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Close-contact melting in vertical annular enclosures with a non-isothermal base: Theoretical modeling and application to thermal storage

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ABSTRACT

In the present study, the effects of close-contact melting (CCM) are studied for geometries suitable for latent heat thermal energy storage. Specifically, a vertical double pipe concentric storage unit with circumferentially finned inner tube is explored experimentally. It is demonstrated that CCM enhances significantly the heat transfer rate, shortening the melting time by almost 2.5 times in that specific laboratory-scale device. These results show that it is favorable to supply heat to the outer shell of a latent-heat storage unit in order to initiate close-contact melting and achieve higher heat transfer rates.

In order to analyze the process more closely, a single-cell vertical enclosure containing a phase-change material (PCM) is explored. A numerical model, which combines an enthalpy method with CCM modeling, is developed and validated experimentally. The solid bulk of the PCM is allowed to sink, thus enabling close-contact melting on the non-isothermal fin surface. The fins are thus much more important than just extended surfaces for heat transfer enhancement. The agreement between the numerical predictions and experimental findings is very good both in terms of the total melting time and instant melting patterns. The validated numerical model is further used for a detailed study, in which time dependent melt fractions and heat transfer rates are obtained for various temperature conditions. In all cases, the findings are compared with a simplified analytical model which accounts for the close-contact melting only, revealing effects not predicted by common CCM modeling approaches in the literature.

The analytical model yields theoretical expressions for the time-dependent melt fraction, heat transfer rate and molten layer thickness in a dimensionless form. For the conditions of the present study, the dimensional analysis indicates that the melt fraction depends on the Fourier and Stefan numbers combined as $FoSte^{3/4}$ only, whereas the Nusselt number and the normalized layer thickness both depend also on the same additional group, $Ste^{1/4}$. Based on these findings, the numerically calculated melt fractions, Nusselt numbers and layer thicknesses are generalized completely, showing a remarkable agreement.

1. Introduction

Latent-heat thermal energy storage systems (LHTES) have been under development during the recent decades. Their main attractiveness lies in the large heat-storage capacity of phase-change materials (PCMs). A wide variety of systems have been studied, addressing their overall characteristics [1,2], solar energy applications [3], modeling methods [4], and possible basic configurations [5]. Of particular concern in the design of these systems is the low thermal conductivity of the PCMs, and various ways to overcome this deficiency have been suggested. As in the other fields of heat transfer and thermal engineering, extended surfaces of various sizes and configurations have been tried, from common fins [6,7] to heat pipes [8–11] and thermosyphons [12].

One of the most common geometries is a finned tube with a radial (circumferential) array of fins (e.g. [13]). A generic view of a typical storage unit is shown in Fig. 1. The heat transfer fluid (HTF) flows in the tube whereas a PCM is stored between the tube and a concentric enclosure. This geometry has been investigated extensively in the past due to its relative simplicity and low manufacturing cost. Both melting and solidification studies are abundant in the literature. Choi and Kim [14] investigated experimentally solidification in a vertical tube with and without radial fins, whereas Ismail and Lino [15] studied solidification in a horizontal tube. Hamdani and Mahlia [16] compared experimentally the melting process in a vertical tube with radial, axial and no fins. Lacroix [17] studied both experimentally and numerically melting in a horizontal radially finned tube, with a good agreement

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Nomenclature

c_p	specific heat, kJ/(kg K)
g	gravitational acceleration, m/s^2
H	height, m
$\tilde{H}$	enthalpy per unit volume, kJ/m^3
k	thermal conductivity, W/(m K)
l_t	fin thickness, m
L	latent heat, kJ/kg
$\dot{m}$	mass flow rate, kg/s
P	pressure, Pa
q	heat transfer rate, W
q''	heat flux, W/m^2
r	radial coordinate, m
R	radius of the solid phase, m
s	solid–liquid interface location, m
t	time, s
T	temperature, °C
u	velocity component, m/s
υ	sinking velocity, m/s
V	volume, m^3
z	axial coordinate, m

Greek letters

α	thermal diffusivity, m^2/s
δ	molten layer thickness, m
$\bar{\delta}$	area-averaged molten layer thickness, m
Δ	difference
μ	dynamic viscosity, kg/(m s)
ν	kinematic viscosity, m^2/s
ρ	density, kg/m^3

Subscripts

Al	aluminum
eff	effective
i	inner
init	initial
l	liquid
m	melting
o	outer
r	radial
s	solid
tot	total
w	wall

between the numerical results and experimental findings. The same geometry was investigated, numerically and experimentally, also by Erek et al. [18]. More recently, Ogoh and Groulx [19,20] numerically simulated a vertical radially finned tube PCM storage device. We note that due to the complexity of the geometry and limited computing resources, it was quite common to use some sort of simplifications, e.g. by neglecting convection or accounting for it in some sort of "equivalent" parameters, thus effectively causing no difference due to orientation in the models, as is done also in some recent studies [21–24].

Some of the most recent works in the field attempt to take a closer look at the details of melting in vertical configurations. Tay et al. [25] studied a finned device by using a 3-D CFD model, coupled with the HTF flow and taking into account heat losses to the outer shell and the environment, but without convection in the molten PCM. Good agreement between the numerical and experimental results was found. Chiu and Martin [26] also studied both experimentally and numerically a vertical device with radial fins.

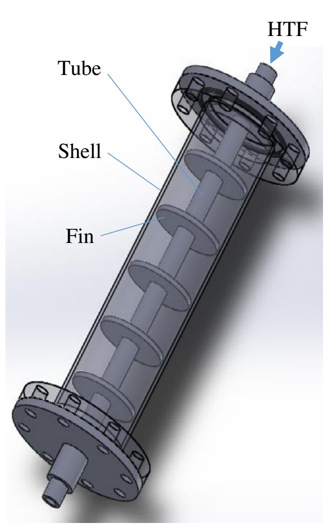

Fig. 1. Generic configuration of a concentric latent heat storage unit with radial fins.

Later on, two numerical models that took into account convection in the melt were compared by the same group [27]: a model using effective thermal conductivity and a model using a full solution of the conservation equations. The full solution model showed excellent agreement with the experimental results, much better than the effective thermal conductivity model.

Fig. 2 presents an original axisymmetric simulation by the authors that illustrates patterns commonly encountered in these devices when the axis is vertical. The tube surface is assumed isothermal. Melting inside the unit is shown in Fig. 2a in terms of the phase distribution. The corresponding flow patterns are given in Fig. 2b. One can see that the melting starts near the fins and tube, propagating into the PCM as time passes. From below, the solid–liquid interface is wavy, due to the effect of Bénard-like convection cells. In order to simulate the exact convection patterns, 3-D effects must be taken into account, but even a two-dimensional simulation captures the essential features quite well. The simulation presented in Fig. 2 uses the most advanced features recently added to CFD modeling [28], and its reliability is quite satisfactory.

As expected, fins enhance heat transfer to an extent that depends on the specific configuration chosen. There is, however, one feature that has not been addressed in the literature but, in our opinion, definitely requires special attention. It is clear, both from the simulation presented and from the detailed results reported in the literature [25,27], that the remaining solid phase at any instant is attached to the envelope, see again Fig. 2. In the experiments, this result is obviously due to the fact that the shell is transparent to visualize the process. Since usually it is exposed to the cool ambient, has a low thermal conductivity and is not connected to the fins, its temperature is low. As a result, no melting takes place at its inner surface, and the solid PCM sticks to it. In this connection, the following three questions arise: (1) does this situation reflect the real picture? (2) what would happen to the rate of melting if the solid is allowed to move? and (3) how to model this process in order to obtain a reliable prediction?

Actually, the second question is the key one, because if the rate of melting can increase significantly, it is worth to design the storage unit such that the solid would not stick to the wall. In this paper, we argue that indeed, due to the solid motion, the rate of melting increases significantly, because of the so-called close-contact