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Novel enthalpy method for modeling of PCM melting accompanied by sinking of the solid phase

Y. Kozak, 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 development of a general model for close-contact melting (CCM), and its associated physical phenomena, namely, convection in the melt and solid bulk motion. An analysis of the literature reveals that although CCM is a well-known phenomenon, the existing numerical methods for solid-liquid phase change simulation, including the enthalpy-porosity approach, are not capable of modeling CCM processes properly. The proposed model is based on solution of all the relevant conservation equations and, in addition, on the force balance for the solid bulk. It allows full coupling between the solid body motion and the melt behavior, including natural convection. This fixed-grid model is based on the enthalpy method, and advanced numerical techniques from the literature are applied to simulate the solid bulk motion by using properly dispersed momentum sources. A special procedure, devised to move the solid across the grid, guarantees that the solid bulk moves as a rigid body and cannot be stretched or deformed like a highly viscous fluid. The new model is verified against benchmark results from the literature. Then, a test case that involves CCM is studied, namely, melting in a rectangular isothermal cavity, heated from all its sides. For this configuration, the new model is compared with a conduction-based CCM model and validated against experimental results from the literature. By using dimensional analysis, both the experimental and numerical results are generalized. It is also demonstrated that the new model can solve complex melting problems, where the solid bulk inertia is not negligible. The proposed model may be extended to include other effects, such as solid bulk rotation and melting over a range of temperatures.

1. Introduction

Solid-liquid phase change processes are encountered in many fields of science and engineering. Classical examples include growth of polar ice [1] and metallurgy [2]. During recent decades, many new engineering applications have emerged, including latent-heat based thermal energy storage and passive thermal management of electronic and photonic devices (see, e.g., [3,4]). In many cases, advanced design of these systems requires detailed analysis of different associated physical phenomena. Since these phenomena usually cannot be described by analytical models, this poses new challenges related to development of reliable numerical modeling techniques.

Different modeling methods for solid-liquid phase-change have been developed in recent decades. Lacroix [5] classified the various methods into two main groups, according to their grid that can be moving or fixed. For instance, a moving grid method can be implemented with a body-fitted curvilinear grid that fits precisely to the solid-liquid interface location. This allows easy implementation of the boundary conditions and a sharp and accurate interface. However, it involves complicated coordinate transformations that cannot be easily implemented for complex geometries or three-dimensional domains. The most common fixed grid methods are the enthalpy and the equivalent heat capacity methods. Their major advantages include the ability to deal with materials that melt or solidify over a range of temperatures. Direct front tracking is avoided, allowing for complex geometries to be solved. Among the variety of fixed grid methods, the enthalpy-porosity method [6] has gained prominence, especially in commercial software packages. It involves solution of all the conservation equations, namely continuity, momentum, and energy, which can be used for modeling convection in the melt.

Of particular interest in this study is proper modeling of "close-contact melting" (CCM) problems [7] – the situations in which the solid phase is completely surrounded by the liquid phase and thus can move in the latter, approaching a hot surface beneath. CCM has been studied for more than three decades (e.g., [8–10]). In this process, a thin molten layer is formed between the solid and the hot surface, and is squeezed by the descending bulk solid to the sides.

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[*] Corresponding author.
E-mail address: gziskind@bgu.ac.il (G. Ziskind).

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Nomenclature

Ar	Archimedes number
B	width, m
C	mushy zone parameter, kg/(m^3·s)
c_p	specific heat, kJ/(kg·K)
f	melt fraction
Fo	Fourier number
g	gravitational acceleration, m/s^2
H	height, m
$\hat{H}$	enthalpy per unit volume, kJ/m^3
k	thermal conductivity, W/(m·K)
L	latent heat, kJ/kg
$\hat{\mathbf{n}}$	normal unit vector
p	pressure, Pa
Pr	Prandtl number
s	solid-liquid interface location, m
Ste	Stefan number
T	temperature, °C
t	time, s
U	solid bulk velocity, m/s
u	velocity component, m/s
V	volume, m^3
v	velocity component, m/s
x	Cartesian coordinate, m
y	Cartesian coordinate, m

Greek letters

α	thermal diffusivity, m^2/s
β	volumetric expansion coefficient, 1/K
δ	molten layer thickness, m
Δ	difference
μ	dynamic viscosity, kg/(m·s)
ν	kinematic viscosity, m^2/s
ρ	density, kg/m^3

Subscripts

init	initial
l	liquid
m	melting
ref	reference
s	solid
w	wall

Thus, more phase-change material (PCM) is melting, keeping the flow in the thin molten layer. The heat transfer rate in this type of melting is high due to the relatively small thickness of the liquid PCM layer, across which the heat is conducted to the solid phase. Various simple geometries in which CCM may occur were studied both experimentally and theoretically. Hirata et al. [11] examined close-contact melting in a rectangular enclosure/capsule with two types of PCM: octadecane and ice. Moallemi et al. [12] studied analytically and experimentally the problem of close-contact melting of a vertical solid cylinder that is heated from below. Among more complex cases, Bareiss and Beer [8] investigated melting in a horizontal cylindrical enclosure with a constant wall temperature. Bahrami and Wang [13] used a similar approach to analytically model close-contact melting in an isothermal spherical shell, whereas Roy and Sengupta [14] solved a similar problem numerically. Fomin and Saitoh [15] solved this problem also for a non-uniform wall temperature. Betzel and Beer [16] studied CCM in a horizontal concentric annulus. Note that only the work by Bareiss and Beer [8] adds natural convection in the upper part, which is treated separately, and that all the works above (see e.g. [8,13–15]) are assuming a certain shape of the solid there. Also, there are several works regarding the problem of close-contact melting on an isothermal flat plate, including the effect of convection in the thin molten layer beneath the solid [17–22].

Recently, the notion that close-contact melting can have a beneficial effect on the performance of latent heat thermal energy storage (LHTES) systems was introduced for the first time: Kozak et al. [23] and Rozenfeld et al. [24] reported CCM in standard laboratory-scale radially- and longitudinally-finned concentric storage units, respectively. For both configurations, it was demonstrated that by allowing solid bulk motion, the unit performance can be improved by 2.5 times in comparison with the case where the solid bulk is fixed. This approach has been furthered by a novel concentric storage unit with a helical fin that combines the advantages of the two above-mentioned fin arrays [25].

Once the merits of solid motion have been proven experimentally, its in-depth analysis becomes the most important task, because it is vital to understand the underlying physical phenomena and aim at their proper description and generalization in terms of dimensionless groups. It appears, however, that modeling of these processes is quite complicated, and involves coupling between the sinking solid and the liquid melt that surrounds it. From the literature analysis, it turns out that modeling this type of CCM problem, with the above mentioned enthalpy-porosity method, can be quite challenging. In general, numerical methods that combine solid-liquid phase change with solid bulk motion and a full solution of the continuity and momentum equations are scarce. A known approach is to utilize an effective variable viscosity that is based on the notion that the entire domain can be solved as if it were liquid, and the effect of the solid phase is taken into account by applying high viscosity values to the solid cells. The solid-liquid modeling can be incorporated quite easily with the enthalpy method. The main problem of this approach is that high viscosity values create numerical stiffness, which can interfere with the solution convergence. Another problem is that solid bulk does not have to move as a rigid body. In fact, mathematically, it is a highly viscous fluid, which can, to some extent, stretch and change its shape. These difficulties can perhaps explain the fact that this method was implemented in very few works. In an apparently first work based on this approach, Asako et al. [26] studied a rectangular solid body that is surrounded by liquid and heated only from below. Natural convection was not taken into account, although convection induced by the solid bulk motion was considered. A special iterative procedure that involved the force balance on the solid bulk was utilized to enhance the solution convergence. The study cases were only for low gravity force, where the liquid layer between the hot surface and the solid bulk can be quite thick. A parametric investigation was conducted studying different governing dimensionless groups, such as the Stefan, Prandtl, and Archimedes numbers. The effects of density change [27] and electromagnetic fields [28,29] were investigated by the same group, for a similar configuration. Ghasemi and Molki [30] solved, with a similar method, the problem of melting in a square cavity heated from all its sides. They used a special relation between the melt fraction and the viscosity to enhance the convergence rate of their scheme. Natural convection was taken into account in their model, and the effect of various dimensionless groups, including the Rayleigh number, was tested. Recently, Kasibhatla et al. [31] implemented the same approach in OpenFOAM software package. They reported convergence issues for high effective viscosity values, and