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Charging and discharging characteristics of cool thermal energy storage system with horizontal pipes using water as phase change material

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ABSTRACT

An experimental investigation of ice formation on cold vertical banks of horizontal tubes subjected to falling-film– jet mode– is conducted. In the charging process, a set of internally cooled vertical banks of horizontal tubes of brine is subjected to a falling film of water. The formed ice is periodically observed, photographed and measured in falling-film jet mode at specific internal coolant (ethylene–glycol solution) flow rates and temperatures. In the discharge process, the same solution is heated and used internally to release ice. Different thicknesses of the released ice are observed and measured. The maximum quantity of released ice is obtained and the optimum ice formation is determined. The results indicate that the ice formation and the solid ice released are controlled by the thermal resistance of the ice, time and pitch between tubes. The maximum gained ice has a thickness that is approximately equal to half of the tube spacing between the tubes utilized, which is formed in approximately 45 min and released in 12.5 min. The variation in heating solution temperature has a slight effect on the gained ice and discharging time.

1. Introduction

There are two methods to store and reuse formed ice. The first method involves storing ice on the tubes of the freezing system. The second method involves releasing ice from the tubes and storing it in an isolated reservoir. In the first method, the freezing system is the storage system. Thus, the ice obtained by the system must be as thick as possible. In the second method, the ice has to be released with the minimum amount of melted ice and stored in an isolated receiver. In this case, the freezing system can be reused several times, which increases its capacity. This latter method is considered in this study.

The topic of ice formation has been explored by some researchers [1,2,4–8,10]; the topic of ice melting has also been examined [3,9,11,12].

Sait et al. [1,2] performed an experimental investigation on the freezing of water falling film on a vertical bank of horizontal cold tubes. The brine flows into the concentric tubes in parallel. The authors focused their work on ice formation characteristics and heat transfer for the three main modes of falling film: droplets, jets and sheets. These researchers determined that the formation of ice depends on falling film and coolant flow rates. In addition, the overall heat transfer coefficients are controlled by the thermal resistance of ice. Habeebullah [3] conducted an experimental study on ice formation around a horizontal long copper tube (L = 12.3 m with tree returned bends of 180° and d = 19.5 mm) immersed in water. This researcher found that there was a slope of the ice thickness, in which the axial distance depended on time but varied with coolant flow rate and Stanton and Biot numbers. The axial growth rate of ice was distinct for low values of the coolant Reynolds number and short freezing times. He also discovered an unexpected enlargement of ice thickness on the surface of the tube bends.

Cabeza et al. [4] added stainless steel pieces, copper pieces and graphite matrix impregnated with water as phase change materials (PCM) to improve heat transfer. They founded that addition of stainless steel pieces in the PCM does not increase the heat flux significantly. However, addition of copper pieces and the use of graphite composite enhance heat transfer significantly. Ismail and Jesus [5] performed a parametric study of the solidification of PCM around a cylinder for an ice-bank application. They concluded that a lower initial temperature of the liquid phase seemed to accelerate the solidification. The thermal conductivity of the tube wall material can have a considerable influence on the velocity of the process. Kayansayan and Acar [6] analyzed ice formation around a finned-tube heat exchanger for cold thermal energy storage. They concluded that under identical flow and inlet conditions, the heat exchanger with finned tube stores a maximum of 45% more energy than the bare tube of a turbulent flow regime (Re > 3000).

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Nomenclature

A	aria (m^2)
Cp	specific heat (J/kg K)
d	tube diameter (m)
h	heat transfer coefficient (W/m^2 K)
k	thermal conductivity (W/m K)
L	latent heat (J/kg)
M	mass (kg)
$\dot{m}$	mass flow rate (kg/s)
$\dot{Q}$	heat transfer rate (W)
T	temperature (°C)
$\overline{T}$	average temperature (°C)
U	overall heat transfer coefficient (W/m^2 K)

Greek symbols

ℓ	tube length (m)
τ	time (s)

Subscripts

cu	copper
exim	experimental ice melting
exo	overall heat transfer coefficient
h	hot
hi	hot in
ho	hot out
i	internal
io	inner of outer tube
Lmice	latent heat of melted ice
Mice	melted ice
o	out
oo	outer of outer tube
s	surface
smice	sensible heat of melted ice
sw	sensible heat of water
tmi	theoretical melting ice
w	water
0	melting point

Eames and Adref [7] studied freezing and melting of water in the type of spherical enclosures that are used in thermal (ice) storage systems. They concluded that 90% of the cold could be extracted from the ice storage element within 70% of the time required for complete discharge. Hirata and Matsui [8] studied heat transfer with freezing and thawing for water flow around isothermally cooled cylinders in staggered and aligned arrangements. They demonstrated that the ice filling rate is strongly affected by the Reynolds number, cooling temperature, and cylinder pitch perpendicular to water flow. Melting occurred twice as fast as freezing occurred. Yingxin and Zhang [9] studied thermal processes for internal melting in an ice-on-coil tank, including the variation in ice-water density. They analyzed both charge and discharge processes for the ice-on-coil tank. They concluded that the discharge model is only applicable for processes that begin when the ice cylinder slightly overlaps and unfrozen water is present, which causes the ice to float. Vargas et al. [10] experimentally and analytically studied the fundamentals of melting ice-shell rides on heated horizontal cylinders. They assumed and proved that natural convection is negligible compared with the natural convection of the heated cylinder. The melted water is drained axially. Most of the melting is due to direct contact with the upper half of the hot cylinder. Their results indicate that the melting process consists of two distinct regimes: the first regime occurs when the cylinder is surrounded by ice, which consumes the majority of the melting time, and the second regime occurs when the cylinder cuts through the upper portion of the ice sleeve. The time until the ice falls off the cylinder can be obtained from a specific graph. Wu et al. [11] studied discharging characteristics by modeling cool thermal energy storage systems with coil pipes using n-Tetradecane as a phase change material. The results demonstrate that the higher the flow rate of the heat transfer fluid or the higher the inlet temperature of the heat transfer fluid, the higher the cool release rates, and less time will be required during the discharge process. The diameter of the coil pipes has little influence on the discharge process compared to the other variables previously mentioned.

Masahiko et al. [12] studied the performance analysis of the liquid–ice thermal storage system for optimum operation. They concluded that intensive melting results when slush ice is pulled by buoyancy to the top of the hot capsule and when close contact occurs. The local heat transfer is most valuable at the top of the vissle and decreases along the vissle wall due to the stratified layer and free convection. The average heat transfer coefficient increases as heat flux increases. The melting rate increases monotonically as a function of time, irrespective of heat flux and solution concentration. Tsuyoshi et al. [13] conducted an experiment on the melting of slush ice in a horizontal cylindrical capsule. Their results demonstrated that the COP was almost the same for all three operation modes, whereas the performance of heat release mode for POR decreases with an increase in running time or storage time. The system simulation suggests the potential for obtaining optimum operational conditions, such as the daily running time of thermal storage, among the employed operational modes.

The previously described study examined freezing and thawing (melting) of stagnant or moving water flow. The freezing of falling water film on horizontal tubes and its characteristics were also examined. For cold thermal storage where, the accumulated ice is used during the peak electrical load periods, it is necessarily to investigate more about the behavior of the discharge cycle (melting process). The present study investigates both charging and discharging of ice on and from tube surfaces, but focusing more on the melting process since the freezing process was explained well by Sait et al. [1,2]. The quantity of optimally formed ice and ice releasing behavior are also investigated for a falling-film jet mode.

2. Experimental apparatus

The experimental apparatus shown in Fig. 1 is designed and fabricated to allow falling film to freeze outside the tubes and to obtain the maximum quantity of released solid ice. A detailed description of the apparatus is provided in Sait et al. [1,2]. The main differences between the two apparatuses are as follows: (a) The coolant in the present study flows through the test concentric tubes in series only to achieve accurate temperature measurements, whereas the tubes were designed in series or in parallel in the previous apparatus. (b) A catching tube is used to get accurate temperature of the outlet falling film or the released iced. (c) A strainer is used under the tubes in this study to separate the released solid ice from the melted ice. (d) The hot solution flow rate and temperatures are recorded during the discharge cycle (melting process), which was not the case in the previous design of [1,2], to determine the heat of release.