Thermal Analysis of Vacuum Distillation Chamber in Pyroprocessing Facility

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Abstract: Non aqueous metal fuel reprocessing involves electrochemical deposition of spent metallic fuel on the cathode of an electrolytic cell. Apart from metal fuel, the cathode deposit would also contain occluded molten salts and liquid cathode. Subsequent purification and consolidation of these heavy metals is conducted in a vacuum retort. Here the cathode deposits are charged into graphite crucible and heated by induction to 900^{o}C and 1300^{o}C at 0.1 mm Hg pressure to distill off liquid cathode and salts respectively. The steady state temperature profile during vacuum distillation of cathode deposits was obtained by a thermal analysis of the vacuum distillation vessel. It was carried out using COMSOL 3.5a. A transient analysis was also done to determine the heating time for a particular frequency and current in the induction coils. This paper highlights the important temperature profiles at steady state which would be helpful in the final mechanical design of the various components. This also gives the time required for heating the crucible to about 1300^{o}C by induction.

Keywords: Pyro processing, vacuum distillation, thermal analysis, Induction heating, COMSOL

1. Introduction

Pyrochemical reprocessing or Pyroprocessing is the best suited method for reprocessing spent metallic fuel from fast breeder reactors. This technique can be used for reprocessing short cooled, high burn-up and high plutonium containing fast reactor metal fuels. Pyroprocess based reprocessing plants are more compact than the ones based on aqueous reprocessing methods. Criticality problems are less severe in this case. In the pyrochemcial reprocessing, Heavy Metals (HM) are separated from the spent metallic fuel by electrorefining. Metal fuel is deposited on a solid rod and will be occluded with molten salt whereas heavy metal and minor actinides will be co-deposited on the liquid cathode of the electrolytic cell. Distillation in vacuum is essential for recovery and consolidation of HM from the cathode deposit. This is carried out in a high temperature, vacuum retort and is shown in Fig.1. Vacuum distillation involves heating the cathode deposit with salt/liquid cathode in the vacuum distillation chamber to distill the salt /liquid cathode from the crucible and then melting the residual actinides by further increasing the temperature. The crucible is then cooled forming a heavy metal ingot in the crucible. Thermal analysis of the vacuum distillation chamber was essential with respect to material selection, mechanical design of components and also suitable geometry of induction heating coils. COMSOL 3.5a was used for the thermal analysis.

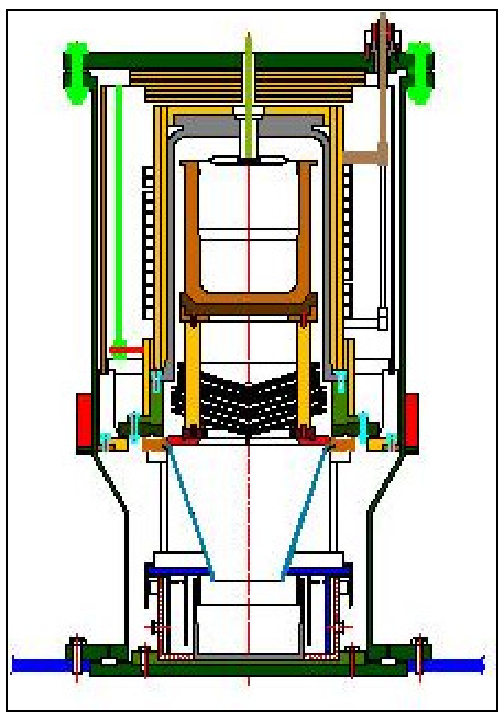

Figure.1. Sectional view of Vacuum distillation chamber.

1.1 Vacuum Distillation chamber

This essentially consists of a graphite crucible enclosed within an induction coil. The heavy metal with adhered salts is loaded in the crucible and heated by induction under vacuum. The salt evaporates as the temperature is raised and the vaporised salt is collected in a condenser section located below the crucible. The operating temperatures vary depending on the boiling point of the impurities. Typically the eutectic salt mixture evaporates at 1100^{o}C and further melting of HM is done at 1300^{o}C. During operation the top half of the chamber is at high temperature and the bottom half is the condensing section and here the temperatures should be just above the freezing point of the salts. The two sections are separated by special radiation shield plates to prevent radiative heat transfer from top to bottom.

2. Mathematical modeling

2.1 Steady State Analysis

A 2-D axisymmetric analysis of the distillation chamber was done. The numerical model is shown in Fig.2.

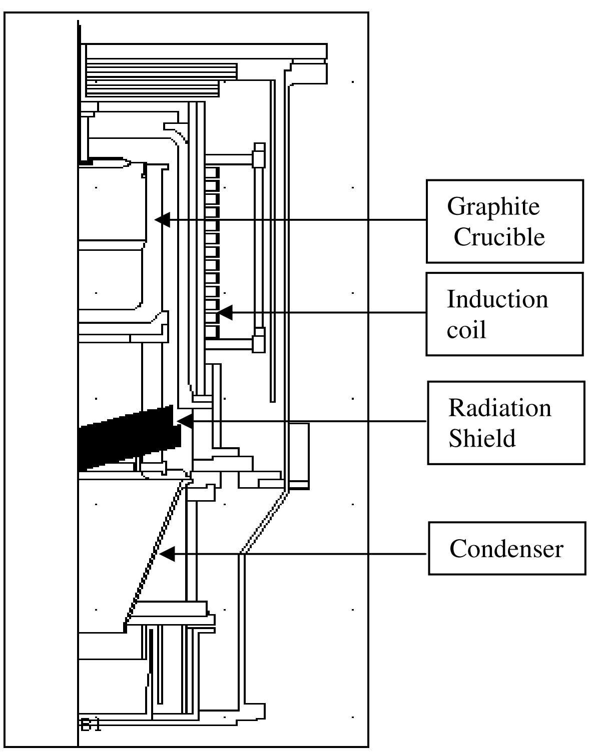

Figure.2. Numerical model

Initial analysis was done to determine the steady state temperature profiles at highest operating temperature of 1300^{o}C for salt distillation.

2.1.1 Boundary conditions

The heat source is the graphite crucible 1300 ^{o}C.
The heat sink is the bottom flange and outer vessel walls, where heat loss is by radiation.
The temperature profile along the radiation shields, condenser wall and induction heater was scrutinised. Similarly temperature profiles were taken for a maximum operating temperature during liquid Cathode distillation which is 900^{o}C.

2.2 Transient Analysis with coupling

In order to estimate the heating time required to raise the temperature of the crucible contents from ambient to 1300^{o}C by induction heating, a transient multiphysics analysis using General Heat Transfer module and AC-DC module of COMSOL was used. The numerical model was the same as shown in Fig.2.

2.2.1 Boundary conditions

The boundary conditions included total current 400A and frequency was varied from 2000 to 10000 Hertz for induction coil.

3. Results of steady state analysis

The steady state temperature profile for 1300^{o}C operating temperature is shown in Fig.3.

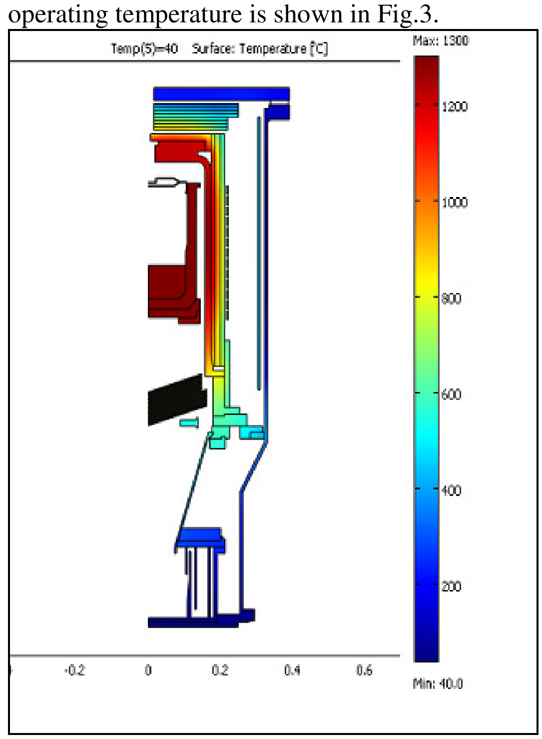

Figure.3. Steady state Temperature distribution

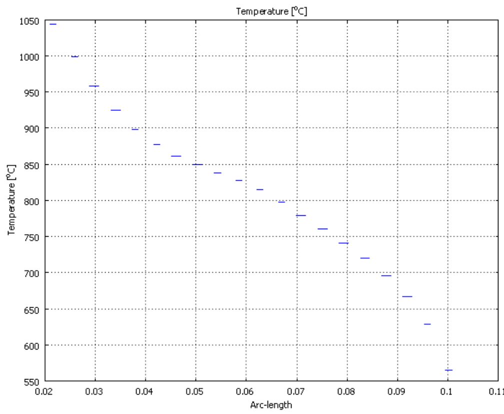

Fig.4. Temperature drop in radiation shield plates for salt distillation.

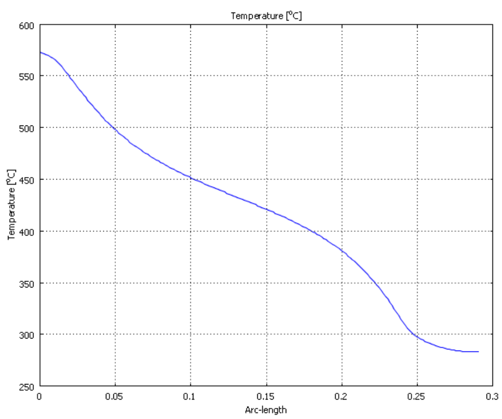

Fig.5. Temperature profile along the condenser for salt distillation.

As shown in Fig.4, with required number of radiation shield plates, a temperature drop from 1050°C to 550°C was obtained. Form Fig.5 the temperature along the condenser wall decreases from 570°C to 300°C at the bottom which is just below the melting point of salt. Similar analysis corresponding to Liquid cathode distillation was done with 900°C as maximum operating temperature.

Fig.6 shows that the temperature drop with required number of radiation shield plates is from 670 to 370°C which is closer to the melting point of liquid cathode.

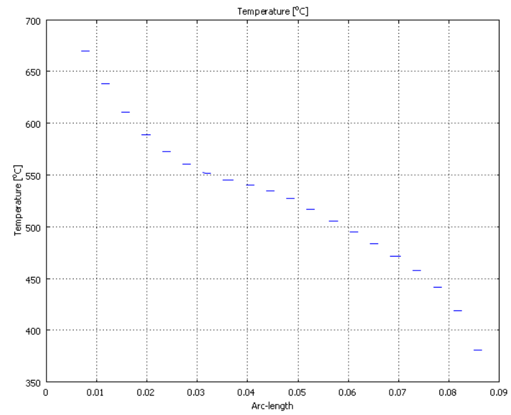

Fig.6. Temperature drop in radiation shield plates for liquid cathode distillation.

4. Results of Transient coupled Analysis

The heating time for the crucible to reach 1300°C was estimated to be around 6 hours, when a frequency of 8 kHz and current of 400 Amperes is given to the induction coil.

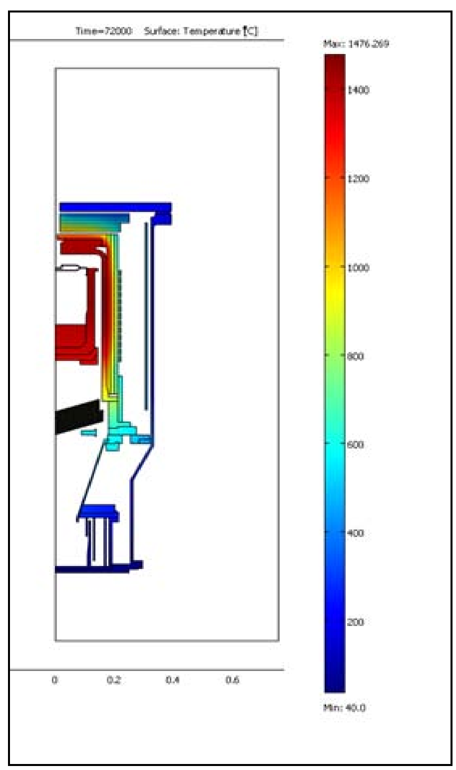

Fig.7. Temperature profile for transient analaysis

5. Conclusions

- During salt distillation at 1300°C, radiation shield plates is adequate to prevent radiative heat transfer to the condenser section.
- Since the condenser surface temperatures are higher than the melting point of salt, salt deposition will not occur in the condenser walls.
- During liquid cathode distillation at 900°C, temperature drop in the shield plates is 300°C and liquid cathode can condense on the shield plates.
- Hence additional heating arrangement has to be provided at the periphery of the shielding plate zone.
- The Grahpite Crucible will reach a temperature of 1300°C when 400 ampere current at a frequency of 8kHZ is supplied to the induction coils. The time required for attaining this temperature was estimated to be 6 hours.