scraped surface plate heat exchangers

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ARTICLE INFO

Article history:
Received 6 February 2014
Received in revised form
19 July 2014
Accepted 22 July 2014
Available online 1 August 2014

Keywords:
Ice slurry
Scraped surface
Heat exchanger
Heat transfer enhancement
Active techniques

ABSTRACT

Heat transfer during ice slurry production in a scraped surface plate heat exchanger (SSPHE) has been experimentally investigated. By using a 7 wt. % sodium chloride brine, a wide range of operating conditions has been tested: scraping velocities from 0.1 to 0.8 s^{-1} and logarithmic temperature differences from 0.5 to 2.5 K. Two different PEEK scraper arrangements have been used, mounted on the driving arms: rigid scrapers and surface adaptable scrapers, pushed by torsion springs. Heat transfer coefficients and ice production rate were measured under batch operating mode. Experimental results shown dependence of the nucleation onset with the scraping speed and the wall supercooling degree. Global nucleation only occurred for high velocities and low supercooling degrees, appearing only on the wall for the other cases. A decrease of the heat transfer coefficient of 1.5 times for increasing logarithmic temperature differences is reported, as a consequence of the ice layer growth with a low effect of the scraping speed. The use of adaptable scrapers provide heat transfer coefficient augmentations from 2 to 4-fold with respect to the rigid configuration.

Analyse des phénomènes de transfert de chaleur pendant la production de coulis de glace dans des échangeurs de chaleur à plaques à surface raclée

Mots clés : Coulis de glace ; Surface raclée ; Echangeur de chaleur ; Amélioration du transfert de chaleur ; Techniques actives

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http://dx.doi.org/10.1016/j.ijrefrig.2014.07.020

Nomenclature

A	heat exchange area (m^2)
C	constant term ($W\ m^{-2}\ K^{-1}$)
D	SSPHE internal diameter (m)
H	SSPHE internal height (m)
H_S	scraper height (m)
L_f	ice specific latent heat of fusion at 273.15 K (J)
N	rotational speed (s^{-1})
Q	heat flux (W)
T	temperature (K)
V	volume of the heat exchanger (m^3)
$\dot{m}$	coolant mass flow ($kg\ s^{-1}$)
c_p	specific heat ($J\ kg^{-1}\ K^{-1}$)
$\hat{c}_p$	apparent specific heat ($J\ kg^{-1}\ K^{-1}$)
e	ice layer thickness (m)
g	gravity acceleration ($m\ s^{-2}$)
h	heat transfer coefficient ($W\ m^{-2}\ K^{-1}$)
i	specific enthalpy ($J\ kg^{-1}\ K^{-1}$)
k	thermal conductivity ($W\ m^{-1}\ K^{-1}$)
n	number of scrapers
t	time (s)
t_{ni}	nucleation induction time (s)
v	coolant velocity ($m\ s^{-1}$)

Dimensionless numbers

Fr	Froude number $(\Omega(D/2))^2/Hg(1-\rho_i/\rho_b)$
Nu	Nusselt number hD/k
Pr	Prandtl number $\mu c_p/k$
Re	Reynolds number $\rho v D/\mu$
Re_{rot}	rotational Reynolds number $\rho N D^2/\mu$
Ri	Richardson number $g\beta\Delta T_{b,w}(H/2)/(\Omega(D/2))^2$

Greek symbols

β	thermal expansion coefficient ($^\circ K^{-1}$)
ΔT_s	wall supercooling degree $T_f - T_w$ (K)
ΔT_{log}	logarithmic mean temperature diff. (K)
μ	viscosity ($kg\ m^{-1}\ s^{-1}$)
Ω	rotor angular velocity ($rad\ s^{-1}$)
ω	solute mass fraction in the brine; mass of NaCl/mass of solution
ω_0	global mass fraction of solute; mass of NaCl/mass of solution and ice
ρ	density ($kg\ m^{-3}$)
φ_m	ice mass fraction
φ_v	ice volume fraction
Φ	viscous dissipation term (W)
ζ	supercooling amplitude ($^\circ$K)

Subscripts

b	brine
c	coolant
e	inlet
F	final
f	freezing
i	ice
max	maximum
o	outlet
p	process
s	subcooling
w	wall
0	initial
n	nth element
calc	calculated
exp	experimental
T	total

1. Introduction

Ice slurries have a wide range of applications, being involved from food processing to water purification processes, with a special relevance on refrigeration and energy storage. The high cooling capacity and constant cooling temperature, together with their easy transportability make the ice slurries a suitable coolant. Among the different techniques available for the production of ice slurries (Zhang and Ma, 2012), the scraper type systems and particularly the scraper surface heat exchangers (SSHE) deserve an special interest. Their ability for the fouling prevention is applied here for the continuous removal of the ice layer, generating small ice crystals and adding them to the mixture. Moreover the continuous removal of the boundary layer enhances the heat transfer between the wall and the surrounding fluid.

The aim of the present work is the experimental study of the ice slurry generation in a SSPHE working in batch mode. An analysis of the phase-change heat transfer process that occurs during the ice slurry generation is presented, based on the appropriate parameters and dimensionless numbers that help describe the involved phenomena. A through characterization of the heat transfer to the scraped-surface wall is accounted for by means of the influence of various parameters (blade rotation speed, type of scrapers, wall supercooling degree, product concentration) for a 7 wt. % wt. NaCl brine. We propose design correlations able to predict the heat transfer at a scraped surface when freezing of water occurs.

1.1. Literature review

Heat transfer in SSHEs, mostly regarding horizontal models –where an inner cylindrical surface is continuously scraped by means of rotating blades – have been widely investigated (Rao and Hartel, 2006). One of the most extensively used models for describing heat transfer in SSHEs uses the *penetration theory*. Although several researchers have questioned its validity in the transition and turbulent region (Abichandani et al., 1987; Cuevas and Cheryan, 1982), other studies confirmed that liquids having low viscosity could be adequately described using the penetration theory (Harriot and 19 59), and it has been subsequently modified to include the effects of parameters such as rotation and number of blades (Skelland et al., 1962).

Several investigations have been reported in the open literature on the production of ice slurries in SSHEs. Qin et al. (2003a) used a horizontal scraped surface plate heat