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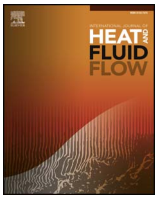

# Numerical and experimental study of the traveling magnetic field effect on the horizontal solidification in a rectangular cavity part 2: Acting forces ratio and solidification parameters

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## ABSTRACT

In recent decades, many phase change processes in metals have been optimized using traveling magnetic fields due to a better understanding of their electromagnetic impact in such applications. In this paper, numerical and experimental study of the effect of traveling magnetic field on the solidification process was evaluated. A three-dimensional numerical model based on the multi-domain method was used to analyze the process of gallium horizontal solidification under the electromagnetic impact in a laboratory-size rectangular cavity. A linear inductor creating traveling magnetic field was designed and built for appropriate measurements and validation the calculations. The analysis was focused on the influence of the ratio between the applied electromagnetic forces and natural convective forces on the solidification front location and shape and on the velocity field. Since the overall electromagnetic force impact on the melt reduced during the solidification, when the melt area was converting into a solid, a new approach to control the solidification parameters was analyzed. In this approach, the value of electromagnetic force acting on the remaining melt during the process was maintained. The main result is the development and improvement of an effective tool for the analysis of direct solidification parameters.

The experimental setup included an ultrasonic Doppler velocimeter (UDV) for noninvasive measurements of the velocities in the liquid part of the metal and the liquid-solid interface position, its profile and displacement. All important characteristics of the process were measured, and the results of computations agreed well enough with experimentally obtained data.

## 1. Introduction

The phase transition study related to the melting and solidification processes is the basis of many mathematical and physical researches, as well as of various engineering applications. In particular, the use of traveling or rotating magnetic fields makes it possible to stir liquid metal and control characteristics of its flow (Moffatt, 1965; Kapusta, 1968; Davidson, 1999) and, hence, to affect heat and mass transfer in the melt (including the phase transition boundary) in the process of crystallization (Ramachandran et al., 2000; Galindo et al., 2007; Dropka and Frank-Rotsch, 2013; Timofeev et al., 2012; Oborin et al., 2014).

The study of interrelation between the parameters of electromagnetic impact and the structure of crystallizing metal, its homogenization degree, mechanical properties etc., as well as the study of the influence of these parameters on the metal melting rate at high-frequency heating and solidification, remain extremely topical until today. Their results can be applied for the development of modern technologies of world-wide level.

Solidification and melting, like many other thermal processes in industry, require strict thermal conditions during the process. For example, homogeneous temperature, solidification rate and temperature gradients at a directional solidification exert a significant influence on a convective flow of liquid during solidification, and therefore have a great effect on the final product (Hurle, 1966,1994). These processes are executed in dedicated furnaces basing on several methods which comply with the process requirements.

The effect of natural convection on the shape and motion of the solid-liquid interface during melting and solidification of a pure substance is generally recognized (Gau and Viskanta, 1984, 1985, 1986; Avnaim et al., 2016; Ben-David et al., 2013). The results have shown that the solid-liquid interface shape, as well as the rates of melting and solidification, are significantly influenced by natural convection in the melt. In addition, when the heat flux direction is not parallel to the

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**Nomenclature**

| | |
|---|---|
| a | distance between adjacent poles (m) |
| B | magnetic field (mT) |
| Cp | specific heat (J/kg K) |
| $\vec{F}$ | force ($N/m^3$) |
| F | forcing parameter |
| $f$ | current frequency (1/s) |
| g | gravity constant ($m/s^2$) |
| Gr | Grashof number |
| H | height (m) |
| h | enthalpy (J/kg) |
| Ha | Hartmann number |
| $\Delta$H | latent heat (J/kg) |
| I | electric current (A) |
| 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) |
| Pr | Prandtl number |
| Ste | Stefan number |
| T | temperature (K) |
| t | time (s) |
| V | volume ($m^3$) |
| $\vec{v}$ | velocity (m/s) |
| $V_s$ | solid volume fraction |
| W | width (m) |
| x,y,z | coordinates |

*Greek letters*

| | |
|---|---|
| $\alpha$ | thermal diffusivity ($m^2/s$) |
| $\beta$ | thermal expansion coefficient (1/K) |
| $\Delta$ | difference |
| $\delta$ | distance from the inductor pole to the bottom of the cavity (m) |
| $\mu$ | dynamic viscosity (kg/m s) |
| $\mu_0$ | vacuum magnetic permeability ($N/A^2$) |
| $\mu_r$ | relative magnetic permeability |
| $\Lambda$ | aspect ratio (H/L) |
| $\nu$ | kinematic viscosity ($m^2/s$) |
| $\rho$ | density ($kg/m^3$) |
| $\sigma$ | electric conductivity (S/m) |
| $\vec{\varnothing}$ | heat flux (W/$m^2$) |
| $\sigma$ | electric conductivity (S/m) |
| $\omega$ | current angular frequency (rad/s) |

*Subscripts*

| | |
|---|---|
| B | magnetic |
| c | cold |
| em | electromagnetic |
| F | front |
| h | hot |
| in | inductor |
| l | liquid |
| m | melting |
| p | pole |
| S | solidification |
| s | solid |

gravity direction, the velocity field induced by the convective heat transfer can change the temperature profile close to the solidification front and, thus, distort the planar solidification front (Avnaim et al., 2016).

Metals solidifying under 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). Several investigations have revealed a significant impact of traveling magnetic field (TMF) on the convection occurring in the liquid phase during the solidification process (Medina et al., 2004; Schwesig

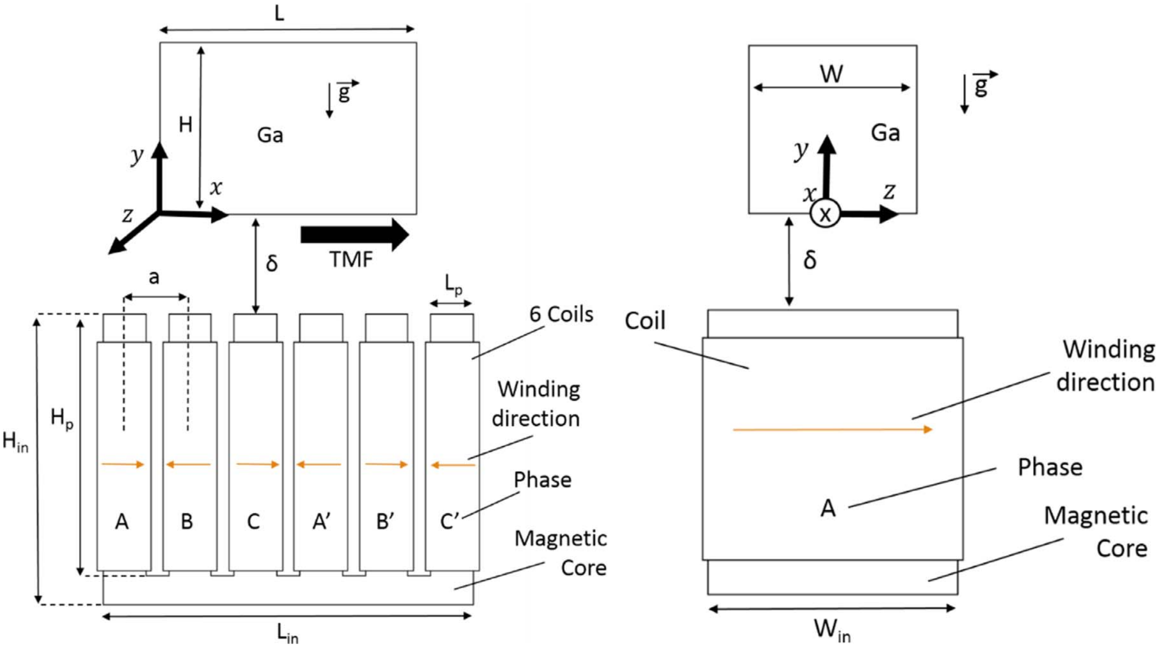

**Fig. 1.** Schematic view of the experimental device geometry. H = 60 mm, L = 90 mm, W = 60 mm, δ = 35\55 mm, $H_{in}$ = 100 mm, $L_{in}$ = 130 mm, $W_{in}$ = 90 mm, $H_p$ = 90 mm, $L_p$ = 15 mm, a = 23 mm.