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Numerical modelling of multiphase flow and heat transfer within an induction skull melting furnace

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ABSTRACT

A numerical and experimental study of free surface motion and heat transfer within an induction skull melting furnace is discussed in this paper. The developed computational domain was three-dimensional with defined periodic boundary conditions, which correspond to the segmented geometry of an actual cold crucible. An electromagnetically driven flow and temperature field within the numerical domain was simulated on the basis of two-way coupling of electromagnetic and fluid dynamic fields. To predict the electromagnetic field, a set of Maxwell's equations was solved. Then, the information regarding the Lorentz force and Joule heat distributions was transferred to a fluid dynamics submodel. These fields appeared as source terms in the momentum conservation and energy equations, respectively. The multiphase flow was considered turbulent with a free surface. It was simulated using a realizable k-ε model and a volume of fluid approach. Moreover, to consider the radiation heat transfer, the discrete ordinates method was applied. The proposed coupled mathematical model was compared with experimental results obtained from an industry induction skull melting furnace. The model validation clearly showed high accuracy in the discussed numerical model despite the applied simplifications. The shape of the free surface obtained from the computational model was within the standard deviation of the measurements, with a relative error under 4%. The charge temperature, after achieving steady state, was predicted with very high accuracy; however, the heating process was slightly underestimated. Finally, a qualitative comparison for the lower part of the meniscus was also performed. In that region, characteristic tooth-shaped peaks in the connection between the charge and crucible walls were identified for both experimental and numerical analyses.

1. Introduction

In modern metallurgy, the technology of levitation melting of metals and alloys is broadly applied. Its unique assets are a very high purity in the final product and the ability of refractory metals casting. To control the smelting and refinement process, it is more convenient to lead this process within the crucible. Therefore, induction skull melting (ISM) furnaces are widely employed in material production for cutting edge technologies such as turbine blades in aviation or implants and prostheses in biotechnology. To analyse the processes within the crucible in an ISM furnace, techniques based on mathematical models and experimental sides are employed. Measurements in a real furnace are very precarious because of the conditions in the vacuum chamber – low pressure and very high temperature; therefore, contactless methods are broadly applied. However, experiments do not provide information regarding local temperature gradients and other details of the process. Therefore, it should be supplemented with additional information from numerical modelling.

The mathematical formulation of processes occurring within the cold crucible needs to solve difficulties with electromagnetic field modelling, multiphase flow with a free surface, radiation and turbulence. The numerical algorithm has to cope with mutual interactions of all constituent phenomena. It is applied by means of the two-way coupling of two different solvers [1]. The main problems, on which the authors of the most recent articles are focused on, are induction heating and temperature distribution within the charge [2,3], mass transfer modelling [4] with special interest on

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the purification process [5] and electromagnetically driven flow with a free surface [6,7]. Some papers also consider the case study to obtain optimal operating conditions and geometrical dimensions of the cold crucible [8].

The literature review shows clearly that one of the most important phenomena within the cold crucible is a multiphase flow with a free surface. Multiphase flow within the charge in induction furnaces is considered turbulent [9]. For this application, a wide range of the turbulence models is reported in the literature. However, the published information is not consistent in this field. Many authors employ the simplified Reynolds-Average Navier Stokes (RANS) formulations, but sometimes more refined models are examined such as large eddy simulation [10]. A comprehensive study on the turbulence modelling for the induction skull melting furnace was performed by Spitans et al. [11,12]. In the first part of the article, k-ω SST was employed to simulate several cases of the real induction furnace with the cold crucible. The obtained free surface shape for both experiment and simulation were very similar for the proposed model. In the second part of the article, mathematical formulation was applied for the levitation using large eddy simulation. Turbulence modelling was also discussed by Asad et al. [13]. The proposed mathematical formulation encompassed two numerical approaches based on implicit large eddy simulation and k-ω SST SAS models. The model validation was performed for the stirred water vessel, for which a particle image velocimetry experiment was conducted. Once comparison showed a good agreement with measurements, the mathematical model was employed for the real induction furnace. It was observed that the magnetic field does not influence the nature of the melt flow.

Another important aspect of mathematical modelling of induction furnaces is the heat transfer and temperature field. Some researchers developed a mathematical model of cold crucible for directional solidification [14–17]. In the first study [14], the heat transfer in the mushy zone of the cold crucible was investigated. The authors simplified the heat transfer to two one-dimensional models. The obtained experimental results confirmed the legitimacy of the introduced simplifications. Yang et al. [15] prepared a two-dimensional mathematical model using the finite element method in commercial software. The developed mathematical formulation was based on coupling between the electromagnetic and thermal fields in a solid charge. For four measured temperature points, the numerical results are in good agreement with experimental data, especially for steady state temperature. The heating process temperature from mathematical model was slightly underestimated. The coupled mathematical model of both thermal and electromagnetic fields was also developed by Hadad et al. [18]. In this study, the stepped diameter crucible with the secondary heating coil was investigated. The numerical domain for the thermal submodel was simplified to two-dimensional, while the electromagnetic submodel was three-dimensional. The validation was performed by means of thermocouples located inside the crucible, showing a good correlation between the simulation and experiment results.

Some researchers are focused on both heat transfer and free surface modelling of the cold crucible charge. In a previous study by the authors, the vacuum induction skull (VIM) furnace was discussed [19]. A simplified two-dimensional model was proposed with volume of fluid (VOF), an enhanced k-ε turbulence model and discrete ordinates (DO) radiation formulation. Numerical results were compared with experimental data from the real furnace. The model validation showed very good agreement with measurements in terms of charge temperature and meniscus height with relative errors lower than 5%. Another comprehensive study was performed by Bojarevics et al. [20]. The proposed mathematical model was validated against experimental data obtained for four materials. The broad validation was performed in terms of the qualitative shape of the meniscus comparison, its height for different coil loads, cooling water temperature and heat losses. All collected data confirmed the accuracy of the developed mathematical formulation.

The main purpose of this study was to mathematically describe the electromagnetically driven flow and heat transfer within the cold crucible of the induction skull melting furnace. The numerical model was formulated by means of an in-house developed coupling procedure to encompass electromagnetic, thermal and multiphase flow fields. The numerical domain of the real induction furnace was simplified to a three-dimensional part of a water-cooled crucible segment with periodic boundary conditions applied. To obtain the electromagnetic field, a set of Maxwell's equations were resolved within the numerical domain. The distribution of electromagnetic force and heat source was transferred to a fluid dynamic submodel. To simulate an electromagnetically driven multiphase flow, the VOF approach was employed. Turbulence within the crucible was modelled according to a simplified realizable k-ε formulation with enhanced wall treatment. To compute the temperature field, the mathematical model encompasses radiation modelling using discrete ordinates methodology. The described mathematical model and the applied procedure were computationally very efficient as the model was also employed to run multi-parameter/variant analysis aiming at the modified crucible design.

Verification of the mathematical model was performed in terms of a grid independent study and a qualitative analysis of multiphase flow and heat transfer, in comparison to the literature. In this stage, proper numerical discretisation was selected and no large errors in the coupling procedure were exposed. Afterwards, a proposed mathematical formulation was validated against experimental data from the real induction skull melting furnace. In terms of the meniscus shape, the mathematical model showed a good agreement with measurements with the average relative error lower than 4%. Slight differences might be caused by the experimental methodology, which was sensitive to local instabilities of the charge free surface. The heat transfer within the cold crucible was also satisfyingly resolved. Thermal results were within the standard deviation of the measurement with the relative error slightly under 2%. The experimental techniques applied in this study provide information regarding the lower part of the meniscus. The contact region between the cold crucible and the melt is crucial in terms of heat transfer and meniscus formation. The proposed mathematical description successfully identified the free surface in this crucial region, which was confirmed by qualitative validation. The characteristic tooth-shaped peaks in the middle of each segment were observed both in the experimental tests and the mathematical model. To the best knowledge of the authors, such an observation has not been reported in the literature so far. Finally, some numerical studies were performed to examine the influence of the charge amount and fixed skull height on the shape of the meniscus. It was clearly observed that the skull at the bottom of the crucible has a notable impact on the free surface of molten charge. Moreover, the importance of the charge amount was identified.

2. Measurements

The experimental site was the industrial vacuum induction furnace, which was cold crucible equipped. This unit was produced by Seco-Warwick and Retech companies and is located in Institute of Metal Technology of Silesian University of Technology. It consisted of a vacuum chamber with a system of pumps, an ingot mould, a coil and crucible made of copper with cooling channels within them. The unit is equipped with a set of three vacuum pumps: