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Impact of rotating permanent magnets on gallium melting in an orthogonal container

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ABSTRACT

Gallium melting in an orthogonal container under the impact of a magnetic field was studied. The main goal of the work was the numerical modeling and study of solid–liquid interface behavior and exploration of the possibility to control its dynamics using a magnetic system. The container comprised heated and cooled side faces with preset temperatures. The fluidized part of the metal was exposed to a rotating magnetic field generated by a system of rotating permanent magnets.

A three-dimensional (3D) numerical model based on COMSOL Multiphysics software that accounted for thermal variations in the metal properties and the presence of a mushy zone was devised. Simulation reliability was verified by comparison with experimental data obtained using ultrasonic Doppler velocimetry.

1. Introduction

The flow regime in a metal melting process considerably affects the dynamics of the solid–liquid interface [1]. Therefore, the ability to control flow should ultimately lead to the possibility of controlling the temperature and concentration fields within the metal volume, the melting front shape and its velocity, and process duration.

Electromagnetic methods of the impact on liquid metals by rotating or traveling magnetic fields (RMF or TMF, respectively) have been known for many years [2–5]. Their application enables numerous problems to be solved including, e.g., problems of liquid metal flow intensification in various devices [6]. However, in this case as in many others, to intentionally affect the melting front and increase the stirring efficiency of the fields generated by the moving (rotating) permanent magnets on liquid metal remains a challenge [7–9]. Compared with RMF, a movable permanent magnet system is preferable due to its design simplicity, relatively small overall size and low power consumption [10].

Well-known papers [8,9] describing such systems mainly focus on integral characteristics ("pump" pressure vs. flow rate). Some hydrodynamic characteristics within limited flow volumes are examined in [11].

The behavior of a metal melting front in a container with a rectangular cross-section with a heated lateral wall were studied earlier both experimentally and numerically and described in many papers (for example [12,13]), including those of the authors, using a three-dimensional (3D) computer model verified in experiments with gallium melting [1]. However, to the best of our knowledge, the possibility of controlling the dynamics of the melting front has not been analyzed.

Previously we numerically and experimentally studied the problem of influencing liquid metal flow characteristics in a limited volume using a system of rotating permanent magnets [10], where we showed a basic possibility of controlling the hydrodynamic structure of liquid metal flow. The obtained results have served as a basis for the present research – 3D computer modeling of the dynamics of a gallium melting front in the presence of an external rotating magnetic field and analysis of the possibility of controlling the behavior of this front. We examine regimes with the same order of magnitude of the velocity of convective liquid metal flow and flow velocity under the action of electromagnetic forces. We compared numerical with experimental results, in the latter of which temperature distribution in a metal is measured by the thermocouples, and the measurement of one of the components of the melt flow velocity is done by Doppler velocimeter.

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Nomenclature

$\vec{B}$	magnetic field (T)
C	Carman–Kozeny constant (kg/m^3 s)
c_p	specific heat (J/kg °C)
d	diameter (m)
$\vec{E}$	electric field (V/m)
$\vec{F}$	force vector (N)
F_l	liquid–solid volume fraction
g	gravity acceleration (m/s^2)
h	height (m)
H	enthalpy (J/kg)
ΔH	modified latent heat (J/kg °C)
Ha	Hartmann number, $B_0R_0\sqrt{\sigma/\rho\nu}$
$\underline{I}$	unit matrix
$\vec{j}$	electric current density (A/m^2)
k	thermal conductivity (W/m °C)
L	latent heat (J/kg)
n	revolutions per minute (RPM)
p	number of pole pairs
P	pressure (Pa)
R	radius (m)
Re	Reynolds number, uR_0/ν
Re_m	magnetic Reynolds number, $\mu_B\sigma u_0R_0$
t	time (s)
T	temperature (°C)
$\vec{u}$	velocity (m/s)
V	volume (m^3)
x,y,z	coordinates (m)

Greek letters

α	thermal diffusivity (m^2/s)
δ	distance between disk surface and gallium (m)
ε	computational constant
Λ	aspect ratio
μ	dynamic viscosity (kg/ms)
μ_B	magnetic permeability (N/A^2)
ν	kinematic viscosity (m^2/s)
ρ	density (kg/m^3)
σ	conductivity (S/m)
ω	angular velocity (rad/s)

Subscripts

0	characteristic scale
B	magnetic
l	liquid
m	melting
p	particle
s	solid

2. Model and method

2.1. Mathematical model description

In the present study we used a 3D approach to solve the complicated problem of metal melting in an orthogonal container in the presence of a rotating magnetic field. The configuration under study is schematically presented in Fig. 1. In addition, the previously developed and tested 3D numerical models of the gallium melting problem [1] and the electromagnetic stirring problem [10] were adapted and effectively employed.

The system of governing equations included electrodynamic, hydrodynamic and heat transfer equations using a number of approximations.

Magnetohydrodynamic (MHD) equations of liquid metal motion under the action of electromagnetic forces were examined in the induction-free approximation [2] (magnetic Reynolds number $\mathrm{Re}_m = \mu_B\sigma u_0R_0 \ll 1$), which facilitates separating the electrodynamics and hydrodynamic parts of the problem, i.e., to compute the electromagnetic force using electrodynamics equations and then introduce the result into the equation of motion (momentum equation). In addition, the low-frequency approximation accepted in MHD equation ($\bar{\omega} = \mu_B\sigma\omega_0R_0^2 < 1$) allowed us to neglect the electric charge distribution problem and to consider the conduction current as a total current [14]. In this case, electrodynamics equations were reduced to the following:

$$\nabla \times \vec{B} = \mu_B\vec{j}, \tag{1}$$

$$\nabla \times \vec{E} = -\frac{\partial \vec{B}}{\partial t}, \tag{2}$$

$$\nabla \cdot \vec{B} = 0, \tag{3}$$

$$\vec{j} = \sigma\left(\vec{E} + \vec{u} \times \vec{B}\right), \tag{4}$$

$$\nabla \cdot \vec{j} = 0, \tag{5}$$

where $\vec{B}, \vec{E}$ are the magnetic flux density and electric field strength; σ, μ_B are the conductivity and magnetic permeability; $\vec{u}$ is the flow velocity and $\vec{j}$ is the electric current density. The magnetic system comprised cylindrical permanent magnets with diameter d and height h that were arranged at a distance R_0 from the rotation axis in parallel to the two side walls of the container and that rotated with angular velocity ω_0. The magnetic field on the end-face of each rotating permanent magnet is $\pm B_0\vec{e}_z$. In our problem, the magnetic field was specified on d-wide ring surfaces on the disks as $B_z|_{z=\pm(Z+\delta)} = B_0\cos\left(\omega_0 t - p\tan^{-1}\frac{y}{x}\right)$, where p is the number of pole pairs, which depends on magnet polarity alternations, δ is the distance between the plane of the end-faces of the driving magnets and the inner surfaces of the lateral walls of the container. The distribution of the magnetic field is shown in Fig. 2.

The flow of the conducting liquid in a rotating field is driven by an electromagnetic body force (EMBF) whose density is determined by

$$\vec{F}_{em} = \sigma(\vec{E} + \vec{u} \times \vec{B}) \times \vec{B}. \tag{6}$$

Besides, in the approximation of a small magnetic interaction parameter $St = \frac{Ha^2}{\mathrm{Re}} < 1$ $\left(Ha = B_0R_0\sqrt{\frac{\sigma}{\rho\nu}}, \mathrm{Re} = \frac{u_0R_0}{\nu}\right)$, we do not take into account the variable electromagnetic force component, and therefore, we only examined its constant part (here $T = 2\pi/\omega_0$ – period of disk revolution):

$$\left\langle \vec{F}_{em} \right\rangle = \frac{1}{T}\int_0^T \vec{F}_{em}dt. \tag{7}$$

Another simplification assumed in the problem was connected with the smallness of the magnetic Reynolds number [12,15]. As such, the effect of the term $(\vec{u} \times \vec{B})$ of Eq. (6) on flow computation results was estimated before [10] for several sets of parameters, and it was determined that this term can also be neglected.

Thus, we obtained a formulation of the problem [1] where the momentum equation contains an additional term $\langle\vec{F}_{em}\rangle$ as a result of electromagnetic impact: