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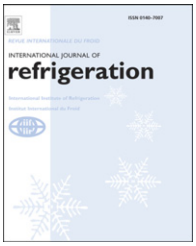

Superheating of ice slurry in melting heat exchangers

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ABSTRACT

One of the main components of an ice slurry system is the melting heat exchanger, in which ice slurry absorbs heat resulting in the melting of ice crystals. Design calculations of melting heat exchangers are mainly based on heat transfer and pressure drop data, but recent experimental studies have shown that superheating of ice slurry should also be considered. This paper presents ice slurry melting experiments with a tube-in-tube heat transfer coil. The experimental results indicate that operating conditions such as ice slurry velocity, heat flux, solute concentration, ice fraction, and ice crystal size determine the degree of superheating. The various influences are explained by considering the melting process as a two-stage process consisting of the heat transfer between wall and liquid and the combined heat and mass transfer between liquid and crystals. Bigger ice crystals and higher solute concentrations decrease the rate of the second stage and therefore increase the degree of superheating.

Surchauffe du coulis de glace dans les échangeurs de chaleur avec fonte de glace

Mots clés : Coulis de glace ; Échangeur de chaleur ; Fusion ; Expérimentation ; Paramètre ; Transfert de chaleur ; Transfert de masse ; Surchauffe

1. Introduction

In the last 10 years, ice slurry has successfully been applied as secondary refrigerant in refrigeration and air-conditioning installations. The application of ice slurry minimizes the required amount of primary refrigerant and enables thermal storage. The latter makes it possible to produce ice slurry at night with the benefits of low electricity tariffs and low condensing pressures, and use it in daytime when cooling loads normally peak. Proper application of thermal storage leads to a reduction of investment and/or energy costs.

After production and storage, ice slurry is transported to applications where it melts and provides cooling for rooms, products or processes. In general, two different methods of ice

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Nomenclature

A	area (m^2)
B_A	area shape factor
B_V	volume shape factor
$c_{1\ldots3}$	constants
c_p	specific heat (J/kg K)
d_{Feret}	average crystal Feret diameter (m)
d	tube diameter (m)
D	diffusion coefficient (m^2/s)
G	growth rate (m/s)
h	enthalpy (J/kg)
Δh_f	latent heat of fusion of ice (J/kg)
k	mass transfer coefficient (m/s)
m	mass (kg)
$\dot{m}$	mass flow (kg/s)
N	number of crystals
n	number of measurements
Nu_{cr}	crystal Nusselt number, $\alpha_{\mathrm{cr}} d_{\mathrm{Feret}}/\lambda_{\mathrm{liq}}$
Δp	pressure drop (Pa)
Pr	Prandtl number, $c_{p,\mathrm{liq}}\mu_{\mathrm{liq}}/\lambda_{\mathrm{liq}}$
$\dot{Q}$	heat (W)
Sc	Schmidt number, $\mu_{\mathrm{liq}}/(\rho_{\mathrm{liq}} D)$
Sh_{cr}	crystal Sherwood number, $k d_{\mathrm{Feret}}/D$
T	temperature (°C)
ΔT_{ln}	logarithmic mean temperature difference (K)
ΔT_{sh}	degree of superheating (K), defined in Eq. (11)
t	time (s)
Δt	measurement interval (s)
U	overall heat transfer coefficient (W/m^2 K)
u	velocity (m/s)
$\dot{V}$	volume flow rate (m^3/s)
w	solute mass fraction
w_0	initial solute mass fraction in liquid
Δx	length of control volume

Greek

α	heat transfer coefficient (W/m^2 K)
ζ	relative superheating, defined in Eq. (12)
λ	thermal conductivity (W/m K)
μ	viscosity (Pa s)
ρ	density (kg/m^3)
τ	period (h)
ϕ	ice mass fraction

Subscripts

cr	crystal
EG	ethylene glycol solution
eq	equilibrium
eqin	equilibrium at inlet
fr	freeze point
he	heat exchanger
i	inside
ice	ice
in	inlet
init	initial
inner	inner
is	ice slurry
liq	liquid
meas	measured
o	outside
out	outlet
real	real
rest	other components
stor	storage
w	wall

slurry melting are used. In the first method, ice slurry is directly poured onto food products for example fish, resulting in high cooling rates and therefore high product qualities (Fikiin et al., 2005; Torres-de María et al., 2005). In the second method, ice slurry absorbs heat in regular heat exchangers cooling a second fluid, for example air in display cabinets for supermarkets or air-conditioning systems. Design calculations for this kind of heat exchangers are mainly based on experimentally obtained heat transfer and pressure drop data for melting ice slurry (Ayel et al., 2003; Egolf et al., 2005; Lee et al., 2006; Niezgoda-Żelasko, 2006; Niezgoda-Żelasko and Zalewski, 2006; Stamatiou and Kawaji, 2005). Recent experimental studies have shown that ice slurry may be significantly superheated at the outlet of melting heat exchangers (Hansen et al., 2003; Kitanovski et al., 2005; Frei and Boyman, 2003). This phenomenon should also be taken into account in design calculations, since superheating increases the average ice slurry temperature in the heat exchanger to a value that is higher than expected from equilibrium calculations. As a result, the temperature difference between ice slurry and the other fluid is lower resulting in reduced heat exchanger capacities.

Ice slurry is considered superheated when its liquid temperature is higher than its equilibrium temperature. Superheating can be explained by considering the melting process of ice slurry as a two-stage process. First the heat exchanger wall heats the liquid and subsequently the superheated liquid melts the ice crystals. The relation between the rates of both processes determines the degree of superheating. For example, when crystal-to-liquid heat and mass transfer processes are relatively slow compared to the wall-to-liquid heat transfer process, the degree of superheating is high.

The degree of superheating is expected to depend on operating conditions, such as ice slurry velocity, heat flux, solute concentration, ice fraction and ice crystal size. However, quantitative data on superheating are only reported by Frei and Boyman (2003) indicating that the degree of superheating increases as the ice fraction decreases. Moreover, the physical mechanisms that determine the degree of superheating are not understood yet. The aims of this paper are therefore to investigate the influence of operating conditions on the degree of superheating and to unravel the physical mechanisms behind this phenomenon. For this purpose, experiments on ice slurry melting have been performed in a tube-in-tube heat transfer coil, during which the influences of various operating conditions on superheating have been investigated.