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## NUMERICAL SIMULATION OF TEMPERATURE DISTRIBUTION ON METAL CASTING IN VERTICAL SOLIDIFICATION

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**Abstract.** *The metals and alloys solidification can be defined as a transient heat transfer process. A liquid/solid transformation is followed by thermal energy liberation, with a movable boundary separating two phases of distinct thermophysical properties. The solidification is of great interest to mechanical and chemical engineers. It is a non-linear transient phenomenon, where heat transfer between the casting and the mold plays a vital role. This paper aims to propose a study of heat flow from the casting to the mold and a numerical technique to compute the temperature history of all points inside the casting. The cooling process consists of water-cooled mold with heat being extracted only from the bottom, resulting in unidirectional vertical solidification. The ANSYS software was used to obtain the temperature distribution in the casting. Good agreement was obtained when the simulation results were compared with the experimental data.*

**Keywords:** *upward solidification, transient heat transfer, numerical simulation*

### 1. INTRODUCTION

The solidification of metal alloys in molds plays an important role in a large number of problems in materials engineering. During this process, a solidification front that progresses in the directions where the liquid metal still exists is formed and propagates at a speed that depends on the rate of heat extraction from the mold. The study of this process provides information of great importance for the determination of solidified metal mechanical properties such as strength, hardness, conductivity etc.

The metals solidification involved in foundries process can be fundamentally defined as a transient heat transfer process (Garcia, 2011) including phase modifications in which some heat energy may be transferred by mould from liquid phase to the ambient, enabling nucleation and solid phase growth (Santos, 2006). Casting rejections are of a major concern in the foundry industry. Great saving of materials, energy and time could be achieved, if casting design can be corrected prior to moulding on the basis of defects prediction (Choudhari, 2013).

These facts make solidification simulation a useful tool to help predicting casting defects. Generally, the theoretical analysis of the solidification problem may be performed using exact analytical methods, approximate and, as shown in the current work, numerical methods. The solidification process presents several complications in their mathematical model, being very common the study of such processes using experiments on a small scale and simplified setups, for example, heat extraction in only one direction.

One of the most used approaches to the treatment of solidifying regards energy conservation by enthalpy and the identification of the liquid-solid transition regions through a pseudo-porosity. The formulation so-called enthalpy-porosity is the one currently implemented in software ANSYS FLUENT. The equations for the flow velocity of the liquid region are also considered. Thus, the solid-liquid mushy zone is treated as a porous zone with porosity equal to the liquid fraction and appropriate terms are added to the conservation equations of momentum and energy to take into account the formation of solid material. Terms sources are also added to the turbulence that equations to be damped or canceled according to the degree of solidity of the region. Unlike the solidification of pure substances, which is

observed in a solid-liquid interface and defined in the alloys there is a "mushy" zone (mushy zone). Treatment of this region has significant impact in predicting microstructures to be formed.

Therefore, the aim of this paper is to correlate the literature experimental profiles to the ones provided from the software aforementioned in order to investigate the physical and mathematical validation of the program. In the present study, the binary Al-3wt.%Si is used.

## 2. COMPUTATIONAL PROCEDURE

The alloy Al-3wt%Si was chosen due to the importance that this system has in the mechanical industry. The casting assembly used in solidification experiments is exposed in the Fig. 1. For the experiment was used a stainless steel mold, which had an internal diameter of 50 mm, height 110 mm, and wall thickness 5 mm. The inner vertical surface was covered with a layer of insulating alumina to minimize radial heat losses, and a top cover made of an insulating material was used to reduce heat losses from metal/air surface. The bottom part of the mold was closed with a thin (3 mm) disc of carbon steel. The alloy was melted *in situ* and the lateral electric heaters had their power controlled in order to permit a desired superheat to be achieved to simulate the correct pouring temperature for the binary. To begin solidification, the electric heaters were disconnected, and the same time, the water flow was initiated. Temperatures in the casting were monitored during solidification via the output of a bank of type K thermocouples (1.6-mm) accurately positioned with respect to the heat extracting surface (Siqueira, *et al.*, 2002). The thermocouples were inserted in the ingot in the positions 4, 8 and 12 from the bottom interface.

The thermophysical properties of Al-Si alloy and the mold plate material utilized in the simulation are presented in Tab. 1. The software ANSYS®FLUENT was used to develop the simulation of the vertical upward solidification with water-cooling. The geometry has 17.920 mesh elements as shown in the Fig. 2. These dimensions are given by experimental setup exposed in Peres (2004).

As boundary conditions, the cylinder was thermally insulated in all the walls, except the bottom where it is in direct contact with a cylindrical metal plate of 4mm width (not shown in figure), which was cooled by water at 300 K. The initial temperature of simulation was 919.15 K, as used in the experimental setup. During this simulation the laminar fluid, energy and solidification models were active. The results were obtained after a total time of 200 seconds, with 0.1 seconds time step. Details regarding the models used on the simulation are available in ANSYS, 2013.

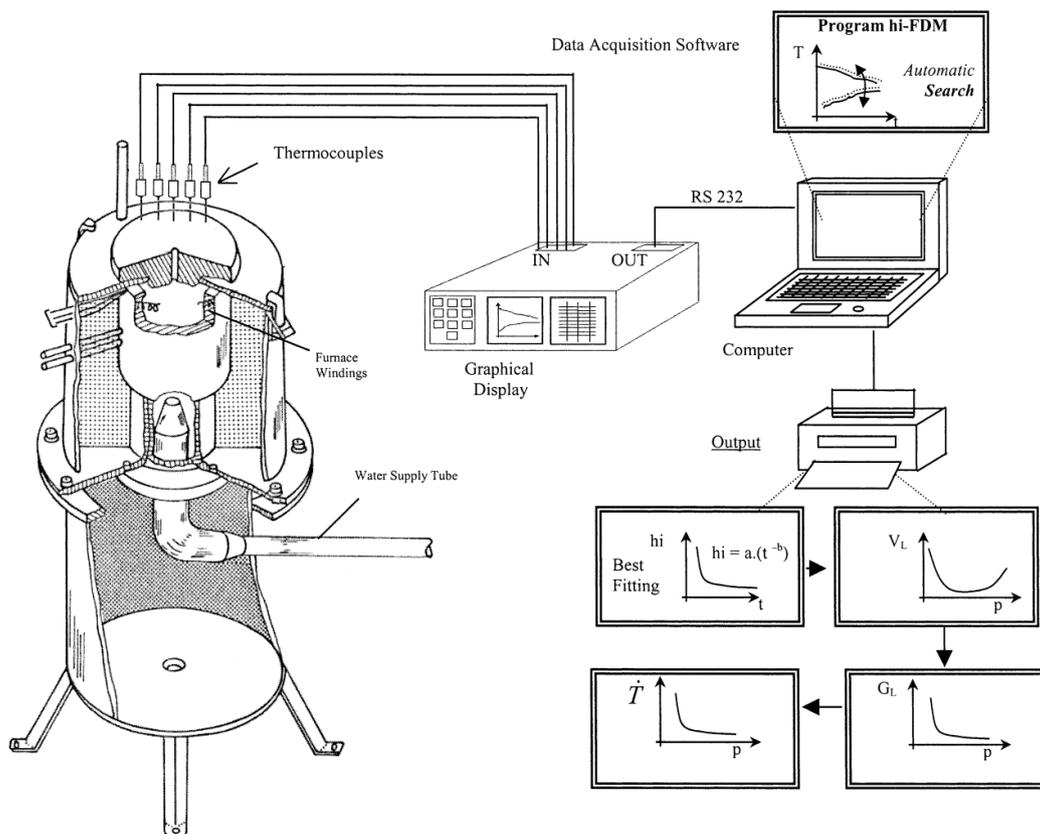


Figure 1. Schematic representation of the experimental apparatus (Siqueira, *et al.*, 2002).

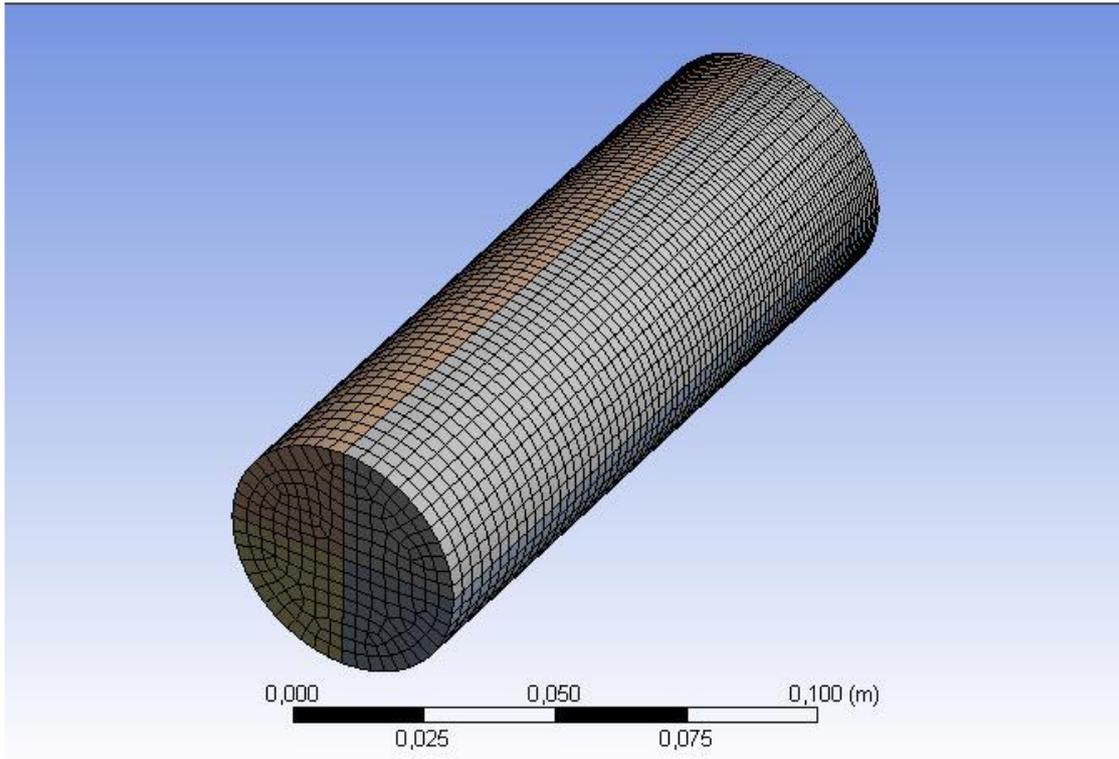
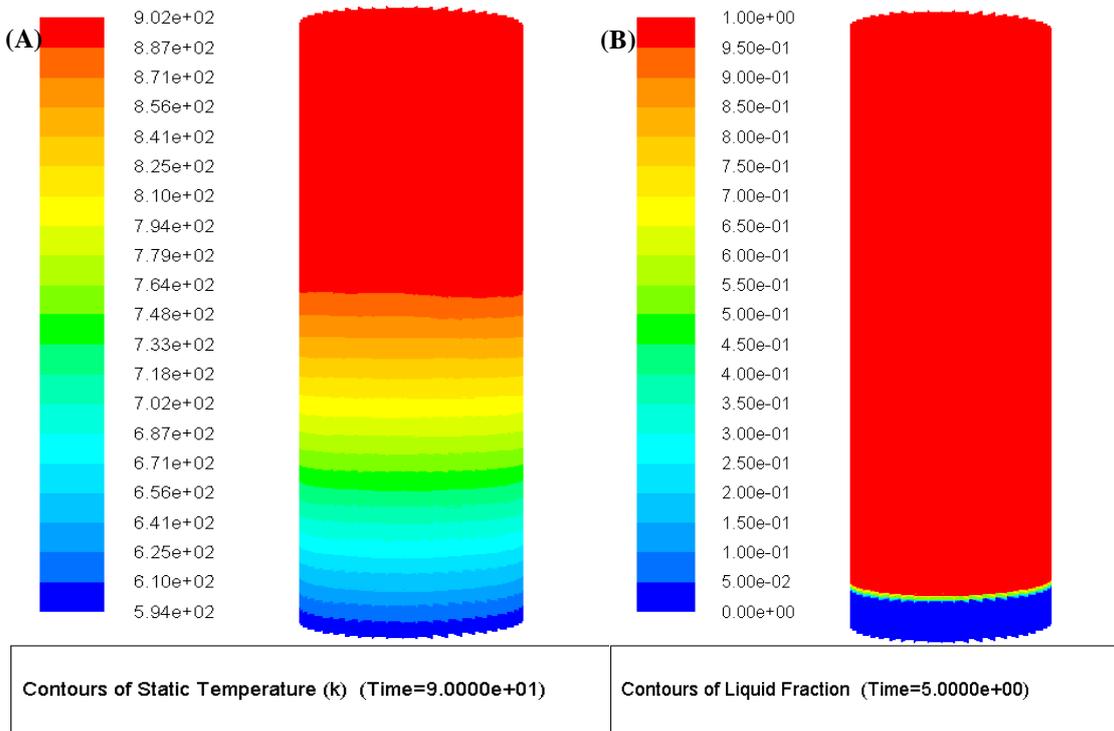


Figure 2. Mesh and geometry used in the simulation.

### 3. RESULTS AND DISCUSSIONS

The Figure 3 exposes the results of the simulation in terms of temperature, liquid fraction and thermal profile. The thermal profiles obtained in simulation are shown Fig. 3C. The experimental profiles are given in Peres (2004).



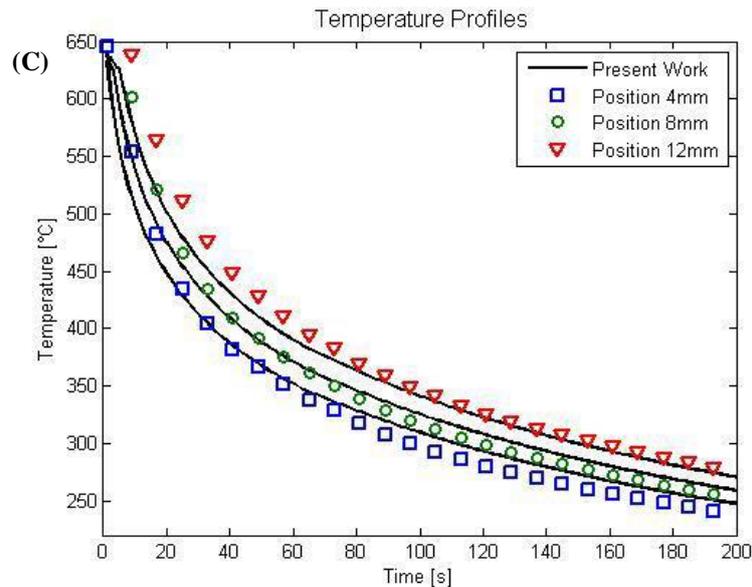


Figure 3. Simulation of a vertical upward system solidification: (A) Temperature distribution at 5 seconds, (B) Liquid fraction at 5 seconds and (C) Experimental and simulated thermal profiles.

Despite the very coarse mesh used in this simulation, no convergence difficulties are observed and numerical results and experimental profiles exhibit good agreement in the thermocouple positions analyzed. In this context, the absence of very detailed experimental data (mainly in the initial seconds), does not allow adjustment of numerical setup. The main concern here is the absence of mathematical and reliable model of metal-mold contact resistance and more information about rate of heat extraction by water.

The Finite Volume Method used in this paper, applying a coarse mesh on the analysis, can be compared with a result presented by Finite Difference Method with no difficulty. However, there is no assertion about the thermal profile difference if the mesh were more refined. Thus, changing the mesh can significantly modify the results presented, since the phenomenon complicating features as phase change and thermosolutal convection.

#### 4. CONCLUSIONS

Simulation done in this work enables visualization of the progress of solidification inside a casting. The relative proximity of the simulated profiles with the experimental shows that the numerical simulation of forced cooling of Al 3wt.%Si alloy vertical upward is efficient and can be used in order to minimize the error and defects in casting process. The fast setup and analysis of new models to heat transfer in metal mold interface can also be done. The numerical simulation allows a great number of solidification models to be applied and compared. Future papers can be done in order to verify if the number of nodes is enough to simulate this type of phenomenon. Different options regarding fluid convection, diffusion and heat transfer are available and will be applied in future approach.

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