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Ice formation in the subcooled brine environment

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ABSTRACT

Generating ice in a fluid immiscible with water is relatively easy but considerably more difficult if the chosen fluid is hydrophilic. Our experimental work showed that, ice can be produced when water is introduced to a bath of subcooled brine and it was believed that, the rate of heat transfer between the two fluids needs to be higher than that of mass transfer to allow the formation of ice to occur as a result. Flow rheology, hence the size of the active surface area of the injected water stream, brine temperature and concentration are the key factors influencing how much ice can be made in the process. Conversion ratios of two ice collection methods are compared over a range of brine temperatures and concentrations. The washing method (wet collection) was found to collect up to 27% more ice than dry collection. Washing is also very effective in rinsing off the brine and salt on the ice's surface and the bulk salinity would drop from 13% to 1%. Since the evaporator temperature has to be higher than the eutectic point of brine, it was suggested that, the coefficient of performance, COP, will be very promising. In addition, this way of ice production should achieve higher efficiency than a scraped surface ice maker and it is simpler in that it requires no complex mechanical harvesting equipment, and with the vast liquid–liquid surface areas possible, promises to be able to produce high quantities of ice per unit volume of equipment.

1. Introduction

Ice slurries have a wide range of engineering applications. Due to the latent heat of fusion of ice which results in their high energy storage capacity, ice slurries are used as secondary refrigerant for thermal storage systems [1–3]. Another successful application of ice slurries is the ice pigging technology [4] which is now commercially used in water and food industries. Researches to employ this technology in hydrocarbon industry are also being conducted [5].

It is inherently difficult to achieve a high rate of ice production in industrial environments with simple, easy to maintain equipments whilst pursuing high coefficient of performances, COP. Amongst the existing ice slurry generation mechanisms [6–14,2], scraped surface is the most widely utilised. With a type of freezing point depressant (FPD) added in water, ice would nucleate and propagate on a cold metal surface before it can further develop into a mushy layer. As the mushy layer thickens on the subcooled surface, it acts as an insulator which reduces the rate of heat transfer and ice formation. For this reason, it is then required to shear off the ice by a mechanical scraper or, less popular, an energy inefficient thermal cycling system to keep the ice layer thin. The mushy layer removal systems require high maintenance cost and increase the size of the equipments. The undesirable growth of ice on cold evaporator surfaces is also a problem for both industrial and domestic freezers and deicing has to be performed on a regular basis [15,16].

A cheaper and more efficient way of generating ice slurries has two separate stages. In the first stage, water is frozen on a cold surface which is cyclically heated to remove the ice once it has reached a certain thickness [17]. Comminution of this bulk ice with brine supplement then completes the process [18]. Per kilogram of ice slurry, this method can reduce energy usage by 32% compared to a scraped surface ice maker provided that the evaporator temperature is elevated by 20 °C, from $-30\,^{\circ}\mathrm{C}$ to $-10\,^{\circ}\mathrm{C}$ and energy consumption of any auxiliary systems are disregarded [19]. With the ice storage and delivery taken into consideration, 20% of saving may be achievable in practice [20]. As for the implementation on ice pigging, the pig is produced at the point of delivery, where bulk ice is crushed into the correct size, instead of being generated overnight and stored and maintained in a stirrer tank where more power is consumed. Although this way of ice slurry generation is

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Nomenclature

α	thermal diffusivity [m^2/s]
ΔG_v	Gibbs energy per unit volume [J/m^3]
ΔT	bath supercooling temperature [K]
ΔT_{SLSH}	unuseful superheat in the suction line [K]
η_{isen}	isentropic efficiency
η_{vol}	volumetric efficiency
v	growth rate of ice [cm/s]
$\phi_v^{\dagger}$	cafetière ice fraction
σ	surface energy [J/m^2]
A	area [m^2]
a	constant
C_B	wt% salt in brine
C_w	wt% salt in water
D	mass diffusivity [m^2/s]
Gr	Grashof number
Gr_m	mass transfer Grashof number
h_h	heat transfer coefficient [$W/(m^2K)$]
h_m	mass transfer coefficient [$kg/(m^2s)$]
m	rate of mass transfer [kg/s]
Nu	Nusselt number
Pr	Prandtl number
Q	available cooling by the refrigeration cycle [J]
q	rate of heat transfer [W]
r^*	critical radius for nucleation [m]
Ra	Rayleigh number
Ra_m	mass transfer Rayleigh number
Re	Reynolds number
Sc	Schmidt number
Sh	Sherwood number
T_B	brine temperature [K]
T_C	compressor temperature [°C]
T_E	evaporator temperature [°C]
T_w	water temperature [K]
W^*	critical energy for nucleation [J]
W_c	compressor work [J]
COP	coefficient of performance

more efficient, it is easy to have the crushed ice to stick together and become larger pieces if the added brine does not fill up the gap between ice particles soon enough and consequently makes it difficult to carry out the 'cafetière test' [21,22] to detect the ice fraction. Whether the quality of the ice slurries would affect electromagnetic wave attenuation which can be used as the fundamental principle of an online ice fraction detection method [23] is not well understood yet. Another method considered inexpensive is to produce ice slurries or flake ice by means of direct contact which requires neither subcooled surfaces nor mechanisms to maintain the rate of production [10–14]. However, this way of ice production requires the mixing of water, refrigerant and compressor oil, making it suitable for the thermal storage application but cannot be implemented in the food industry.

In this study, a novel method of ice production is proposed whereby ice is generated in a fluid with a temperature below the freezing point of water. Water at about 0 °C is introduced into a bath of brine with a range of salt concentrations by weight (from eutectic point, 23.3% to 21%), at temperatures of about −18 °C. Provided the rate of transient heat transfer exceeds that of mass transfer so that the latent heat of fusion can diffuse away quickly, ice would form. Experimental progress is presented in this paper.

2. Background

2.1. Preliminary experimental observations

It is relatively easy to generate ice when the heat sink fluid is immiscible with water, as in the direct contact method, but considerably more demanding if brine is used instead because water can easily mix with the cooling media in this later case. There are two real life examples that enlightened us to consider making ice with a choice of hydrophilic solution, brine, and both of them are based on the fact that heat transfer can be higher than mass transfer in fluids.

The first is the simple water droplet experiment, which is performed by releasing a few drops of water to the surface of a bath of cold brine. If the brine temperature is much lower than 0 °C, a disc of ice would form. This phenomenon indicates that the transient heat transfer, mainly by conduction, is higher than mass transfer and the Lewis Number, $Le = Sc/Pr = \alpha/D$, which measures the relative boundary layer thickness of temperature and concentration, in this case should be greater than unity.

Another high Le number example is found in a bottle of naturally stratified brine at a concentration below its saturation. Despite it is well mixed in the first place, a concentration gradient will slowly develop along the bottle and eventually remain unchanged if it is left untouched long enough in a room where the ambient temperature fluctuates from day to nigh; at some point, mass transfer will almost stop while heat transfer continues.

These two observations show that it is possible to produce ice through introducing water to a bath of subcooled brine provided the heat and mass transfer is carefully controlled so that the latent heat of fusion can dissipate away from the boundary layer before phase transformation completes.

2.2. Heat and mass transfer fundamentals

Water has low value of thermal conductivity (~0.5 W/mK) and convection of mass, which consists of advection and diffusion, makes it a good heat transfer media. The driving force of advection is the temperature and concentration led density difference that initiates buoyancy with the presence of gravity. Heat and mass transfer can be expressed in Eq. (1a) and (1b) where h_h and h_m are heat and mass transfer coefficient governed by a range of physical properties.

$$q = Ah_h(T_w - T_B) \tag{1a}$$

$$m = Ah_m(C_w - C_B) \tag{1b}$$

h_h can be determined through the Nusselt number, Nu. In most cases, Nu is a function of the Rayleigh number, Ra, and the Prandtl number, Pr, for natural convection only ($Gr/Re^2 \gg 1$); if not, Nu is a function of Ra alone (2a). In forced convection scenario ($Gr/Re^2 \ll 1$), Nu is a function of the Reynolds number, Re, and Pr (2b). If neither convective regime dominates ($Gr/Re^2 \approx 1$), Nu is a function of Re, Gr and Pr; natural and forced convections are in the same order of magnitude (2c) [24–27].

In natural convection, the boundary layer flow would remain laminar if the distance it has travelled is short enough so that the Grashof number, Gr, is below the order of 9 for a wide range of fluids with various Pr values. One can also use $Ra \sim 10^9$, by