Electromagnetic and Thermal Modeling of Vacuum Distillation Furnace

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Abstract: Vacuum distillation furnaces (VDFs) are employed for purification and consolidation of heavy metals from their dendritic forms which are entrained with molten salts. The VDF is an induction heated furnace which is operated at a temperature of 700-1400 °C and at a pressure of 0.01-600 torr. To arrive at the adequate design of such type of furnace, magnetic field and temperature distribution need to be accurately predicted inside the furnace. This paper describes the electromagnetic and thermal modeling of vacuum VDF using COMSOL Multiphysics to arrive at the suitable values of various controlling parameters like coil voltage, frequency , number of radiation shields, etc.

Keywords: electromagnetic/induction heating, vacuum distillation furnace, multiphysics

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 salt and metal vapours. The process is carried out in vacuum in order to eliminate the concerns about metal oxidation and purity during melting.

Figure 1 shows a layout of the VDF .The major components are the vessel, the induction-heated-furnace region inside the vessel at the top, and the condenser/collector region inside the vessel at the bottom. The induction-heated-furnace region uses a passively cooled induction coil and a graphite furnace liner that acts as the susceptor. The condenser region includes a passively cooled condenser and a receiver crucible which collects the condensate. The temperature gradient between furnace region and condenser region is maintained with the help of radiation shields. Isolation of the induction coil from the crucible assembly is necessary to prevent the migration of vapour species to the coil during operation. . The vacuum is maintained by using mechanical pumps, which are connected to the vessel through an assembly of piping, manifolds, and valves. The copper liner prevents the coupling of stainless steel vessel with magnetic field generated by the coil. The susceptor heats the process crucible by radiation. The VDF is capable of operating temperatures as high as 1400 °C and pressures less than 10 Pa. Distillate material (salt) in the vapour phase is transferred to the condenser region from the process crucible through annular space between the crucible and the susceptor and collected in a receiver crucible. After distillation the left out phase (heavy metals) melt, get consolidated in crucible and finally form an ingot on cooling. The induction heating power supply is rated to 30kW output at 2500 Hz [1, 2].

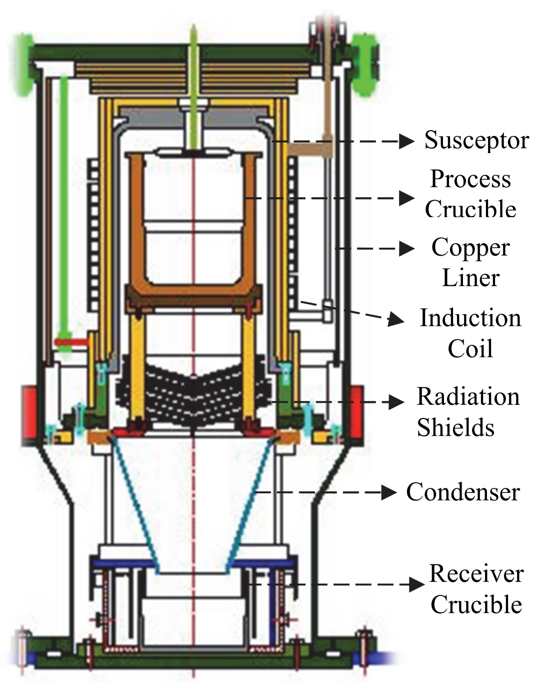

Figure 1: Schematic diagram of VDF

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The two dimensional axisymmetric model of VDF is considered in this computational analysis, using COMSOL Multiphysics.

2. Use of COMSOL Multiphysics

2.1 Numerical model

The induction heating process in VDF 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.

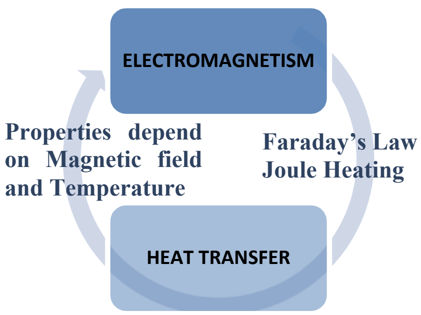

Figure 2: Coupling of different fields in induction heating.

The magnetic field generated by the coil creates induced currents in the susceptor. These induced currents heat the furnace liner by joule heating. The process crucible gets heated by the radiation from the susceptor to attain required temperature. 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 are considered to model the induction heating process in the furnace. The vaporization and melting processes have not been modeled in this study.

2.2 Geometry

A simplified 2D axi-symmetric model of VDF was setup in COMSOL. The model has the same dimensions as that of the VDF. The geometry was imported from Auto-CAD and later modified using Geometry tool of COMSOL. Materials were assigned to different domains of the model using COMSOL Material Library and along with some user defined materials. Physics controlled extremely fine mesh was used for the model using Mesh tool. Frequency transient study was carried out for the model along with parametric sweep studies for voltage and number of radiation shields. The important parameters used in the model are given in Table 1.

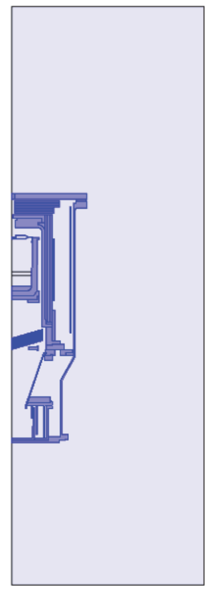

Figure 3:2D-axisymmetric COMSOL Multiphysics model of VDF.

S. No	Parameter	Value
1	Frequency	2.5 kHz
2	Coil Voltage	100-300 V
3	Time of heating	8 hours
4	Time step for computation	60-100 s
5	Number of radiation shields	10 & 20

Table 1: Important parameters used in simulation

2.3 Main features of the model.

To model induction heating in VDF, it is possible to approximate it as a 2D axisymmetric geometry due to the cylindrical symmetry and ignoring the power feed-through which supply power to the coil. The pre-defined frequency transient, induction heating, electromagnetic heating mode in the heat transfer module is used. 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/argon, crucibles, coil, vessel, shields, 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. Among the voltage, current and power as input data, the coil was modeled with voltage, which was found to give more reliable results for axisymmetric coils. The frequency value is set to 2.5 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 contour representation of z-component of magnetic flux density (Tesla) in VDF at 2.5 kHz and after 2 hours when the voltage is 250 V. 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 [3].

Figure 5 shows the three-dimensional temperature distribution in the VDF after 5 hours and when 20 number of radiation shields are used. The hottest region is the furnace region. Figure 6 shows the surface plot displaying two-dimensional temperature distribution in the VDF after five hours.

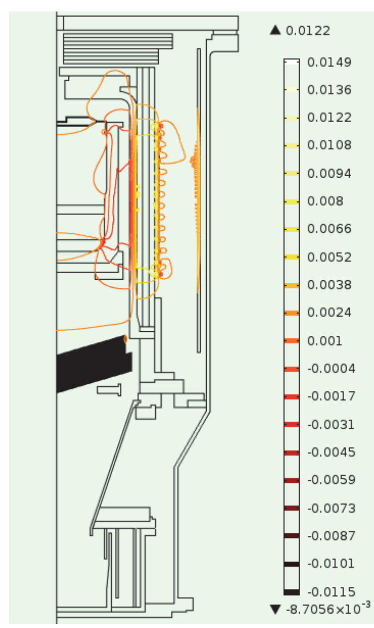

Figure 4: Magnetic flux density inside the furnace at 2.5 kHz and coil voltage of 250. (z component)

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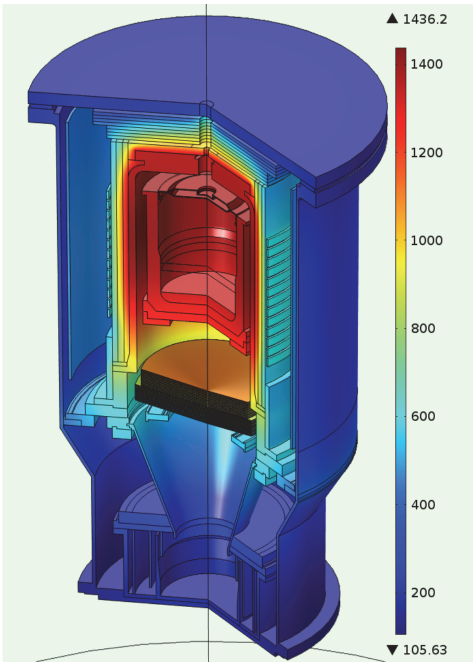

Figure 5: 3D Temperature distribution in VDF furnace after 5 hours

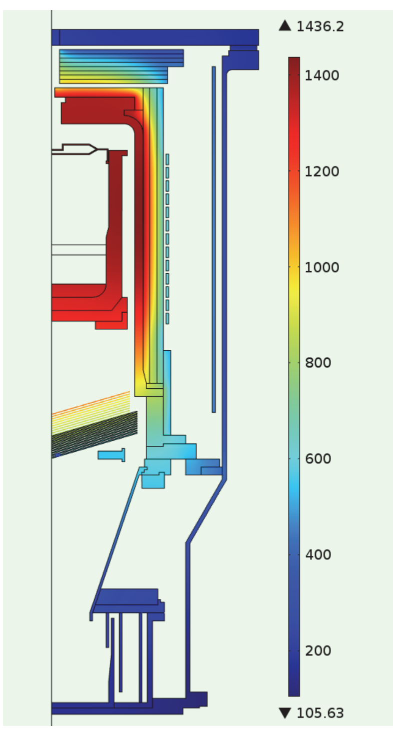

Figure 6: 2D Temperature distribution in mock-up induction furnace after 5 hours

The maximum temperature is attained by the susceptor (1436 $^{\circ}$C) which is followed by crucible. It is because the susceptor is coupled to the coil where maximum heat generation takes place. The coil temperature is 600 $^{\circ}$C which is higher than the acceptable value (400 $^{\circ}$C) from mechanical strength considerations. This suggests that the coil needs cooling to limit its temperature within permissible operating value.

Figure 7 shows the average temperature rise of crucible with time. The voltage of the coil used is varied from 100 V to 300 V while the frequency is kept constant at 2.5 kHz. From the plot, the 250 V seems to be suitable for the process.

Figure 8 shows the temperature profile in the radiation shields plotted with the help of cut-line passing through the shields. The voltage of the coil is 250 V, frequency is 2.5 kHz and the number of radiation shields is ten. To account for the heat carried by the salt vapour, heat flux equivalent to the super heat carried by the vapour is additionally given to the top shield. Figure 9 shows the temperature profile with 20 number of shields keeping all the parameters same as with the 10 number of radiation shields. The plots show both the combination of shields is able to bring down the temperature of the lower shield to around 650 $^{\circ}$C which is suitable for the operation of condenser located below the shields.

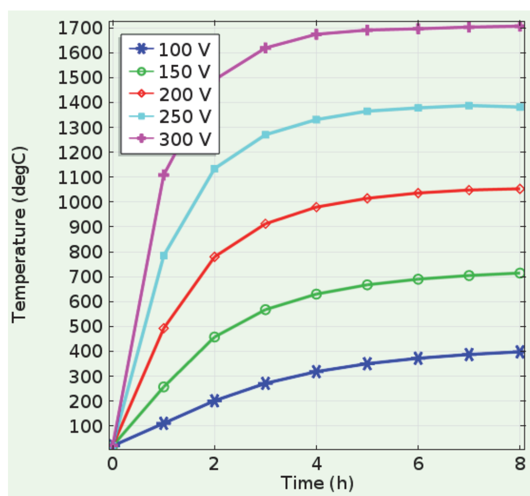

Figure 7: Average temperature rise of crucible with time at different coil voltages.

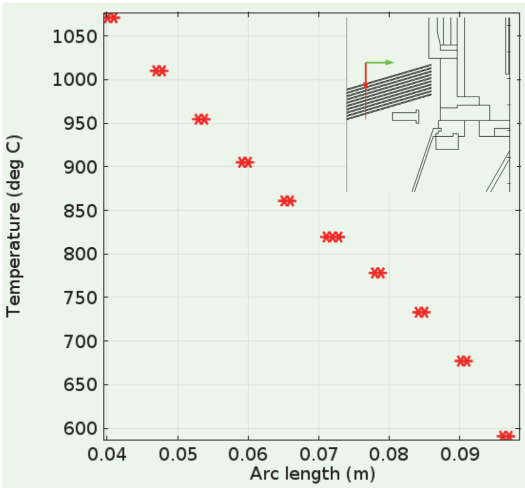

Figure 8: Temperature profile in the radiation shields with 10 numbers (gap = 4 mm between the plates) and added vapour heat flux.

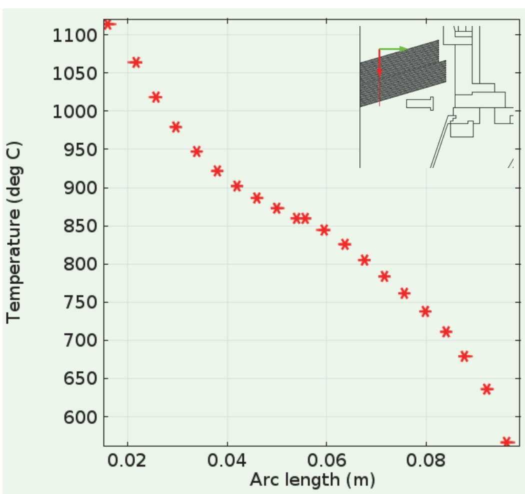

Figure 9: Temperature profile in the radiation shields with 20 numbers (gap = 2 mm between the plates) and added vapour heat flux.

4. Conclusions

This paper presents the solution of induction heating problem in the VDF with focus on evaluation of operating parameter like voltage and number of required radiation shields. Based on the assumption that induction heating setup is invariant in one dimension, a 2D- axisymmetric model of VDF was setup in COMSOL Multiphysics and the frequency transient solution, with parametric studies for various parameters, was generated. The results of this study have shown that at the operating frequency of 2.5 kHz, the requisite maximum temperature in the crucible is attained at coil voltage 250 V. The studies reveal that in place of 20 number of radiation shields 10 number is also sufficient to maintain the suitable temperature gradient between the vaporization region and condensation region based on the process requirement. The analysis of VDF using COMSOL Multiphysics serves as a valuable tool for the mechanical, thermal and process design of VDF.

5. References.

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