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3D numerical and experimental study of gallium melting in a rectangular container

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ABSTRACT

Gallium melting in a rectangular container with a heated side face has been investigated. The focus of the research is the advancement of the numerical model to 3D status taking into consideration thermal variations of medium properties and the presence of mushy zone, and the model experimental verification using known data and new data obtained on a specially developed experimental setup. This setup is oriented to trace the liquid–solid interface position and profile and melt velocity using ultrasonic Doppler velocity measurements in the liquid phase.

The numerical model was based on COMSOL Multiphysics software. 2D and 3D versions were built to calculate the melting regime and the flow process characteristics. Outputs of both versions were compared with known experimental data and new data obtained in the present study.

The results revealed a better agreement between 3D computational and experimental data indicating to a profound effect of the container boundaries on the problem under study.

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1. Introduction

Metal melting in a rectangular container has been studied for many years [1–18], but the respective analytical solutions are known only for the simplest cases. Meanwhile, heat convection and metal properties dependence on temperature play an important role in real melting processes. They complicate the analysis and make it necessary to perform computer simulations and validation by low-temperature physical experiments.

Both kinds of investigations complement each other, since the assessment of computer simulation efficiency is realized by comparison with available experimental data, and in a number of cases a certain discrepancy between computed and experimental results is observed [3,18,20]. The latter can be due to either experiment imperfections or computation methods deficiency.

The known numerical methods make it possible to solve melting and solidification problems taking into account both the heat conduction mechanism, which is essential at the initial melting stage, and the convective heat transfer playing an important role in the dynamics of the melt and liquid–solid interface [17,18].

In this research, computer simulations and physical low-temperature experiments have been carried out for gallium melt in a rectangular container with a heated side face (Fig. 1). To improve the comprehension of such a process, it is necessary to estimate the influence of the numerical model dimension (2D and 3D), temperature dependence of the metal physical properties and boundary conditions on the problem solution. Therefore, it is advisable to specify the necessary aspects and to modify computational approach and adapt experimental methods as required.

Industrial-scale hot melting experiments are very expensive and complicated. Moreover, as known, until now there are no workable technical means for velocity measurements in high-temperature liquid metals. Therefore, melting experiments at low temperature using gallium or PCM (phase change material) are performed in various forms in order to understand the melting process and heat transfer and flow mechanisms. Gau and Viskanta [1,2], used pure gallium and performed vertical and horizontal melting, measuring the solid–liquid interface temperature and position. For this purpose, thermocouples and special L-shaped probes for draining the container filled with melt were used to expose the solid–liquid interface. These measuring methods are invasive, disturb the melting process and do not provide information about the melt flow.

A noninvasive method was applied by Campbel and Koster [3] who used gallium and measured the solid–liquid interface shape and position by real-time radioscopy method. X-ray observation showed a sharp contrast between molten and solid phases with a 3% density difference. Another method can be found in Menon et al. [4], Pal and Joshi [5] and Katsman et al. [6]. All of them used different kinds of PCM and performed melting experiments in glass tubes, which allowed the registration of the solid–liquid interface shape and position by a high-contrast camera. These methods are

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Nomenclature

B	computational constant (kg/ms)
c_p	specific heat (J/kg °C)
C	Carman–Kozeny constant (kg/m^3 s)
F_l	liquid–solid volume fraction
$\vec{F}$	force vector (N)
H	enthalpy (J/kg)
ΔH	modified latent heat (J/kg)
L	latent heat (J/kg)
$f(T)$	enthalpy temperature function (J/kg)
k	thermal conductivity (W/m °C)
T	temperature (°C or K)
P	pressure (Pa)
t	time (s)
g	gravity acceleration (m/s^2)
d	diameter (m)
V	volume (m^3)
$\vec{u}$	velocity vector (m/s)
x,y,z	coordinate (m)
Q	heat quantity (J)
I	unit matrix
h	container height
Ra	Rayleigh number, $(\rho - \rho_m)gh^3/\rho_m\alpha_l\nu_l$
Pr	Prandtl number ν_l/α_l
Ste	Stefan number $c_{pl}(T_H - T_C)/L$
T_H T_C T_{int}	Temperatures of hot and cold walls and initial temperature, accordingly

Greek letters

μ	dynamic viscosity (kg/ms)
Δ	difference
ρ	density (kg/m^3)
ε	computational constant
ν	kinematic viscosity (m^2/s)
Λ	aspect ratio
α	thermal diffusivity (m^2/s)

Subscripts

m	melting
s	solid
l	liquid
p	particle

indeed noninvasive, but they cannot provide any quantitative information about the melt flow in the liquid phase. Moreover, they are not suitable for opaque media such as metals. All experimental results show a great influence of convective flow on the melting process and the solid–liquid interface shape.

One of noninvasive measurement methods in phase-change experiments is the use of ultrasound instruments. Beginning with medical applications, this method of measuring the velocity of fluid flows found its use in scientific and engineering research, especially when dealing with opaque and aggressive liquids, including liquid metals [7] and [8].

As an example, one can cite the study [9], where mean velocities of the melt flow and liquid–solid interface have been found experimentally during the study of the magnetic field effect on the alloy solidification.

Unlike known experiments using UDV (ultrasonic Doppler velocimeter) technique, in our study we define the liquid–solid interface position and profile, its displacement and longitudinal mean velocity during the metal melting process.

There are two main approaches to the calculation of moving solid–liquid interface. The first can be found in Ramachandran et al. [10], Gadgil and Gobin [11], Albert and O'Neill [12] and Vynnycky and Kimura [13] who have developed deformable grids which follow the moving solid–liquid interface. The moving boundary approach may be appropriate when tracking a sharp boundary interface is required. However, specific models describing the interface motion are needed. Since these models use several simplifying assumptions, the accuracy of interface movement and shape is questionable. Following [13], the analytical solution describing the moving solid–liquid boundary "is not uniformly valid for all time, and tends to overestimate the final thickness of the solid layer". Besides, the moving boundary approach does not consider the mushy zone and is more complicated numerically, and therefore the calculation time for the 3D problem can be much longer. An alternative approach is the use of a fixed grid, which simplifies the numerical modeling requirements. Examples of such approach can be found in Morgan [14], Gartling [15] and Voller et al. [16–18]. In this approach, conservation equations are solved for the entire volume, and therefore the velocity of the solid phase should be zero. Gartling [15] employs a simple way of making the viscosity of the metal a function of enthalpy: by decreasing extra enthalpy ΔH from the latent heat value to zero, he drives the viscosity to a high value.

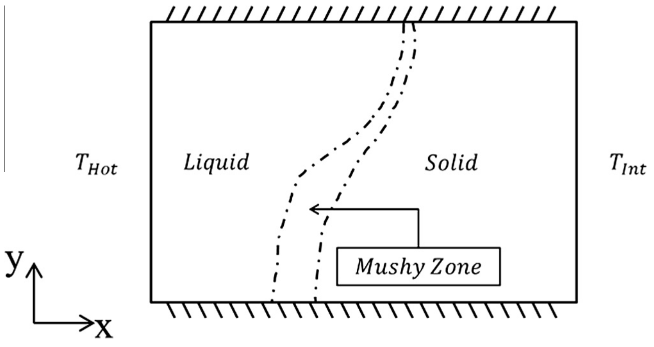

Fig. 1. Melting process scheme.

2. Present study

In the present study, the enthalpy-porosity method, which allows a fixed-grid solution of the momentum and energy equations, was adopted. This method was developed by Voller and Prakash [17]. It is based on solid–liquid volume fraction, while the phase change is assumed to occur within a narrow temperature range. In addition, the Darcy source approach is used to simulate motion in the mushy zone, which consists of solid particles dispersed in a liquid. Because of lack of information about the solid particles diameter, the Carman–Kozeny equation [19] for modeling drag forces in porous media is used. The momentum equation contains a source term, which depends on the local liquid fraction F_l and the Carman–Kozeny constant C. When the local liquid fraction equals zero, there is only solid at this location. The Carman–Kozeny constant is mostly influenced by the morphology and viscosity of the mushy zone. Voller and Prakash [17] and Shmueli et al. [20] investigated the influence of this constant on the solution using a

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