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Numerical and experimental study of the traveling magnetic field effect on the horizontal solidification in a rectangular cavity part 1: Liquid metal flow under the TMF impact

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ABSTRACT

Traveling magnetic field is one of effective tools for controlling phase change processes in metals. A better understanding of electromagnetic impact in such applications can help to improve and simplify technological processes. In this paper, numerical and experimental study of the electromagnetic force generated by traveling magnetic field and its ability to control liquid gallium flow and, consequently, affect the characteristics of solidification and melting processes are evaluated. Three-dimensional numerical model for calculating the magnetic field distribution and electromagnetic force acting on liquid gallium in a laboratory-size rectangular cavity was analyzed. Specific values of the TMF impact were chosen for the cases of interest in order to use such impact in our further work with horizontal gallium solidification process. The traveling magnetic field inductor was designed and built for making appropriate measurements and validating calculations. The analysis was focused on the electromagnetic force and the obtained velocity field. The experimental setup included an ultrasonic Doppler velocimeter for noninvasive measurements of the velocities of liquid metal flow. The comparison of computations with the experiments has shown a good agreement.

1. Introduction

In recent decades, numerous industrial applications of the electromagnetic effect on electrically conductive melts have been successfully developed. The electromagnetic methods have a number of obvious advantages allowing a flexible and purposeful impact on liquid metals flow and heat transfer processes. The corresponding principles are described in detail in (Davidson, 2001; Seyf and Henry, 2016; Davidson, 1999; Ramachandran et al., 2000; Cramer et al., 2011).

Traveling magnetic field (TMF) and rotating magnetic field (RMF) are the most common tools used for this purpose in various devices and applications (Moffatt, 1965; Kapusta, 1968; Lantzsch et al., 2007). Metals solidifying under the electromagnetic impact have been studied for many years (for example, in the process of crystal growth and melt stirring) (Ramachandran et al., 2000; Yesilyurt et al., 2004; Wang et al., 2012). Electromagnetic field is of a particular interest because it makes it possible to influence the melt flow without a direct contact between the inductor and the melt (Stiller et al., 2013; Nikrityuk et al., 2006; Grants and Gerbeth, 2004). The use of electromagnetic fields and the arising electromagnetic forces affect the liquid metal flow in the process of its solidification. It can change heat and mass transfer, as well as microstructure formation during the solidification process (Medina et al., 2004; Schwesig et al., 2004; Hurle, 1994). However, optimization of the magnetic field distribution and the possibility to control the solidification process are still of interest (Yan-qing et al., 2010; Dadzis et al., 2016; Bouabdallah and Bessaïh, 2012).

A major part of the published studies of the traveling magnetic field (TMF) effect on the melt flow deal with a vertical cylinder (Lantzsch et al., 2007; Stiller et al., 2013). There are only a few examples of the implementation of TMF in a rectangular cavity, especially for horizontal solidification. Dubke et al. (1988a,b) investigated experimentally the TMF stirring in a rectangular container using a linear inductor and introduced analytical computation of the electromagnetic driving force, and Wang et al. (2009a, b) investigated the effect of modulated TMF on the flow. Dropka et al. analyzed TMF stirring of silicon melts in large-scale crucibles (Dropka et al., 2010, 2012, 2013). Ben-David et al. (2016) studied the effect of moving permanent magnets on gallium melting in a rectangular cavity.

The current study is devoted to the exploration of the electromagnetic force caused by a linear TMF inductor as a base for the further work (Avnaim et al., 2017) exploring its effect on the horizontal solidification process. The results are accompanied by a respective

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Nomenclature

a	distance between adjacent poles (m)
B	magnetic field (mT)
Cp	specific heat (J/kg K)
E	electric field (V/m)
$\vec{F}$	force (N/m^3)
F	forcing parameter
f	current frequency (1/s)
g	gravity constant (m/s^2)
Gr	Grashof number
H	height (m)
Ha	Hartmann number
I	electric current (A)
J	current density (A/m^2)
K	wave number (1/m)
k	thermal conductivity (W/m K)
L	length (m)
L_B	wave length (m)
$\vec{n}$	normal
P	pressure (Pa)
p	pole pitch (m)
Re	Reynolds number
Re_m	magnetic Reynolds number
T	temperature (K)
t	time (s)
V	volume (m^3)
$\vec{v}$	velocity (m/s)
W	width (m)
x,y,z	coordinates

Greek letters

α	thermal diffusivity (m^2/s)
β	thermal expansion coefficient (1/K)
Γ	time period (s)
γ	magnetic field decay factor (1/m)
Δ	difference
δ	distance from the inductor pole to the bottom of the cavity (m)
μ	dynamic viscosity (kg/m s)
μ_0	vacuum magnetic permeability (N/A^2)
μ_r	relative magnetic permeability
μ_B	magnetic permeability (N/A^2)
Λ	aspect ratio (H/L)
ν	kinematic viscosity (m^2/s)
ρ	density (kg/m^3)
σ	electric conductivity (S/m)
ω	current angular frequency (rad/s)

Subscripts

B	magnetic
em	electromagnetic
h	hot
in	inductor
m	mean
p	pole

experimental validation for different conditions.

2. Present study

The present study includes numerical and experimental researches. A three-dimensional (3D) numerical model of the magnetic field distribution and of the resulting electromagnetic force was created using the COMSOL Multiphysics software. For validating the predictions of the numerical model, an experimental system for applying TMF by a dedicated inductor was designed and created. A schematic presentation of the experimental system including a rectangular container with gallium above the TMF inductor is shown in Fig. 1. The longitudinal mean velocity during the metal solidification process was measured non-invasively using the ultrasonic Doppler velocimeter (UDV).

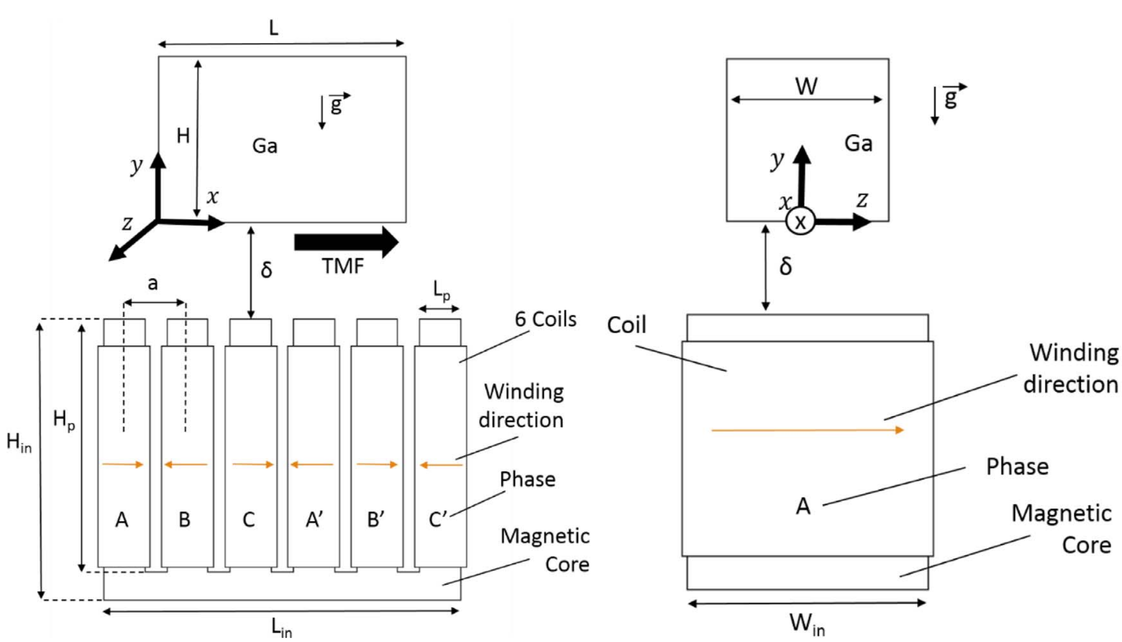

Fig. 1. Schematic view of the experimental device geometry. $H = 60$ mm, $L = 90$ mm, $W = 60$ mm, $\delta = 35–55$ mm, $H_{in} = 100$ mm, $L_{in} = 130$ mm, $W_{in} = 90$ mm, $H_p = 90$ mm, $L_p = 15$ mm, $a = 23$ mm.