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Numerical study of ice melting inside rectangular capsule under cyclic temperature of heat transfer fluid

Amr O. Elsayed *

Faculty of Engineering, Zagazig University, P.O. Box 44519, Zagazig, Egypt

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Abstract

The periodic melting of encapsulated ice for cold thermal energy storage has been investigated numerically. A horizontal rectangular container is used as a storage capsule, since warm coolant fluid (glycol) flows over the upper and lower walls of the capsule, melting the ice. The enthalpy method is employed to model the phase change at the two moving interfaces. The effect of cyclic time variant coolant fluid temperature on the heat transfer efficiency and the corresponding energy stored has been investigated. Also, the influence of the convection heat transfer coefficient and coolant fluid temperature on the melting behavior has been studied and reported. The results show that the coolant fluid temperature markedly affects the melting behavior rather than the convection heat transfer coefficient.

Keywords: Ice melting; Cyclic coolant temperature; Rectangular ice capsule; Cool thermal storage; Energy storage

1. Introduction

Cold thermal energy storage [1] has been a main topic of research due to its benefits, such as reduction of electricity demand at peak periods and reduction of chiller capacity. Two basic types are known in ice storage technology [2]; ice building systems (static) and ice harvesting systems (dynamic). For static production of encapsulated ice, the storage tank is filled with sealed capsules of water. These capsules are made of thin plastic walls to accommodate the expansion of ice upon freezing inside them. The most commercially used shapes of the capsules are dimpled balls and rectangular containers.

In practical use of energy storage capsules, two melting techniques can be found. In the first one, the solid is unfixed inside the capsule, and the melting is dominated by close-contact heat transfer between the solid and the capsule wall (e.g. [3,4]). While in the other technique, the solid is fixed around the center of an axis of the capsule (e.g. [5,6]). Hirata et al. [6] investigated the melting characteristics of octadecane and ice inside isothermally heated horizontal rectangular capsules. Experiments were performed for three kinds of aspect ratios (H/W = 1/3, 1 and 3) of capsules, and a simple model was proposed for estimating the molten mass fraction by using empirical correlations for the natural convection heat transfer coefficient. They found that the melting curve of ice for the capsule with aspect ratio 1/3 lies close to that of pure conduction heat transfer. Prusa et al. [7] offered the details of a mathematical model to predict the thermal performance of a latent heat energy storage system. The phase change material was held in rectangular containers, where unsteady conductive heat transfer in the liquid and solid phases had been considered in the mathematical model.

Comprehensive review articles on water freezing and ice melting problems under a variety of conditions were provided by Fukusako and Yamada [8,9]. They showed [8] the melting of ice by heating the wall from above or below and ice melting by a radiant heat source as well as the melting with vapor condensation.

Arnold [10–12] proposed a series of experimental and numerical investigations on freezing and melting of encapsulated ice. From the experimental measurements of a

* Tel.: +2 055 3204997; fax: +2 055 3204987.
E-mail address: amro9992000@yahoo.com

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Nomenclature

A	surface area, m^2
c	specific heat, J kg^{-1} K^{-1}
h	heat transfer coefficient, W m^{-2} K^{-1}
H	container height, m
ΔH	latent heat content, J kg^{-1}
k	thermal conductivity, W m^{-1} K^{-1}
L	container length, m
Nu_{L}	Nusselt number, $h\mathrm{L}/k_{\mathrm{f}}$
L	latent heat, J kg^{-1}
Pr	Prandtl number, $c_{\mathrm{f}}\mu/k_{\mathrm{f}}$
Q	cumulative heat stored, J
Re_{L}	Reynolds number, $\rho_{\mathrm{f}}\, v\, \mathrm{L}/\mu$
S	source term in Eq. (1), W m^{-3}
t	time, s
T	temperature, K or °C
v	coolant fluid velocity, m s^{-1}
W	container width, m
x, y, z	space coordinates in cartesian system
Z	melting front location, m

Greek symbols

μ	viscosity, Pa s
ρ	density, kg m^{-3}

Subscripts

f	coolant fluid
i, j, k	grid nodal points
l	liquid
L	lower
Lat	latent
m	melting
sens	sensible
U	upper
w	wall

single capsule calorimeter, Arnold [11] found that a large variation in heat transfer occurred during the phase change and the rate of heat transfer during melting was affected by the temperature of the water formed in the interstice between the capsule skin and the residual ice. Arnold [10,12] prepared and developed a dynamic simulation model for an encapsulated ice store. The rates of heat transfer that were used in the model are dependent on the ice fraction during the phase change. These measured rates of heat transfer were based on the calorimeter results.

A periodic phase change process dominated by heat conduction has been investigated numerically and experimentally by Casano and Piva [13]. In the experiments, a plane slab of phase change material was periodically heated from above. A one dimensional control volume computer code has been developed for the solution of the mathematical model. The comparison between the numerical predictions and experimental results showed good agreement.

From the above review, it can be concluded that there is little information available about the melting of ice under cyclic temperature of the heat transfer fluid. The main objective of the present work is to characterize the melting of ice inside a horizontal rectangular capsule under oscillatory variation of the coolant fluid temperature and also to study the effect of convection heat transfer coefficient on the heat transfer efficiency and the corresponding melting behavior.

Understanding of the ice melting characteristics is very useful for the design and operation of this type of cool storage system.

2. Mathematical formulation

The physical configuration of the melting problem under consideration is schematically illustrated in Fig. 1. Ice is contained in a horizontal rectangular enclosure with initial temperature equal to its phase change temperature. The upper and lower walls of the capsule are heated by the flow of the warm coolant fluid (glycol) that circulates inside the storage tank. Thus, the upper and lower walls are exposed to forced convection heat transfer, and two moving boundaries take place inside the capsule. The side walls of the capsule are assumed to be adiabatic.

To simulate the phase change of ice, the enthalpy method [14] is employed. In this method, explicit tracking of the solid–liquid interface is eliminated. The transient part of the energy equation is written in terms of total enthalpy instead of temperature. By following the source based technique [15] for the enthalpy formulation, the sensible and latent enthalpies are separated in the transient term and latent heat is isolated in a source term in the energy equation. The relationship between the latent heat and the temperature is defined based on the characteristics of the phase change material.

To facilitate the formulation, the following assumptions are adopted:

- The thermophysical properties of the solid and liquid phases are constant.

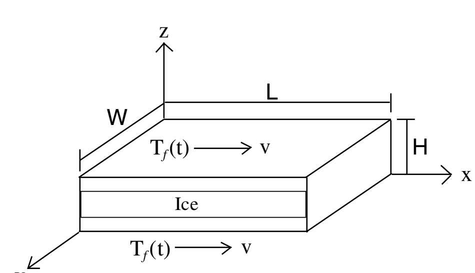

Fig. 1. Schematic description of the physical configuration.