



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 analysis 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.

INTRODUCTION

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. 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. Distillate material 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.

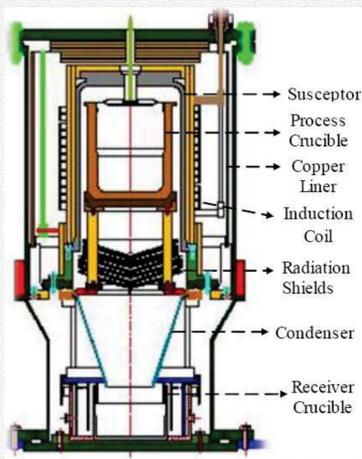


Figure 1: 2D schematic layout of VDF

MODELING IN COMSOL

Salient Features in Modeling

To model induction heating in VDF, it is possible to approximate it as a 2D axisymmetric model due to the cylindrical symmetry and ignoring the power feed-through and other penetrations. The Induction Heating Module under Heat Transfer Interface was being used for this analysis. A simplified 2D axi-symmetric model of VDF was set up in COMSOL (Figure 3). The geometry was imported from AutoCAD 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. Table 1 gives the important parameters used.

Table 1: Important parameters used in simulation

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

Governing Equations

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

$$B = \nabla \times A$$

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

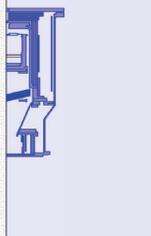


Figure 3: 2D axis-symmetric model VDF.

Boundary Conditions

The Maxwell's equations are solved in entire domain. In the outer boundaries of domain the magnetic insulation boundary condition is used, which imposes that the normal component of magnetic field has to be zero. 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. The heat conduction equation is solved in solid computational domains of the model. 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 calculated values of heat transfer coefficients.

RESULTS

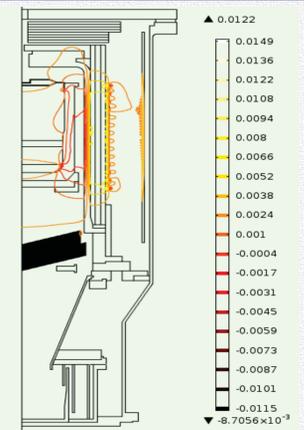
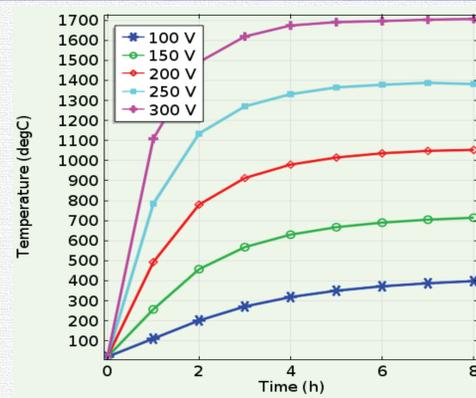


Figure 6: Magnetic flux density inside the crucible with time at different coil voltages. VDF at 2.5 kHz and coil voltage of 250 V.

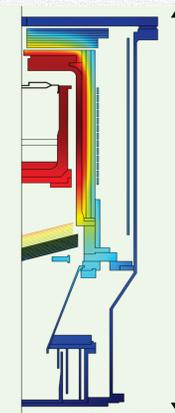
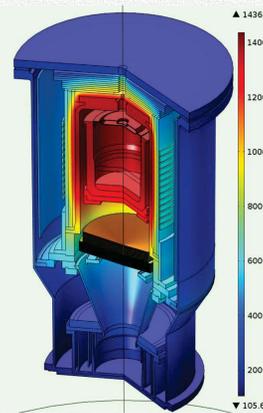


Figure 7: 3D and 2D temperature distribution in VDF after 2 hours at 3 kHz.

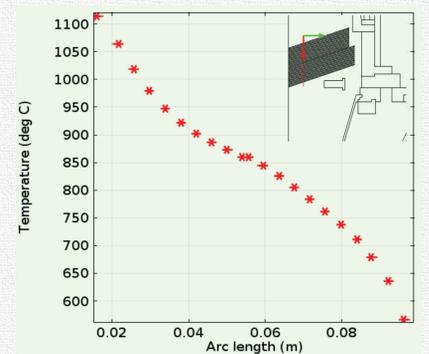
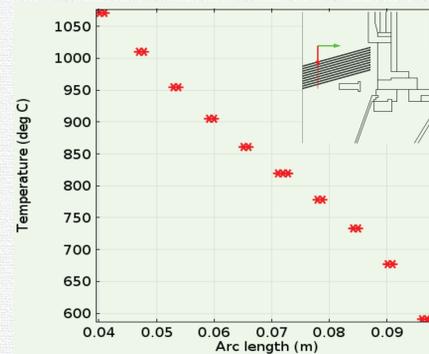


Figure 8: Temperature profile in the radiation shields with 10 and 20 number of radiation shields and added vapour heat flux

CONCLUSIONS

This analysis 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. 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 250 V. The studies reveal that in place of 20 radiation shields 10 numbers is also sufficient to maintain the suitable temperature gradient between the vaporization region and condensation region. The analysis of VDF using COMSOL serves as a valuable tool for the mechanical, thermal and process design of VDF.