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Mathematical Model of Heat Transfer for a Finned Tube Cross-flow Heat Exchanger with Ice Slurry as Cooling Medium

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Abstract

Using ice slurry as a secondary refrigerant in HVAC systems has many potential benefits for its high cooling capacity. In order to investigate heat transfer characteristics such as heat transfer rate and heat transfer coefficient in finned tube cross-flow heat exchangers with ice slurry as cooling medium, a mathematical model describing heat transfer process of the heat exchanger has been developed, which are based on three sets of partial differential equations (PDEs) of energy balance. Then an analytical solution has been obtained through solving the PDEs model. The analytical solution of the proposed model presents a reasonable agreement with the experimental data from the published literature when ice mass fraction is between 5% and 25%. In addition, the relationship between the heat transfer rate and the melting amount of ice crystals is also obtained.

Keywords: Mathematical model; Heat exchanger; Ice slurry; Analytical solution

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1. Introduction

Ice slurry is a mixture of small ice crystals (diameter usually between 0.1 and 1 mm) and a carrier fluid which is consisted of water and freezing point depressant[1]. It has great potential in delivering energy because of its huge latent heat from ice crystals melting. Compared to conventional HVAC systems, using ice slurry instead of chilled water as cooling medium has many benefits for its high cooling capacity, for instance, reducing flow rate, downsizing pipe networks or pumps. Heat exchangers with ice slurry as cooling medium can be used in air conditioning system as air handling units, like which is used in CAPCOM building in Osaka, Japan[2]. However, heat transfer characteristics of ice slurry are extremely different from single phase fluid owing to the complex transfer mechanisms. Thus, the heat transfer performance of the terminal heat exchangers using ice slurry as cooling medium is one of the focuses concerned to design or optimize HVAC systems.

There are already some researches on the heat exchangers with ice slurry as cooling medium by either experimental measurements and/or numerical simulation methods. Fernández and Diz[3,4] experimentally measured the heat transfer coefficients and the heat transfer rate of ice slurry in an offset strip-fin plate heat exchanger and a terminal fan-coil

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unit. It is found that the fan-coil heat transfer rate with ice slurry (ice concentration between 5 wt% and 20 wt%) is higher than that with chilled water (7/12°C) by factor over 3. Besides, an empirical correlation of the ice slurry heat transfer coefficient for the offset strip-fin plate heat exchanger was determined by applying the Wilson plot method. However, the empirical correlation is just suit for some special flow regime in particular type of heat exchangers. Some other different correlations of the ice slurry heat transfer coefficients were validated with the experimental data in the paper of Grozdek et al.[5] It is also found that those proposed correlations are not so precise or just get accuracy results for special flow regime or ice concentration. The application field of the empirical correlations is limited. Other experiments were also implemented by Illán and Viedma[6,7], Bédécarrats et al.[8], and Renaud et al.[9] Lots of available and relative accurate data were obtained from all these experimental investigations. Nevertheless, experimental measurements are usually expensive in time and cost, and the results obtained are just usable for the given experimental condition.

Nomenclature

A'	heat transfer area per unit length of the finned tube, m
A_a	heat transfer area of airflow, m^2
A_cis	cross-sectional area of the finned tube, m^2
c'_m	thermal capacity of metal (tube and fins) per unit length of the finned tube, J/(m·°C)
c_p	specific heat, J/(kg·°C)
h	heat transfer coefficient, W/(m^2·°C)
L'	latent heat of ice melting per unit temperature change of ice slurry, J/(kg·°C)
L_f	length of the finned tube, m
L_t	length of the overall tube (including U-tube bends section), m
$LMTD$	logarithmic mean temperature difference between the airflow and the tube wall, °C
$\dot{m}$	mass flow rate, kg/s
$\dot{m}'$	mass flow rate per unit length of the finned tube, kg/(m·s)
Nu	Nusselt number
Pr	Prandtl number of the carrier fluid
Q	heat transfer rate, W
Re	Reynolds number of the carrier fluid
SHF	sensible heat factor
t	time, s
t^*	dimensionless time
T	temperature, °C
v	velocity, m/s
x	distance from the ice slurry inlet, m
x^*	dimensionless distance from the ice slurry inlet
η_0	overall fin efficiency of the heat exchanger
θ	dimensionless temperature
ρ	density, $\mathrm{kg/m}^3$
φ_m	ice mass fraction at ice slurry inlet, %

Subscripts

a	air
ai	air inlet
ao	air outlet
c	carrier fluid
i	ice crystals
is	ice slurry
ref	reference state, which is 0°C
t	tube