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Close-contact melting in a horizontal cylindrical enclosure with longitudinal plate fins: Demonstration, modeling and application to thermal storage

T. Rozenfeld, Y. Kozak, R. Hayat, G. Ziskind *

Heat Transfer Laboratory, Department of Mechanical Engineering, Ben-Gurion University of the Negev, P.O.B. 653, Beer-Sheva 84105, Israel

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ABSTRACT

The present study deals with melting in a horizontal double-pipe concentric storage unit with a longitudinally finned inner tube. This geometry, applicable for thermal energy storage, has been extensively studied in the past. However, close-contact melting (CCM), which may significantly increase the melting rate, has not been explored for this sort of systems.

In the present experiments, a laboratory-scale three-fin unit is transparent and thus the processes inside it are observed and recorded. Close-contact melting is achieved by supplying heat to the outer shell of the unit: the solid phase is detached from the shell and moves in the liquid phase. In the upper part of the unit, the solid phase translates vertically and melts on the inclined fin surfaces. In the lower parts of the unit, the solid phase approaches the vertical fin by rotation, while its outward surface slides on the shell. It is shown that close-contact melting shortens the melting time by a factor of 2.5 in that specific laboratory-scale device.

A novel theoretical model includes gravity-induced rotational motion of the solid, primary melting on a vertical fin with non-uniform temperature distribution, secondary melting at the shell, and frictional resistance at the latter. The model is validated using the experimental results, and then used for a parametric investigation and dimensional analysis. It is revealed that the melt fraction depends on the Fourier and Stefan numbers combined as $FoSte^{3/4}$, whereas the Nusselt number depends also on an additional group, $Ste^{1/4}$. Further generalization is achieved when different angles between the fins are considered.

The present paper presents a further proof of the special role that close-contact melting (CCM) can play in thermal energy storage units and finned systems in general. It is demonstrated that the fins, when properly designed and oriented, induce CCM in their vicinity, leading to a very significant increase in the melting rate.

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1. Introduction

The main attractiveness of latent-heat thermal energy storage systems (LHTES) stems from the large heat-storage capacity of phase-change materials (PCMs). Different systems have been studied in the literature, addressing their overall characteristics [1], materials [2], solar energy applications [3], and modeling methods [4]. 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 [5–7] to heat pipes [8–11] and thermosyphons [12].

One possible implementation of a latent heat thermal storage device is a finned tube with an array of fins. The tube can be enclosed in a cylindrical shell filled with PCM. A heat transfer fluid (HTF) flows through the tube and heat is conducted from the tube to the fins that are in contact with the PCM. The thermal storage charging/discharging process is driven by a hot/cold HTF inside the tube that causes the PCM to melt/solidify. This type of storage unit can be set in different orientations, usually with the tube axis vertical or horizontal. Two types of fins are the most common, radial (circumferential) fins and longitudinal fins, although many other configurations, including somewhat exotic ones, have been also suggested [13].

* Corresponding author. Tel.: +972 8 6477089.
E-mail address: gziskind@bgu.ac.il (G. Ziskind).

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Nomenclature

c_p	specific heat, kJ/(kg K)
g	gravitational acceleration, m/s^2
k	thermal conductivity, W/(m K)
L	latent heat, kJ/kg
M	moment per unit depth, N
p	pressure, Pa
q''	heat flux, W/m^2
r	radial coordinate, m
R	radius of the solid phase, m
s	solid–liquid interface location, m
S	cross-section area, m^2
t	time, s
T	temperature, °C
u	velocity component, m/s
x	Cartesian coordinate, m
Xc	center of mass coordinate, m
y	Cartesian coordinate, m
Yc	center of mass coordinate, m

Greek letters

α	angular displacement of the solid
α_l	thermal diffusivity, m^2/s
δ	molten layer angular dimension
δ_r	molten layer thickness at the fin, m
θ	angular coordinate
μ	dynamic viscosity, kg/(m s)
ν	kinematic viscosity, m^2/s
ρ	density, kg/m^3
τ	shear stress, Pa
φ	auxiliary angle used at the envelope
ϕ	angle between fins

Subscripts

Al	aluminum
avg	average
eff	effective
env	envelope
i	inner
l	liquid
m	melting
o	outer
r	radial
s	solid
w	wall
$w0$	fin base

Latent heat thermal storage units with radial (circumferential) arrays of fins have been comprehensively explored in the past, for both solidification and melting. A recent paper [14] surveys some representative examples [15–22]. Most recent papers address such diverse issues as comparison with pinned tubes [23], effectiveness analysis [24], and entropy generation [25].

Latent heat storage units with longitudinal fins have been studied both experimentally and theoretically for more than 30 years. Sparrow et al. [26] conducted experiments for solidification on a vertical tube with and without a longitudinal fin array. It was found that the presence of fins significantly enhances the solidification process. Bathelt and Viskanta [27] studied experimentally melting and solidification on a horizontal finned tube with three longitudinal plate fins, and compared the results with the case of an unfinned tube. Also, the effect of different fin orientations was examined. The same configuration was investigated experimentally by Betzel and Beer [28], where two different fin materials were used: copper and PVC. The results were generalized and a correlation for the Nusselt number was derived. Padmanabhan and Krishna Murthy [29] numerically simulated melting/solidification on a tube with an arbitrary number of longitudinal fins. A two-dimensional numerical model was developed under the assumption that the only heat transfer mode is conduction. The simulation results were generalized by a correlation for the melt fraction. Al-jandal and Sayigh [30] compared experimentally melting on a vertical finless tube with radially and longitudinally finned tubes. It was found that the fins enhance the heat transfer rate and that natural convection plays a significant role in the melting process. Ismail et al. [31] developed a two-dimensional numerical model, based on heat conduction only, for the solidification process on a vertical longitudinally finned tube. The numerical findings were close to experimental results. Also, the effects of fin geometry and tube temperature were examined. Solomon and Velraj [32] tested experimentally a tube with eight longitudinal fins compared with a finless tube. Different parameters which were examined included the fin length. Agyenim et al. [33] explored a storage unit based on a horizontal tube, with and without fins. Two types of fin configurations were compared: radial and longitudinal. Later on, the longitudinal finned storage unit was further investigated by the same group [34–35]. Hamdani and Mahlia [36] examined various cases for melting in a vertical tube: the case of a tube without fins was compared with a tube with radial and longitudinal fin arrays. Mat et al. [37] studied a horizontal storage unit with three concentric tubes, where the HTF flows in the most inner and most outer tubes, and the PCM is in the middle tube. The effect of longitudinal fins attached to the inner and outer tubes was tested. This configuration was further explored by the same group [38–39]. Most recently, Liu and Groulx [40] studied experimentally the melting and solidification processes in a horizontal finned tube with four longitudinal fins. Two different fin orientations, which may be defined as "X" and " + ", were tested. The same authors studied a similar vertical system under different conditions [41–42]. The most recent work on this subject introduces a certain configuration of fins [43].

Fig. 1 presents an original two-dimensional CFD simulation by the authors that illustrates patterns commonly encountered in units with a longitudinally-finned inner tube with a horizontal axis. This type of CFD simulation has been introduced by [44] and allows to study the role of convection in the melt, the effects of fin design and the influence of the storage device working conditions. Here and below we are going to define the presented 3-fin system as "Y" configuration, noting that it has much in common with "X" and " + " configurations [40] which have 4 fins. One can see in Fig. 1 a number of important features of the process. For instance, in the upper part of the unit melting is dominated by conduction at the early stages of the process, whereas at the later stages convection plays the decisive role. In the lower parts of the unit, the role of convection also increases with time. As a result, melting in the unit occurs mostly by convection, and as heating from below is more effective, melting in the upper part of the unit is more rapid. Also, due to convection the solid phase in the lower parts of the unit is not located symmetrically as related to the fins. It will be demonstrated later that the patterns in Fig. 1, which prove the positive effect of fins, are indeed encountered experimentally under commonly used conditions. Still, the molten material between the hot fin surfaces and the remaining solid presents a significant thermal resistance which impedes the process.

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