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Investigation on flow and heat transfer characteristics of ice slurry without additives in a plate heat exchanger

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ABSTRACT

Ice slurry without additives plays a positive role in direct contact food and medical protective cooling applications, as we all now there are not adequate research on the flow and heat transfer characteristics of ice slurry without additives. Thus, experiments are conducted to determine the flow and heat transfer characteristics of 0–20 wt% ice slurry without additives through a plate heat exchanger (PHE) in present research. The results indicate that the pressure drop of ice slurry is about 5.5–61.0 kPa as the flow rate increased from 0.414 to 1.1 m^3/h, it is about 1.2–1.6 times of that of chilled water. The pressure drops of ice slurry could be presented as a function of flow rate, ice fraction and Reynolds number, which are greater than that of the chilled water. The flow rate has a greater impact than ice fraction on pressure drop, which has an increment of 20% as the flow rates varying from 0.414 to 1.270 m^3/h. The pressure drop of melting ice slurry is much smaller than that without heat exchanging, and it has no significant change as ice fraction decreases from 5% to 20% during heat exchanging. Based on the experimental results, the flow friction factor correlation is developed, and the local heat transfer correlation for ice slurry is also established with consideration of effect of latent heat on the heat transfer. In addition, the heat transfer analysis shows that the overall heat transfer coefficient of heat exchanger increases with the increase of flow rate. The flow rate plays a more important role than ice fraction in determining the overall heat transfer coefficient. The overall heat transfer coefficient and cooling duty increase with the of increase inlet water temperature and flow rate. And cooling duty has about 18.5–32.6% increment as the ice fraction varies from 0 to 5 wt%, but its increment is very small as the ice fraction is between 5 wt% and 20 wt%.

1. Introduction

Ice slurry is a mixture of ice crystals, water or with an additive such as glycol, salt or alcohol to lower the freezing point [1], it is a solid–liquid binary fluid. Ice slurry has very good transport properties and huge latent heat. Therefore, ice slurry can provide the same cooling load in much lower volume flow rates or the cooling load can be increased for the same refrigerant charge, which can significantly reduce pumping cost and equipment size. Besides, the ice slurry of moderate concentrations can be easily pumped, transported and stored without needing to change pumping equipment, distribution networks or accumulation tanks [2]. These prominent advantages of ice slurry make it widely use in direct and indirect applications. As a secondary fluid, Ice slurry has been employed in air conditioning systems, commercial refrigeration and industrial production processes in most of the indirect applications [3].

The ice slurry also plays a very important role in direct applications. It is effectively used in food industry, medicine, pigging, firefighting, etc. The direct applications in food industry mainly involve processing and preservation of food products, including the direct contact cooling ice slurry technology is applied in bakery, produce packing, and fishery applications [4]. Kauffeld et al. [5] showed that the fish is totally covered with ice slurry leaving no air pockets between the product, which increases the cooling of fish and decreases the growth of bacteria, resulting in longer product life. Piñeiro et al. [6] found that some fish species like seabass exhibit cloudy eyes in the brine-based ice slurry. This is due to the precipitation of an eye component at subzero temperature level to negatively affect the appearance and quality of fish. Kauffeld et al. [4] reported that freshwater-based ice slurry is able to cool the dough, this method is more friendly compared with CO_2 “dry ice” for dough cooling. Moreover, Ice slurry is easily mixed

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Nomenclature

ΔP	pressure drop (Pa)
f	friction factor (–)
L	plate length (m)
D	hydraulic diameter (m)
u	fluid velocity (m/s)
q, r	constants (–)
a_1, b_1, c_1, a_2, b_2, c_2	constants (–)
m	mass flow rate per channel (kg/s)
S	cross-sectional area of passage (m^2)
U	cooling duty (kW)
M	mass flow rate (kg/s)
C_p	specific heat (kJ/(kg·K))
T	temperature (°C)
h	heat transfer coefficient (W/(m^2·K))
A	overall heat transfer area (m^2)
Re	Reynolds number (–)
Nu	Nusselt number (–)
Pr	Prandtl number (–)
ΔH	enthalpy change (kJ/kg)
ΔT	temperature difference (°C)
X	mass ice fraction (–)

Greek symbols

ρ	density of fluid (kg/m^3)
μ	the fluid dynamic viscosity (kg/(m·s))
λ	thermal conductivity (W/(m·K))
δ	thickness of heat exchanger plate (m)
W	total uncertainty in the measurement

Subscripts

p	heat exchanger plate
h	hot fluid
c	cold fluid
i	heat exchanger inlet fluid
o	heat exchanger outlet fluid
LMTD	logarithmic mean value
overall	overall value
cf	carrier fluid
ice	ice
is	ice slurry

in the dough ingredients and evenly control the dough temperature, which can ensure consistence and quality of dough. For many fresh vegetables, ice slurry is also a very effective post-harvest cooling medium to maintain the vegetables in a low temperature during storage and processing. Kauffeld et al. [4] pointed out that rapid icing via ice slurry to the field-packed broccoli in waxed cartons after harvesting prevents wilting and suppresses enzymatic degradation. Meanwhile, this cooling can also inhibit the growth of decay-producing microorganisms and reduce ethylene production. In addition, ice slurry cooling is researching for inducing targeted organ protective cooling with surgical applications. In 2000, ice slurry medical cooling has been started developing by Argonne engineers and UC medical researchers for inducing protective hypothermia in critical organs [7]. Argonne engineers and UC neurocritical-care doctors are exploring the ice slurry cooling technology, using ice slurry to cool the spinal cord and brain to protect from ischemia and neurological impairment. Ice slurry cooling can slow metabolism and reduce the need for oxygen which slows cell death, providing more time for medical treatment. To reduce ischemia damage and extend surgery time in kidney surgery, the investigations is also underway to adapt ice slurry cooling technology for use in laparoscopic surgeries [8]. Other studies found that cooling and maintaining the heart myocardium at a protective temperature with ice slurry requires only 1/3 of the volume of chilled saline. This gives ice slurry cooling a significant advantage since a smaller volume can be used to maintain the desired protective temperature, thus reducing the chance of bio-system overload [4]. Upwards researches reflect that ice slurry exhibits plenty of advantages for direct contact food products and medical protective cooling applications, but it requires the ice slurry must be environmental friendly, harmless and non-toxic. The ice slurry without additives has potential advantages in those fields. Although the ice slurry without additives has been applied in some ways, the application isn't widespread for few knowledge for flow and heat transfer characteristics of ice slurry without additives. Therefore, in order to extend ice slurry without additives application, it is necessary to investigate deeply the flow and heat transfer characteristics of ice slurry which is made up of freshwater without additives.

With continuous research on flow and heat transfer character of ice slurry, much progress has been made. Kitanovski et al. [9] investigated rheological characteristics of 10% water/ethanol ice slurry in heterogeneous flow. They found that the ice slurry can be treated as Newtonian-fluid at higher average velocities, and lower average concentrations. Mellari et al. [10] showed that ice slurry of 11% initial MPG concentration gives the best results for transport purposes. Illán et al. [11] researched the mathematical relationship of dimensionless parameter of the friction coefficient. Shire et al. [12] investigated the pressure drop for a 5% NaCl/water ice slurries flowing in a industrial PHE. The results indicated that the pressure drop is exponential function of ice fraction. Mika et al. [13] discussed the pressure drop and pressure loss coefficient of ice slurry made from 10.6% ethylene alcohol in pipe fittings. Monterio et al. [14] explored the pressure drop characteristics and rheological model of ice slurry flow in horizontal pipes. The study indicated that the variation of the pressure drop presents as a function of slurry velocity. Egolf et al. [15] also summarized some aspects of thermodynamic and heat transfer characteristics of ice slurry, Nusselt number is described emphatically. Kousksou et al. [16] predicted the heat transfer coefficient for 9% ethanol/water ice slurry flowing in a horizontal pipe. Li et al. [17] researched on heat transfer characteristics of ice slurry (based on ethyl alcohol aqueous solution with initial concentration of 10.3%) flowing in pipe by numerical method. Illán et al. [18] investigated the heat exchanger performance by means of analytical method when using ice slurry (based on 9% NaCl brine) as secondary refrigerant. The study found that ice slurry has potential of reducing energy consumption. Fernández et al. [3] analyzed the thermo-hydraulic behavior of ice slurry based on a 10% ethylene glycol solution. The results showed that the fan-coil capacity is higher with melting ice slurry than that with chilled water. Long et al. [19] have experimentally studied the heat transfer for a finned tube cross-flow heat exchanger with ice slurry as cooling medium. Fernández-Seara et al. [2] analyzed the thermo-hydraulic behavior for a 10% ethylene glycol/water ice slurry in an offset strip-fin PHE. Bellas et al. [1] reported on the results of experimental investigations into the melting heat transfer and pressure drop ice slurry with 5 wt% propylene/water solution flowing in a commercial PHE. Pronk et al. [20] investigated the superheating for ice slurry made from 20 wt% ethylene glycol–water solution. The results showed that ice slurry velocity, heat flux,