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Numerical Simulation of Induction Channel Furnace to Investigate Efficiency for low Frequencies

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Abstract. The foundry industry worldwide commonly uses induction channel furnaces to heat and melt alloys. The operating frequency is one of the main issues when constructing an efficient channel furnace. It is possible to choose operating frequencies lower than 50 Hz using a modern IGBT power converter. This work shows the simulation results using ANSYS with the goal of finding the best electrical frequency necessary to operate the induction furnace. First, a two-dimensional model is used to calculate the efficiency depending on frequency. Then, the channel model is extended to a more realistic three-dimensional model. Finally, the influence of frequency, inductor profile, and several components of the induction channel furnace are discussed.

1. Introduction

The basic structure of an induction channel furnace is equal to a transformer (Fig. 1). The short-circuited secondary coil with one winding is the melting channel where Joule heat is generated and used to heat the melt in the tank above. The excellent coil flux guide for the magnetic field results in a very good flux coupling between the inductor coil and the melting channel which represents the secondary coil. This is an important reason for the good electrical efficiency of the induction channel furnace in comparison to the induction crucible furnace. There are further problems to consider when operating an induction channel furnace. We aim to prevent undesirable erosions or depositions at the surface of the refractory material. The heat is generated in the channel and must be transported to the melt in the tank. The power input to the channel is limited to prevent overheating.

A main goal when operating induction channel furnaces is to improve life time and energy savings in order to reduce costs and to increase competitiveness. For many years researchers have continually optimized the components of induction channel furnaces, aiming to optimize melt flow and Lorentz forces, to reduce heat losses in the housing or to construct an optimal melting channel shape. Using frequencies less than 50 Hz is an interesting possibility for improving the electrical efficiency, since modern low-cost generators with Insulated-Gate Bipolar Transistors are available [2-5]. There is no induction channel furnace available to carry out experimental investigations since a great disadvantage is the fixed geometry. It would take a great effort to modify the channel shape and the inductor profile. The frequency range is determined by the selected generator. Thus, numerical simulations using finite elements are very suitable to investigate the influence of low frequencies on the electrical efficiency.

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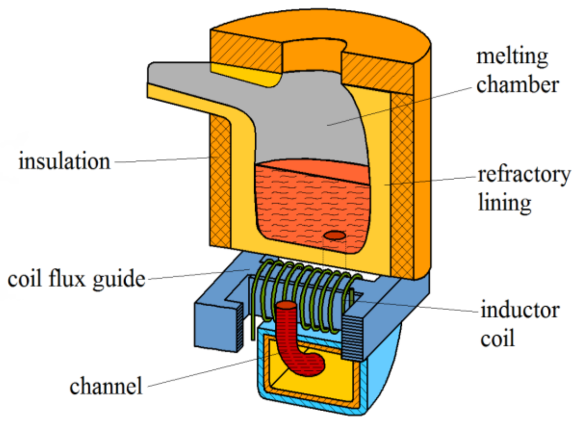

Figure 1. Simplified sketch of an induction channel furnace [1].

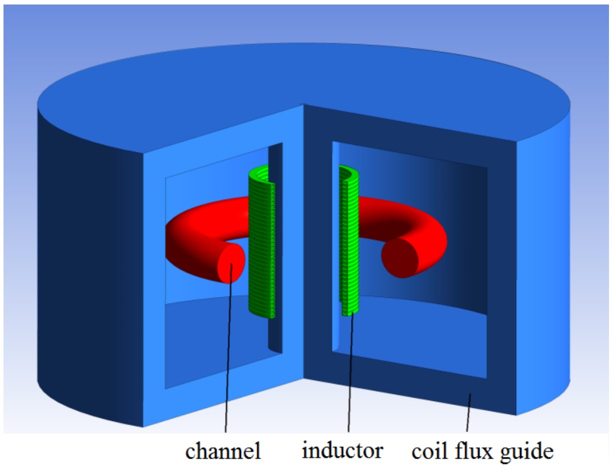

Figure 2. The simplified axisymmetric shell-core model.

2. The Axisymmetric Shell-Core Model

We aim to investigate the interplay between channel shape and inductor coil depending on frequency. That's why the inductor coil profile is considered in detail. Since a three-dimensional inductor coil model is very complex and time-consuming, we use the simplified axisymmetric shell-core model (see Fig. 2). The axisymmetric shell-core works as coil flux guide to ensure the excellent interlink between inductor coil and channel. The melting tank and the pass from the channel to the tank do not exist for these calculations. It is not possible to consider hysteresis loss and eddy current loss in the shell-core in the calculations. Further, the housing and the cooling shell geometry cannot easily be transformed into the axisymmetric model. Thus, eddy current loss is neglected as well. Numerical variables such as the winding pitch, inductor inlet, and housing elements must also be neglected. This axisymmetric model represents a cross-section of the magnetic flux guide, the channel, and the inductor, which are 360° around the Z-axis. This model aims to reduce the computing effort while maintaining sufficient numerical calculation accuracy. Therefore, for our simulations we use the one-loop channel furnace model, which is the simplest induction channel furnace.

The Maxwell equations are solved using the so-called magnetic vector potential and the Finite Element Method (FEM). To simulate the shell-core model, the in-house code PROMETHEUS is used [4]. Additional calculations are done using the commercial software-program ANSYS-MAXWELL [7]. The FEM-theory is state-of-the-art and a large number of publications are available regarding this topic. Detailed investigations regarding the shell-core model are published in [8].

3. Simulation of the Induction Channel Furnace

Experimental investigations using low inductor current frequencies below 50 Hertz for induction channel furnaces have shown that it is possible to improve the electrical efficiency [6]. This improved electrical efficiency could be caused by the hysteresis loss in the coil flux guide and eddy current losses in the housing, which are both reduced when the frequency decreases. The influence of the frequency on the current density distribution in the inductor and in the melt depends on geometry and shall be investigated for a special kind of induction channel furnace. For this work, the construction data of a 250 kW channel furnace with one loop for melting cast iron was considered. This type of channel furnace was investigated in the famous BMFT - joint research project [2].

3.1. The Axisymmetric Shell-Core Model

Using the geometry data, the one-loop induction channel furnace will be transformed into the simplified axisymmetric shell-core model (see Fig. 2). To simulate, we use a very fine mesh, which results in a very highly accurate electrical efficiency calculation depending on frequency.

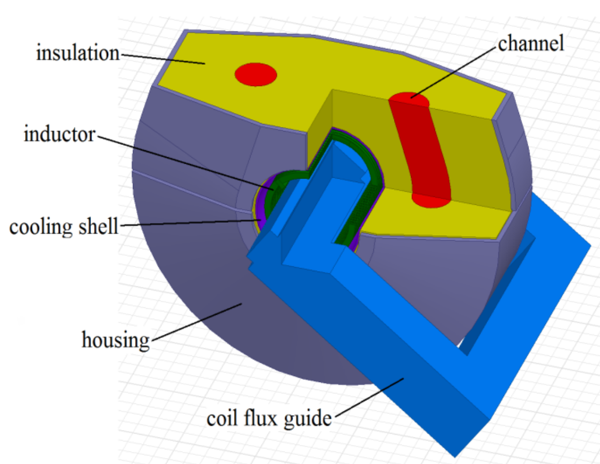

Figure 3. The three-dimensional model with housing and cooling shell (sketch without melting tank).

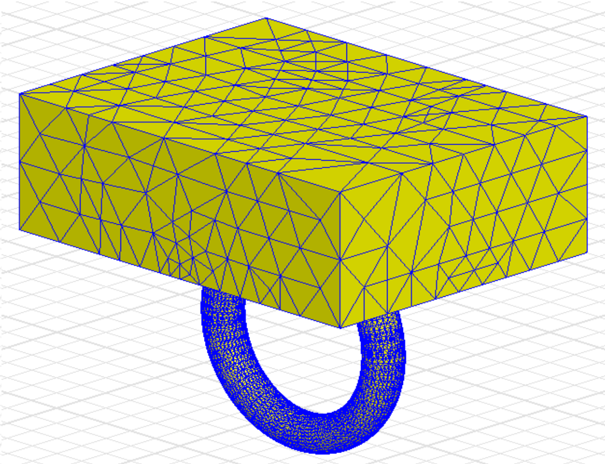

Figure 4. Mesh of simplified tank and channel (MAXWELL).

3.2. The Three-Dimensional Model

Our goal is to predict the influence of the simplifications coming from the shell-core model and to increase the model accuracy. To achieve this goal, we use the program ANSYS-MAXWELL to carry out a three-dimensional simulation of the induction channel furnace including housing, cooling shell, and realistic flux guide for the magnetic field (see Fig. 3). Fig. 4 shows the three-dimensional adapted mesh of the melting channel and the melting tank. The mesh is typical for MAXWELL calculations. In this case the element size is partially much coarser than in the case of the two-dimensional axisymmetric simulation of the shell-core model.

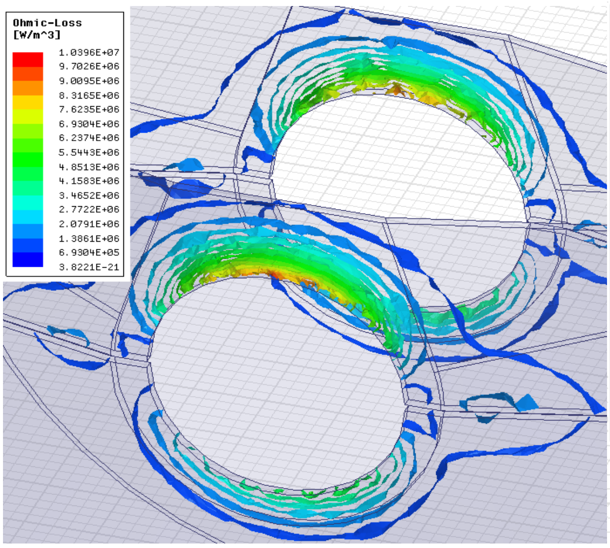

Figure 5. Joule heat in housing.

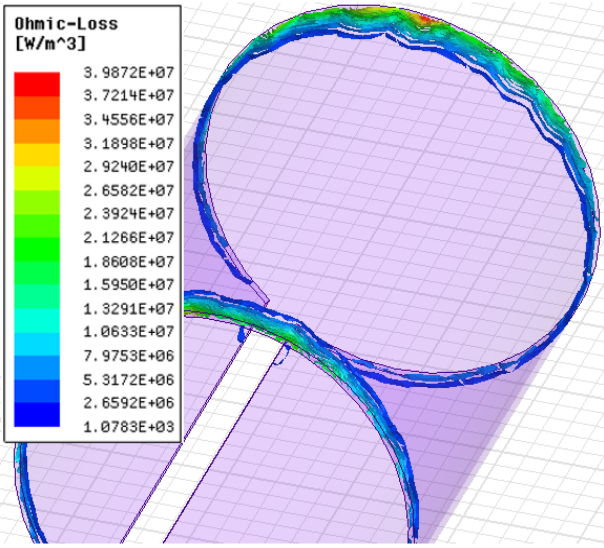

Figure 6. Joule heat in cooling shell.

4. Simulation Results

Detailed results of the two-dimensional shell-core model investigations are published in [8]. One important improvement of the three-dimensional model is considering the Joule heat in the housing (see Fig. 5) and in the cooling shell (see Fig. 6). Usually FEM-programs (MAXWELL, PROMETHEUS) are able to parameterize particular quantities. Mesh, material properties, and impressed currents are assumed to be constant and finally the frequency is the parameter.

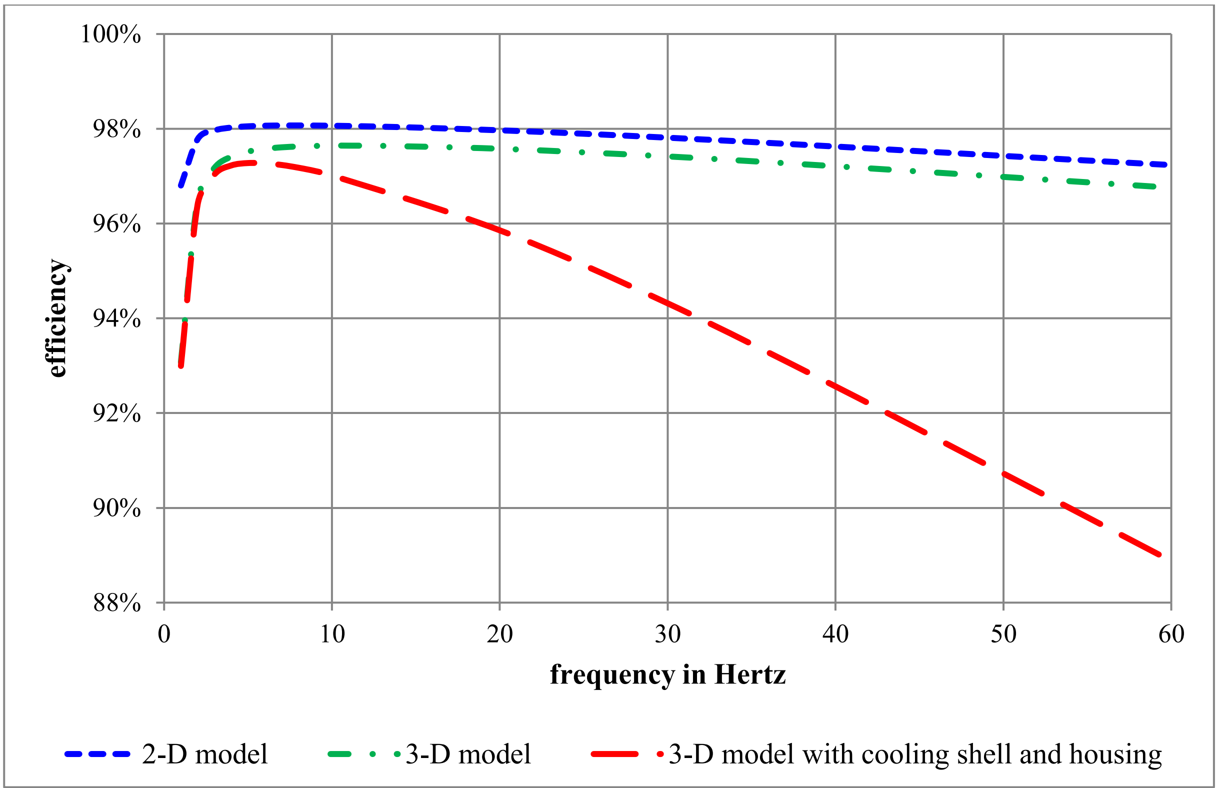

Figure 7. Comparison of the two-dimensional shell-core model and three-dimensional model.

The frequency is divided in 1 Hz steps beginning at 1 Hz up to 60 Hz. The simulation will be done for every frequency step and all important quantities will be saved. The frequency-dependent electrical efficiency is shown in Fig. 7. Regarding the shell-core model (two-dimensional axisymmetric) we find the highest electrical efficiency of 98 % at the remarkably low frequency of 9 Hz. We further aim to evaluate the accuracy of the shell-core model using a three-dimensional simulation without housing and without cooling shell since the shell-core model is not able to consider these slotted structural elements. Even though the three-dimensional model uses a partially much coarser mesh we can observe a relatively good agreement of the electrical efficiency depending on frequency (see Fig. 7: 2-D model – 3-D model). The maximum electrical efficiency of the three-dimensional simulation without housing and without cooling shell is equal to 12 Hz. In the frequency range lower than 10 Hz the difference between both curves increases. In the frequency range higher than 10 Hz the distance between both curves is nearly constant. The difference can be explained by the total resistance of the channel. The total electrical resistance of the channel combined with the melting tank (three-dimensional model) is lower than the total electrical resistance of the axisymmetric shell-core model. The lower resistance leads to a smaller electrical efficiency.
The third curve of the three-dimensional model in Fig. 7 shows the electrical efficiency depending on frequency of the complete model including housing and cooling shell. The maximum electrical efficiency can be seen at a surprisingly low value of 5 Hz. Upon increasing the frequency, the electrical efficiency decreases stronger than the electrical efficiency of the shell-core model. The only reason can be the Joule heat in the housing and cooling of the three-dimensional model, which increases depending on frequency.
Two -dimensional simulations are better suited for our purpose, as can be seen by comparing the calculations. The 2-D model (MAXWELL, 340MB memory, about 53 000 elements) needs about 1 minute to reach an error lower than 0.01 %. The 3-D model (MAXWELL, 8.35 GB memory, about 1 370 000 elements) needs about 3.5 hours to fall below an error of 1 %. In this case it is not possible to

achieve the error limit of 0.01 %. The calculations were done using a modern PC with an Intel® Xeon® Processor E5-2650 (2.3 GHz) and 758 GB memory.

5. Conclusions

This work aims to provide the numerical simulation of the frequency dependence with regard to the electrical efficiency of induction furnaces. Using the axisymmetric shell-core model, numerical simulations are well suited to investigate the influence of the inductor profile, of different channel cross-sections or sizes, and of different element positions. All elements of the model can be described using a very fine mesh in order to achieve highly accurate simulation results. The advantage of the two-dimensional simulation is the acceptable calculation time needed to compute the given frequency range step by step, ensuring a low simulation error. The systematical error, caused by the simplifications of the two-dimensional shell-core model must be accepted. Three-dimensional simulations are done to verify the shell core-model. The comparison shows a good agreement between the electrical efficiency depending on frequency. Differences can be explained by the simplifications of the shell-core model. The maximum efficiency lies at nearly the same position.

The copper coil profile can be modeled very exactly using the 2-D model. Using the 3-D model, the coil profile can only be approximated with a coarse mesh. The 2-D model and 3-D model results are in good agreement. As a consequence, the 2-D model is ideal for studying different types of special copper profiles.

The realistic three-dimensional model including the housing and the cooling shell provides further arguments for the use of low frequencies to improve the electrical efficiency of induction channel furnaces. Further work is needed to consider thermal field effects, since the overall efficiency of the induction heating system is a combination of both thermal and electrical efficiency. The disadvantage of the three-dimensional model is the high computation time to calculate the electrical efficiency for all frequencies.

The induced power is an important condition which we have to consider. It is basically possible to use a frequency of 10 Hz. Using a frequency of 5 Hz is critical because the induced power starts to decrease rapidly. But there is another non-technical problem. The channel furnace produces noise and a frequency below 25 Hz generates painful infrasound, so that manufacturers won't apply frequencies below 25 Hz. If future casting houses are fully automated, then applying frequencies below 25 Hz will greatly increase electrical efficiency.

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