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Experimental demonstration, modeling and analysis of a novel latent-heat thermal energy storage unit with a helical fin

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ABSTRACT

This paper presents a novel configuration suitable for latent-heat thermal energy storage systems based on the use of phase-change materials (PCMs). It is a double-pipe unit with a helical fin attached to the inner tube in which a heat-transfer fluid (HTF) flows. Experiments in the unit are performed both for regular conditions, when its shell is exposed to ambient air, and for a slightly heated shell which allows to achieve close-contact melting (CCM). It is clearly shown that CCM in the suggested unit is possible and shortens the melting time by a factor of three.

In addition to the experimental demonstration, the paper includes comprehensive modeling of the unit. Both analytical and numerical models are included, describing the phenomenon of close-contact melting on a helical surface. The analytical model, made possible under the assumption that the fin is isothermal, accounts for other main features of the process and also reveals its governing dimensionless parameters, including the Fourier, Stefan, Archimedes and Prandtl numbers, along with the group representing the unit geometry. The numerical model includes a complete solution for the time-dependent fin temperature distribution, and can account also for the sensible heat of the PCM.

A very good agreement of the numerical predictions and experimental findings is achieved. Then, a dimensional analysis, based on the analytical model, is applied to the numerical results. Generalized behavior is obtained for such parameters as the temperature difference between the heat-transfer fluid and the PCM, and the helical fin pitch. The analysis is then extended to a non-isothermal fin, suggesting an additional physically-meaningful dimensionless group which completely generalizes the results for different fin radii, fin thicknesses and fin-to-PCM volume ratios.

It is argued that the suggested configuration may have a number of advantages in comparison with the existing fin-array systems. These advantages include enhanced melting, prevention of increased pressures in melting (or solidification if the material is anomalous like water) and voids in solidification, and highly-convenient handling and maintenance of the system. Also, the helical fin might be attached to the outer tube (shell), and a configuration in which the HTF flows across the shell is possible while preserving all important features of the unit explored.

1. Introduction

One of the major problems in practical implementation of latent-heat thermal energy storage (LHTES) systems is that most of the materials with high latent heat have low thermal conductivity. Along with other methods of heat transfer enhancement, a common solution to this problem is the use of extended surfaces. Thus, many of suggested LHTES units are built of concentric tubes, where a phase-change material is stored between the tubes and a fin array attached to the inner tube, in which the heat transfer fluid is flowing.

Two types of fins are the most common, radial (circumferential) fins and longitudinal fins, although many other configurations, including somewhat peculiar ones, have been also suggested [1]. Latent heat thermal storage units with radial arrays of fins have been comprehensively explored in the past, for both solidification and melting. A recent paper [2] surveys some representative examples [3–10]. According to [2], the melting starts near the fins and tube, propagating into the PCM as time passes. As expected, fins enhance heat transfer to an extent that depends on the specific configuration chosen. From below, the solid-liquid interface is wavy, due to the effect of Bénard-like convection cells, and melting

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Nomenclature

A	area, m^2
Ar	Archimedes number
b	fin width, m
C,c	constants
c_p	specific heat, J/(kg K)
D	pressure matrix constant
Fo	Fourier number
f	number of fin elements
f_{fluid}	force due to pressure, N
f_{body}	force due to weight, N
G	geometrical factor, m^{-2}
g	gravitational acceleration, m/s^2
H	height, m
h	heat transfer coefficient W/(m^2 K)
h~	enthalpy per unit volume, kJ/m^3
K	fin temperature matrix constant
k	thermal conductivity, W/(m K)
L	latent heat, J/kg
$\dot{m}$	mass flow, kg/s
M	mass of PCM, kg
P	pressure, N/m^2
Pr	Prandtl number
q	heat transfer rate, W
q''	heat flux, W/m^2
R	geometrical constant, m
r	radius, m
Ste	Stefan number
s	sinking, m
T	temperature, K
t	time, s
$\dot{U}$	internal energy change rate, J/s
u	velocity component, m/s
V	volume, m^3
υ	velocity of melting fluid, m/s
z	vertical coordinate, m

Greek letters

α	thermal diffusivity, m^2/s
γ	pitch for unit of angle, m
Δ	difference
δ	molten layer thickness (perpendicular), m
δ^*	molten layer thickness (z direction), m
θ	circumferential angle
μ	dynamic viscosity, kg/(m s)
ρ	density, kg/m^3
φ	fin tilt angle

Subscripts

Al	aluminum
$conv$	convection
i	inner
j	numerical index, radial direction
l	liquid
m	melting
o	outer
p	perpendicular to the fin
PCM	related to phase change material
r	radial
r_j	related to radius j
RHS	right hand side
s	solid
w	wall
z	related to z direction
ζ	numerical index, vertical direction

Superscripts

n	time step number

is enhanced by convection. Recent papers on the subject address such diverse issues as comparison with pinned tubes [11], effectiveness analysis [12], and entropy generation [13].

Latent heat storage units with longitudinal fins have been also extensively studied, both experimentally and theoretically. These studies addressed vertical and horizontal tubes, melting and solidification, different fin orientations and shapes [14–33], as was recently discussed in [34]. There, a horizontal longitudinally-finned unit was analyzed. It was shown that, commonly, 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.

From the existing studies, it has become evident that fins enhance heat transfer to an extent that depends on the specific configuration chosen. Still, the molten material between the hot fin surfaces and the remaining solid presents a significant thermal resistance, which impedes the process. As argued in [2,34], based on simulations and experiments in both circumferentially- and longitudinally-finned units, the remaining solid phase at any instant was attached to the envelope at which no melting took place. It became obvious that if the PCM solid bulk were detached from the shell, it would sink and approach the hot surfaces, thus leading to a so-called close-contact melting (CCM).

In CCM, a thin molten layer is formed between the solid and the hot surface, as the melt is squeezed to the sides by the descending solid bulk. Thus, the PCM is melting continuously, providing for the flow in the thin molten layer. CCM allows high melting and heat transfer rates due to the relatively thin layer of a liquid PCM, across which heat is conducted to the solid phase. This phenomenon was studied in the past for such diverse cases as melting in a horizontal cylinder [35,36] and in a spherical enclosure [37–39], migration of a hot spherical [40], cylindrical [41] and arbitrary-shape [42] body through solid PCM, melting in an isothermal rectangular capsule [43], melting of a vertical solid cylinder heated from below [44], and direct contact melting with asymmetric load [45]. Generalized results were found for five simple geometries: cylindrical, spherical and rectangular capsules and migrating cylinder or sphere [46].

It has been demonstrated recently that, under carefully chosen conditions, melting in a finned system may be speeded up drastically, by utilizing the effect of close-contact melting, where the solid phase is allowed to move in the molten material under the effects of gravity. The idea that solid sinking may significantly reduce the melting time was proved experimentally in laboratory-scale devices with commonly used radial fins [2] and longitudinal fins [34], while analytical and numerical models were developed to provide insights in the underlying physical phenomena and to achieve generalization of the results in terms of dimensionless groups [2,34,47]. It was concluded that the role of fins is much more important than just to commonly serve as extended