

Thermal Analysis of Induction Furnace

A. A. Bhat^{*1}, S. Agarwal¹, D. Sujish¹, B. Muralidharan¹, B.P. Reddy², G.Padmakumar¹ and K.K.Rajan¹

¹Fast Reactor Technology Group, ²Chemistry Group

Indira Gandhi Centre for Atomic Research, Kalpakkam-603102, India.

*Corresponding author: PPES, FRTG, IGCAR, Kalpakkam, 603102; asifbhat@igcar.gov.in

Abstract: Induction heating furnaces are employed for vacuum distillation process to recover and consolidate heavy metals after electrorefining operation. Induction heating furnaces of suitable heating rates are required to be developed for this purpose. Hence it is planned to set up a mock-up induction furnace which will simulate the conditions to be realized in actual induction heated vacuum distillation furnace. The mock-up induction furnace will be used to demonstrate the melting of copper. Preliminary results of the mock-up furnace are aimed at understanding the induction heating process and control which will be useful for the design and operation of actual vacuum distillation furnace. The mock-up induction furnace has been modeled in COMSOL Multiphysics. Prior to that the Induction Heating Interface algorithm under the Heat Transfer Module of COMSOL Multiphysics was validated with the experimental data reported in the literature. This paper describes the thermal and electromagnetic modeling of induction furnace and discusses the numerical results obtained. These results will be compared with the experimental results which will be obtained during the operation of mock up facility.

Keywords: Electromagnetic/induction heating, Induction melting, vacuum distillation furnace.

1. Introduction

The high-temperature vacuum distillation furnace is able to melt and consolidate the heavy metals, distill the volatile metals, be operable in argon containment box and heat reasonably fast while being capable of holding temperature. The furnace is induction heated to ensure equipment durability, long term availability and compatibility with metal vapours. The process is carried out in vacuum in order to eliminate the concerns about metal oxidation and purity during melting.

1.1 Validation model

In this section induction heating interface algorithm of COMSOL was validated with experimental literature data [1]. The induction heating system consists of stainless steel work-piece the upper part of which is placed inside the induction coil consisting of six irregularly spaced windings made of copper. A thermocouple is spot welded at 5 mm distance from the top of the work-piece to ensure good thermal contact for accurate temperature measurement. The power is supplied at 10 kHz. The coil voltage is 77 V and the time of heating is 25s. The geometry and mesh networks for this system are created using COMSOL and is shown in Figure 8. The numerical temperature evolution at the thermocouple location obtained from the simulation is compared with the experimental temperature history in Figure 2. Good agreement is found between the experimental results and numerical simulation. This validates the induction heating algorithm used for mock-up induction furnace.

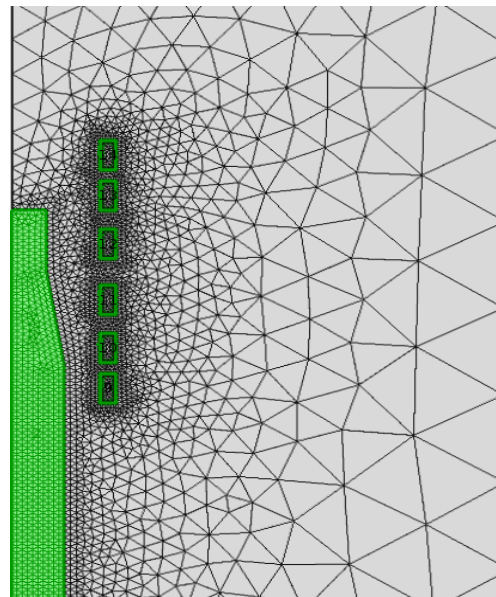


Figure 1: The 2D axisymmetric model (with mesh) of the induction heating set up.

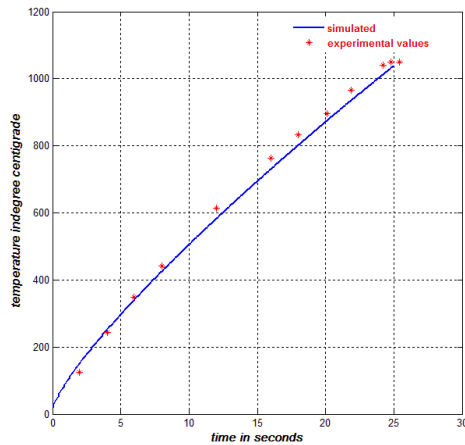


Figure 2: Comparison of experimental and simulated temperatures at thermocouple location.

1.2 Mock-up induction furnace

The mock-up induction furnace consists of furnace liner (susceptor), crucible, induction coil, copper-liner, graphite felt insulation and alumina refractory. These furnace components are enclosed in stainless steel vacuum vessel. Figure 1 shows the schematic layout of the equipment. Induction heating is achieved by supplying AC power at 2-8 kHz to the coil. The furnace liner made of high density graphite encloses the graphite crucible containing solid copper pellets. The induction coil is a 13 turn coil made of solid copper bar with rectangular cross section [2]. The furnace liner essentially gets coupled with the magnetic field generated by the induction coil, heats up and indirectly heats the crucible by radiation heat transfer. The melting of copper takes place in crucible. The copper liner prevents the coupling of stainless steel vessel with magnetic flux lines. The carbon felt insulation is used to prevent the heat loss to the coil and other parts. The melting is carried out under vacuum and the contents in the crucible (copper) need to be heated to 1500 °C in 2-5 hours. These conditions are sufficient for melting process. After melting, the crucible is cooled to form the metal ingot which is then removed. The induction coil is not water cooled due to safety considerations. The coil is only cooled by radiation to the walls of vacuum vessel which can be cooled by water.

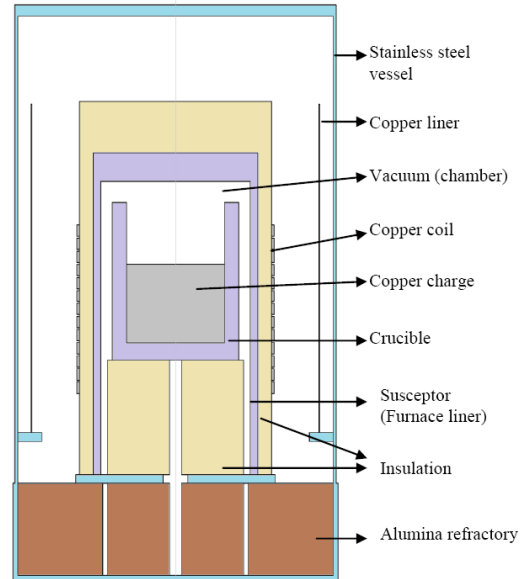


Figure 1: Schematic model of mock-up induction furnace

The two dimensional axisymmetric COMSOL model of the furnace is used to study the induction heating in the mock-up furnace.

2. Use of COMSOL Multiphysics

2.1 Numerical model

The induction heating process in mock-up furnace is a complex process where different physical fields i.e., electromagnetic and heat transfer phenomena are strongly coupled due to inter related nature of physical properties [3, 4]. The coupling is shown in Figure 2.

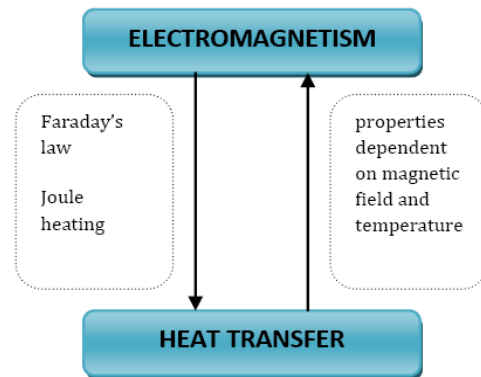


Figure 2: coupling of different fields in induction heating.

The magnetic field generated by the coil creates induced currents in the furnace liner. These induced currents heat the furnace liner by joule heating. The crucible gets heated by the radiation from the furnace liner and reaches the temperature where melting of the copper charge takes place. Once the susceptor temperature increases its electric, magnetic and thermal properties change, varying the values of induced currents and temperature gradients. Hence non-linear properties of the materials need to be considered to model the induction heating process in the furnace. The melting part of this process has not been modeled in this study.

2.2 Geometry

A simplified 2D axisymmetric model shown in Figure 3 was built in COMSOL. The model has the same dimensions as that of the mock-up induction furnace. The crucible has the diameter of 265 mm and that the coil inner diameter is about 400mm. The important parameters used in the model are given in Table 1.

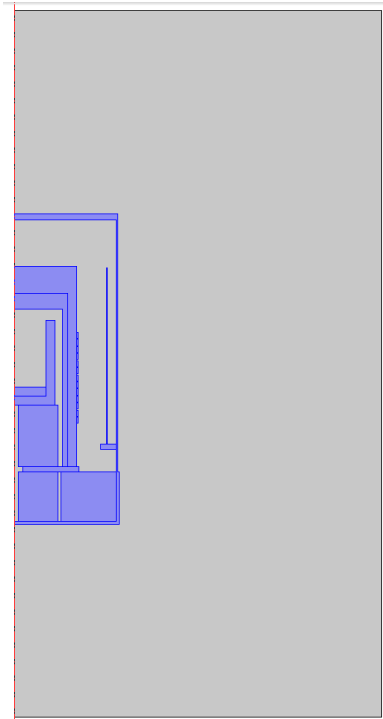


Figure 3: 2D-axisymmetric COMSOL Multiphysics model of mock-up induction furnace.

S. No	Parameter	Value
1	Frequency	8 kHz
2	Current	400 A
3	Height of copper in the crucible	30 mm (for 3.5 kg)
4	Time of heating	7200 s (2 hours)
5	Time step for computation	60 s

Table 1: Important parameters used in simulation

2.3 Main features of the model.

For the mock up induction furnace it is possible to approximate it as a 2D axisymmetric geometry due to the cylindrical symmetry and ignoring the power feed-throughs which supply power to the coil. The pre-defined frequency transient, induction heating, electromagnetic heating mode in the heat transfer module is used for the model. It is a one step approach where electromagnetism and heat transfer are solved simultaneously to give the magnetic fields and temperature distribution. The induction heating simulations use quasi static, time harmonic induction currents application mode to solve for magnetic vector potential, the predefined couplings then use the calculated volumetric heating as a source term in the energy equation for a transient heat transfer simulation [5]. The model has different domains air, crucible, air, coil, susceptor, vacuum etc.

2.4 Governing equations and boundary conditions:

The electromagnetic field is governed by Maxwell's equations. These equations are solved in COMSOL Multiphysics using the following formulation:

$$(j\omega\sigma - \omega^2\epsilon_0\epsilon_r)A + \nabla \times (\mu_0^{-1}\mu_r^{-1}B) = J_e$$

$$B = \nabla \times A$$

where A is the magnetic vector potential, B is magnetic flux density, J_e is external current density, ω is the frequency, ϵ_r is the relative

permeability and ϵ_0 is the permittivity of vacuum,

These equations are solved in entire computational domain (including copper charge, coil, crucible, susceptor insulation). The input data for the coil is 400 A external current with a working frequency of 8 kHz. In the outer boundaries of computational domain the magnetic insulation boundary condition is used, which imposes that the normal component of magnetic field has to be zero. The transient heat transfer is governed by Fourier equation which is solved in COMSOL using the following formulation.

$$\rho c \frac{\partial T}{\partial t} = \nabla \cdot (k \nabla T) + Q$$

Where T is the absolute temperature, ρ is the density, c is the specific heat capacity, k is the thermal conductivity and Q is the energy generated in the material per unit volume and time (heat source term). This equation is solved in solid computational domains of the model. For the heat transfer boundary conditions, all the initial temperatures are set to 30°C. All the inside free surfaces in the model are allowed to participate in surface to surface radiation. The outer vessel wall surfaces are allowed to participate in surface to ambient radiation and convective cooling using suitable values of heat transfer coefficients [6] for top bottom and vertical surfaces.

3. Numerical Results

Figure 4 shows the streamline representation of magnetic field inside the mock-up induction furnace at 8 kHz. It is seen from the figure that the copper liner absorbs the magnetic field thus shields the stainless steel vessel from the coil magnetic field which otherwise would lead to undesirable heating of the vessel. The result is in agreement with the theory.

Figure 5 shows the three-dimensional temperature distribution in the mock up induction furnace after two hours. The hottest regions are the susceptor liner and the crucible enclosed inside the susceptor. It is because the susceptor is coupled to the coil where maximum heat generation takes place. The susceptor in turn heats up the crucible by radiation. .

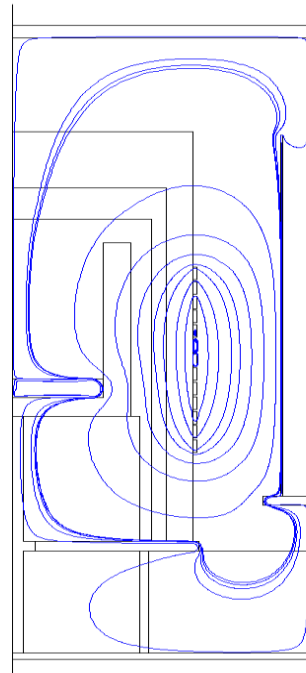


Figure 4: Magnetic flux density inside the furnace.

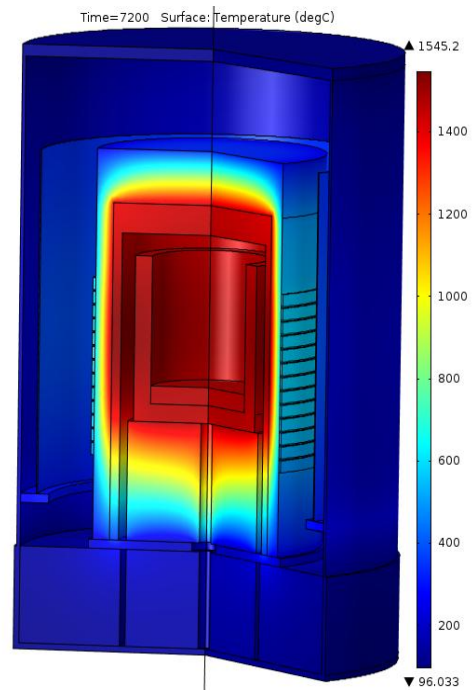


Figure 5: 3D Temperature distribution in mock-up induction furnace after 2 hours

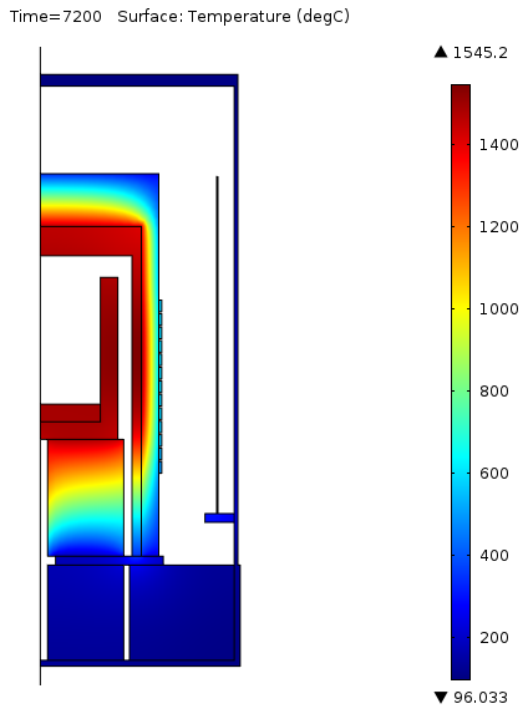


Figure 6: 2D Temperature distribution in mock-up induction furnace after 2 hours

Figure 6 shows the surface plot displaying two-dimensional temperature distribution in the mock up furnace after two hours. The maximum temperature in the susceptor is 1545 °C while crucible and charge maximum temperatures are around 1530 °C. The coil maximum temperature is 590 °C which is higher than the acceptable value (400 °C). This suggests that the coil needs cooling to limit its temperature to permissible value.

The transient temperature plots which are important for process operation and control have also been plotted. Figure 7 displays the temperature evolution with time at the indicated positions on the susceptor and the crucible respectively. The blue curve gives the temperature of the crucible and the red one gives the temperature of the susceptor. The temperature of crucible is seen to be 10-15 °C lesser than the susceptor.

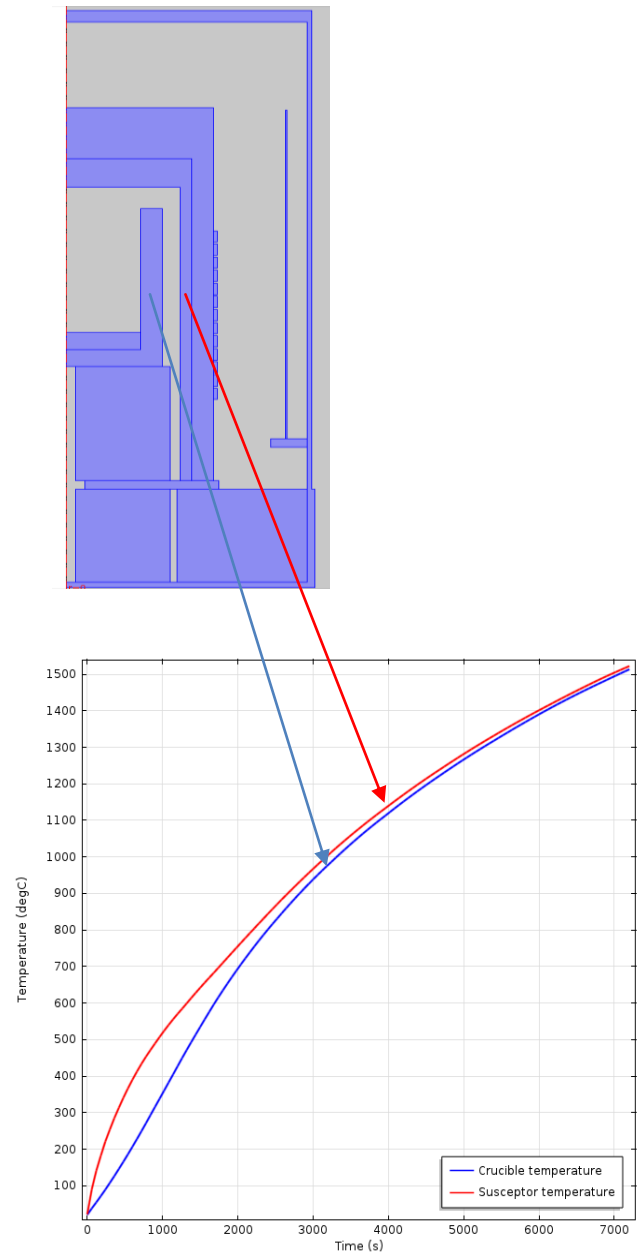


Figure 7: Temperature rise with time at the indicated points on the susceptor and crucible respectively.

4. Conclusions

This paper shows how to solve the induction heating problem in the induction furnace with complex geometry. The results of this study have shown that the temperature of the crucible rises to 1500 °C in 2 hours of heating time at frequency of 8 kHz and current of 400 A. Hence these conditions are favorable for melting of copper (melting point = 1085 °C) in the crucible. The studies reveal that copper-liner is effective in reducing the electromagnetic coupling between the coil and the vessel and thus prevents vessel from getting heated up by this effect.

5. References.

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6. Acknowledgements

The authors thank to the Homi Bhabha National Institute (HBNI) and Department of Atomic Energy, Government of India for their support.