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Heat transfer performance of a newly developed ice slurry generator: A comparative study

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Abstract An advanced super-cooling type heat exchanger is presented as an ice slurry generator. It reduces investment costs and it can be operated with high heat transfer rates and at less power consumption compared with traditional heat exchangers of super-cooling type of shell and tube design, and of scraped surface type, which are commonly used up to now. The different ice slurry generation methods were reviewed. A super-cooling ice slurry generator type was experimentally tested and compared with a traditional scraped surface type. Some interesting advantages were observed in case of super-cooling type, developed in this paper. The stable operating range was slightly smaller compared with the traditional scraped surface type, and heat transfer coefficients were somewhat smaller due to smaller amount of generated ice fraction as common super-cooling type. It is supposed that higher velocity of the super-cooled water jets than reported will lead to increase the produced ice concentration.

1. Introduction

Ice slurries consist of aqueous solutions in which small ice crystals are present. Compared to commonly used brines, the application of ice slurries in indirect refrigeration systems shows interesting advantages, such as (i) the possibility of enhanced thermal storage and (ii) the reduction of transport friction losses due to the higher volumetric heat capacity. However, a widespread utilization of ice slurry systems has not taken place yet which is mainly attributed to the high investment costs of commercially available ice slurry generators [1].

2. Literature review

A review of the literature shows that there are six methods for ice slurry generation namely: (i) mechanical scraper method or harvest method, (ii) fluidized bed method, (iii) direct contact or direct injection method, (iv) vacuum freezing method, (v) oscillatory moving cooled wall method, and (vi) super-cooling water. The investment cost of each of these methods is an important parameter during system selection procedure.

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Nomenclature

A_o	heat exchanger area (m^2)
C_p	specific heat (J/kg K)
$C_{p,app}$	apparent specific heat (J/kg K)
$C_{p,cf}$	specific heat of the carrier fluid (J/kg K)
$C_{p,ice}$	specific heat of Ice (J/kg K)
D	diameter (m)
D_{eq}	equivalent diameter (m)
h	height (m)
$h_{is,\exp}$	experimental average heat transfer coefficient on ice slurry side (W/m^2K)
h_{ref}	average heat transfer coefficient on primary refrigerant side (W/m^2K)
Δh_f	heat of fusion of water (J/kg)
IC	volumetric ice fraction (%)
m^o	mass flow rate (kg/s)
Nu	Nusselt number, $(h\ D_{eq}/\lambda)$ (–)
$Nu_{is,\exp}$	experimental Nusselt number, $(h_{is,\ \exp} D_{eq}/\lambda_{is})$ (–)
$Nu_{\text{is,pred}}$	predicted Nusselt number, $a\text{Re}^b_{a,is}\text{Re}^c_{r,is}\text{Pr}^d_{is}\omega^e_o$ (–)
N	scraping mechanism rotating speed (rps)
p	pressure (Pa)
Pr	Prandtl number, $(C_{p,liq}\ \lambda_{liq}/\mu_{liq})$ (–)
Pr_{is}	ice slurry Prandtl number, $(C_{p,app}\ \lambda_{is}/\mu_{is})$ (–)
Q^o	total heat flux (W)
Re	Reynolds number (–)
$\text{Re}_{a,is}$	axial Reynolds number, $\rho_{is}\ V_a\ D_{eq}/\mu_{is}$ (–)
$\text{Re}_{r,is}$	rotational Reynolds number, $\rho_{is}\ N\ D^2_{eq}/\mu_{is}$ (–)
t	time (mins)
T	temperature (°C)
$\Delta T_{\ln}$	logarithmic mean temperature difference (LMTD) (K)
U_o	overall heat transfer coefficient (W/m^2K)
V_a	axial velocity inside the ice slurry generator (m/s)
V^o	volume flow rate (m^3/s)
x_{if}	ice fraction by mass (%)

Greek symbol

δ	thickness (m)
λ	thermal conductivity (W/m K)
μ	dynamic viscosity (Pa s)
ρ	density (kg/m^3)
ω_0	global mass fraction of solute; mass of solute/mass of solution and ice (%)

Subscripts

a	axial
cf	carrier fluid
eq	equivalent
exp	experimentally measured
evap	evaporating
f	experiment end point
ice	ice
in	at inlet conditions
is	ice slurry
ifp	initial freezing point
inner	inner diameter of the inside pipe
jet	super-cooled water jet
liq	liquid
max	maximum
min	minimum
o	overall
outer	outer diameter of the inside pipe
out	at outlet conditions
pred	predicted
r	rotational
ref	primary refrigerant
sh	shaft of the scraping mechanism
shell	outside shell
w	wall
0	experiment start point

Abbreviations

ACCU	air cooled condensing unit
EG	Ethylene Glycol
FC	fluorocarbons
FM	flow meter
HCFC	hydrochlorofluorocarbon
HCFC-22	chlorodifluoromethane (R-22)
ISG	ice slurry generator
IV	isolating valve
ISP	ice slurry circulating pump
MV	flow modulating valve
MCC	motor control centre
PG	pressure gauge
RDL	refrigerant discharge line
RSL	refrigerant suction line
RLL	refrigerant liquid line
SG	sight glass
T	temperature sensor
TXV	thermostatic expansion valve
TST	thermal storage tank
VFD	variable frequency drive

In the first method, the mechanical scraper method or "harvest method", the refrigerant evaporates in a double-wall cylinder. Through the inside space, bounded by the inner cylinder, the water or aqueous solution flows and the ice crystals are created. A rotary knife scrapes the ice growing on the cooling surface. The scraped surface generator has a large surface for the ice crystal creation per unit volume of ice slurry generator. Stamatiou et al. [2], Pronk et al. [3], and Daitoku and Utaka [4] are examples for researchers that studied the harvest method.

In the second method, fluidized bed method, the ice slurry generation process is performed using liquid–solid fluidized bed heat exchangers. This method has been investigated by many researchers such that Klaren and Van der Meer [5], Pronk et al. [6], and Meewisse and Infante Ferreira [7].

In the third method, direct contact method or direct injection method, the refrigerant is directly injected into the water domain. Liquid droplets of refrigerant enter through nozzles, normally at the bottom of the generator, and start to