Thermal Analysis of Salt Storage Vessel

A. S. Vipin[*1], A.A. Bhat [1], S. Agarwal [1], S. P. Ruhela[1], D.Sujish[1], B. Muralidharan[1]
1. Indira Gandhi Centre for Atomic Research, Kalpakkam, TN, India
*Corresponding author: PPPDS, PPED, MC&MFCG, IGCAR; vipin@igcar.gov.in

Abstract

Eutectic mixture of LiCl-KCl is used in nuclear applications for electrochemical processes. This salt mixture is having a melting point of 355 °C. This paper gives the details of thermal analysis study carried out for preheating of a molten salt storage vessel of 1000 kg capacity. During preheating condition the vessel will be heated to a temperature of 500 °C using surface heaters. Thermal analysis was carried out using COMSOL Multiphysics®. Heat transfer studies were carried out for heating and cooling conditions with argon gas as the medium inside the vessel.

Introduction

Molten LiCl-KCl is used as electrolyte in one of the experimental set up at IGCAR. A salt storage vessel is used for storing of purified eutectic mixture of LiCl-KCl. Purified salt is transferred into the storage vessel in molten state at 500°C through heated pipelines. The storage vessel will be preheated to molten salt temperature to prevent freezing of salt in transfer line inside the vessel and this also will avoid thermal shock to vessel walls. The salt transfer line is ½ inch pipe which is heated by tape heaters.

The storage vessel for which the study has been carried out is a cylindrical vessel of vertical orientation with material of construction SS316L. The vessel is having a diameter of 1000 mm, height of 1600 mm and wall thickness 6 mm with torispherical dished ends at top and bottom. Thermal insulation is provided around the vessel as shown in Fig. 1. A central dip pipe is provided up to bottom of vessel for transfer of molten salt. Surface heaters are provided on the vessel bottom dished end and side walls up to a height of 1200 mm from bottom of vessel. Argon is used as inert cover gas since the salt used is hygroscopic and also to prevent oxidation of vessel inside surface at high temperature.

Objective of analysis is to find the temperature distribution inside the vessel, evaluate the temperature along the salt transfer line inside the vessel, to study effect of argon cover gas during preheating condition and to evaluate variation of temperature with time during heating and cooling.

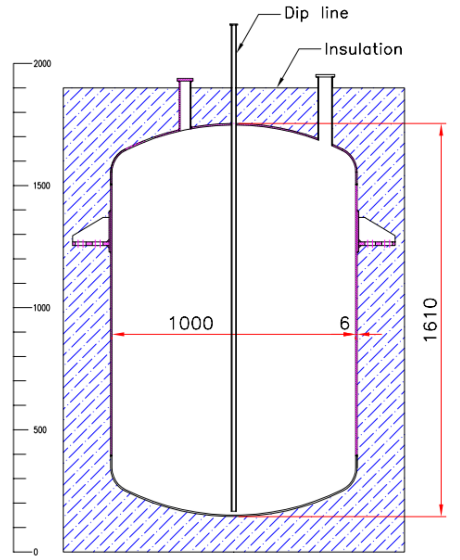

Figure 1.Geometry of vessel

Heating and Cooling Cycle

Heating of the vessel is carried out by energizing surface heaters. Heating rate is limited to 50 °C/hour. The PID controller set points of heaters are changed at this rate. Since surface heaters are having sufficient capacity, the outer wall attains set point temperatures within 15 minutes and the set point is raised once in an hour. During shut down condition the vessel gets cooled by natural convection. The heat is slowly dissipated through insulation.

Numerical Analysis

Numerical analysis was carried out to study the heat transfer in the vessel. The physics used for the model was heat transfer in solids, surface to surface radiation and laminar flow model. One stationary study with natural convection of argon inside the vessel was modelled with conjugate heat transfer analysis. Further, results from the stationary study were used for transient analysis to evaluate the time dependent values. Since the geometry and boundary conditions are symmetric about the axis of vessel, 2D axisymmetric model is used for analysis. Numerical model uses coupled physics of heat transfer and fluid flow.

Physics controlled mesh is used for meshing the model. Mesh with normal density with two boundary layer elements was used for convection study. Triangular mesh was used for solids.

Governing Equations

This numerical model includes all three modes of heat transfer. The governing equations for conduction, convention and radiation heat transfer are solved in this numerical simulation. The equations are given below.

For heat transfer in solids,

$$\rho C_p u.\nabla T + \nabla.q = Q$$

Where, $q = -k\nabla T$, k denotes thermal conductivity and ρ is density of material.

For laminar flow both continuity and momentum equations were solved which is given below,

$$\rho(u.\nabla)u = \nabla.\left[-pI + \mu(\nabla u + (\nabla u)^T) - \frac{2}{3}\mu(\nabla.u)I\right] + F + \rho g$$

And $\nabla.(\rho u) = 0$

Here u denotes the velocity of fluid, μ is viscosity and g is acceleration due to gravity.

Gravity is defined in negative y-direction as volume force and Boussinesq approximation is used in multiphysics coupling [2].

For radiation heat transfer,

$$-n.q = \varepsilon(G - e_b(T))$$

$$e_b(T) = n^2\sigma T^4$$

Where ε is emissivity of surface. Surface to surface radiation heat transfer is calculated for internal surface of vessel and surface to ambient radiation heat transfer is calculated for external surfaces.

Boundary Conditions

Temperature boundary condition and convective heat flux boundary conditions were used in the model. Heater temperature was directly specified at the vessel outer surface. There is convective cooling of insulation outer surface by ambient air. This is specified as heat flux boundary condition. Radiation heat transfer inside the vessel is specified by defining a diffuse surface on all internal surfaces.

Study-1 was carried out to evaluate the heat transfer inside the vessel and insulation when the surface heaters are set to a temperature of 500 °C. In this study conjugate heat transfer model is used. Natural convection inside the vessel is predicted to be in laminar flow regime from Grashoff number [1]. Since the bulk argon temperature is also rising with heating of vessel, maximum temperature difference is assumed as 50 °C for Gr number calculation.

$$Gr = g\beta(T_s - T_\infty){L_c}^3/\nu^2 = 1.78\text{x}10^8$$

Study-2 was carried out to model the transient characteristics of vessel heating and cooling. Actual heating and cooling process is simulated in this model. Modelling convection of argon inside the vessel for this case is computationally intensive and the temperature variation inside argon is not of much interest, so in this case the heat transfer in argon is assumed to be by conduction only and equivalent thermal conductivity of argon is used. Equivalent conductivity model uses an adjusted value of thermal conductivity of fluid which produces similar heat transfer characteristics and fluid flow equations are not solved. Heating is carried out by raising the set points of surface heaters at a rate of 50 °C/hour. This condition is simulated by using piecewise linear function to define the temperature at boundary. Cooling of vessel was modelled by using the solution at heated condition as initial value. Heater temperature boundary condition was disabled in this study which simulate heater switched off condition.

Results and Discussion

Temperature contour of convective heat transfer analysis is shown in Figure 2. Temperature plot of argon gas alone is shown in Figure 3. Internal surfaces of vessel and the molten salt transfer line exchanges heat predominantly by radiation heat transfer. Salt transfer line temperature is well above meting point of salt so salt can be transferred in to the vessel without any freezing issues in the line.

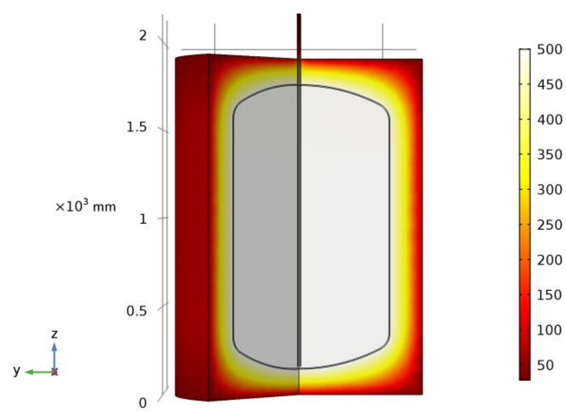

Figure 2. Study-1(Steady state): Temperature distribution in vessel.

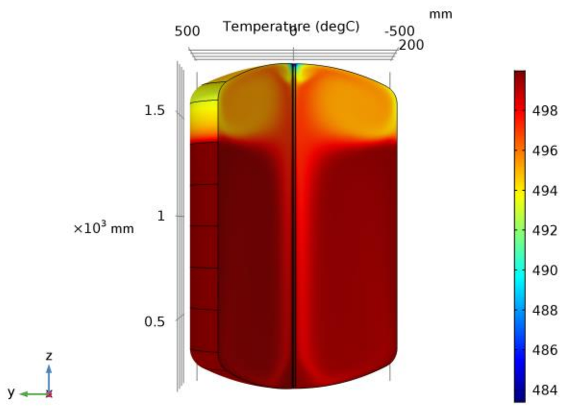

Figure 3. Study-1(Steady state): Temperature distribution in Argon.

Streamline plot of Argon shows two main loops formed as shown in Figure-4. Maximum convective velocity is 0.16 m/s which is near the axis of vessel in downward direction. The top loop of argon continue to be at 5°C less than bulk since it does not mix with bottom loop.

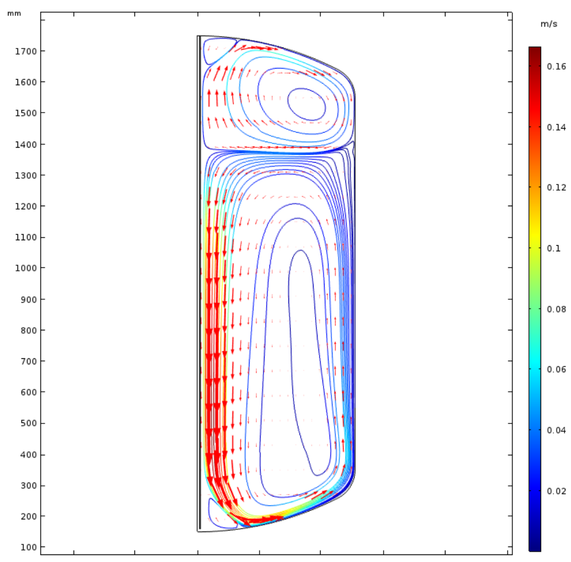

Figure 4. Study-1(Steady state): Streamline plot.

Transient analysis result is shown in Figure-5 which gives the heating and cooling cycle time requirements. Average argon temperature reaches 500°C in 11 hour duration and it takes 24 hours to cool to temperature less than 200°C. Since the vessel is insulated all around, cooling time required is comparatively longer. Heat loss is through convection and radiation heat transfer on insulation outer surface.

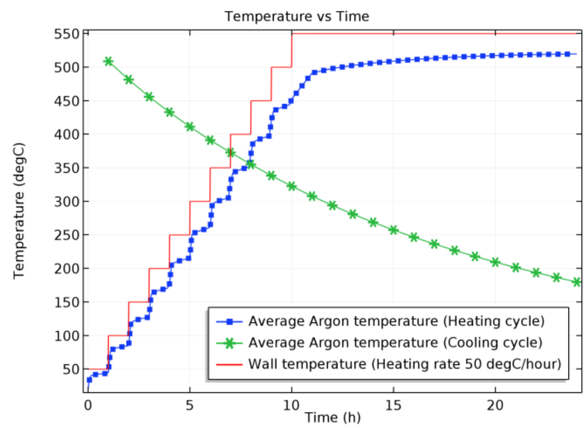

Figure 5. Study-2(Transient): Average argon temperature variation with time in heating cycle and cooling cycle.

Conclusions

Preheating condition of salt storage vessel was numerically modelled. Temperature distribution inside vessel was obtained. Convection in argon is found to be in two loops. Temperature difference within argon gas is found to be less than 8°C. The salt transfer line inside vessel also gets heated by radiation from internal surface of vessel and the temperatures are above melting temperature of salt. Transient analysis shows that vessel can be heated to 500°C in 11 hours and after switching off the heaters, vessel gets cools below 200°C in 24 hours duration. Use of equivalent thermal conductivity method is computationally efficient for similar transient problems.

References

1. COMSOL Multiphysics®, *Reference guide*, **version 5.3.**
2. Yunus A. Cengel, *Heat transfer a practical approach*. McGraw-Hill Education (2002)