TRANSIENT HEAT TRANSFER ANALYSIS TOWARDS A ROBUST DESIGN OF LEAK COLLECTION TRAY FOR SODIUM COOLED FAST REACTORS

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ABSTRACT

Sodium leak collection trays (LCT) are provided below sodium pipes of fast reactors to minimize the hazardous effects of sodium fire. LCT collects the leaked sodium in a hold up vessel, suppress the sodium fire by oxygen starvation and guide the sodium to inert sodium transfer tank. Towards this, a network of carbon steel pipelines is laid out connecting all the LCT to sodium transfer tank, with each pipe having a fusible plug. The plug separates air environment in LCT and argon environment in transfer tank. Woods metal with low melting point is the preliminary choice for the plug. Leaked sodium by virtue of its high temperature melts the plug and drains into transfer tank. Transient thermal hydraulic investigations have been carried out to predict fusing characteristics of the plug. Detailed parametric studies indicate that effective plug melting and trouble free sodium draining are possible for 3 mm thick plug.

Keywords: sodium leak, leak collection tray, anaylitical solution, numerical solution, fusible plug

I. INTRODUCTION

Leakage of hot liquid sodium and its subsequent combustion in the form of a pool fire cannot be completely ruled out in a Fast Breeder Reactor (FBR) plant in spite of many provisions for adequate safety measures. To protect the plant against the hazardous effects of smoke, heat and flame, one of the passive protection devices used in FBR plants is the leak collection trays (LCT). The design of LCT is based on immediate channeling of burning liquid sodium on the funnel shaped 'sloping cover tray' to the bottom 'sodium hold-up vessel' in which self-extinction of the fire occurs due to oxygen starvation. In the secondary heat transfer circuits of FBRs, leakage of liquid sodium from the pipelines is postulated as one of the design basis accidents with probability of occurrence at 10^{-2} per reactor year. LCT collect the leaked sodium in a hold up vessel, suppress the sodium fire due to oxygen starvation and guide the sodium to an inerted 'sodium transfer tank' located at the bottom most elevation of the SGB. The procedure of draining the leaked sodium into the transfer tank has been envisaged as a defense in depth measure against the handling of un-burnt sodium and to guard against larger leak rates than that can be handled by the LCT effectively. Towards this, a network of carbon steel pipelines are laid out connecting all the LCT and the transfer tank through headers in strategic locations, each having a fusible plug. The fusible plug separates the air environment in LCT and argon environment in sodium transfer tank. Woods metal is the preliminary choice for the fusible plug. It is an alloy of 50% Bi, 25% Pb, 12.5% Sn and 12.5% Cd with a melting point of 72°C. The transfer tank is filled with argon at ~ 0.03 bars-g pressure. Both the header and the tank are at room temperature during normal conditions. Leaked sodium by virtue of its high temperature has to heat up the fusible plug to melt the same and drain into the transfer tank. Extensive investigations were carried out by Huber et al. [1] to test these novel sodium catching pan (area of 4.5 m^2) made up of ferritic steel with cover consisting of a folded plate resembling a roof, thereby producing parallel collection drain. Series of experiments were carried out by Newman et al. [2] to investigate the basic principles of operation for sodium fire suppression devices and the effect of drain hole size of fire suppression baffles over a collection tray. Experimental studies were carried out on different types of sodium collection trays by Raju and Kale [3]. They concluded that the area of openings in the tray greatly influences the amount of un-burnt sodium. Parida et al. [4], conducted the experimental study and observed that the collection efficiency of the tray with a single drain mechanism is higher than that of the tray with multiple drain holes. All these studies mainly focused on the different configurations and sizes of the sodium collection trays and fire suppression efficiency. The present study focuses on the draining issue of the collected sodium to sodium transfer tank located at the bottom most elevation of the building to avoid spill over the LCT. Towards this, carbon steel pipelines (called headers) are laid out in the plant connecting all the

LCTs and the transfer tank. The schematic of the typical LCT arrangement under sodium piping is shown in Fig. 1. The drain pipes from LCTs to sodium transfer tank are provided with 25 mm thick mineral wool insulation covered with aluminum cladding, as indicated in the figure. Each LCT is of approximate 1 to 1.2 m length and resting of support members. As mentioned earlier, the fusible plug connects the header and the tank. Both the header and the tank are at room temperature during normal conditions. In the unlikely event of a sodium leak, the leaked sodium by virtue of its high temperature has to heat up the fusible plug to melt the same and drain into the transfer tank, thus mitigating the consequent sodium fire potential. However, it has to be established if the heat capacity of the leaking sodium is adequate enough to heat up the entire header and melt the fusible plug. The main concern is that the sodium should not freeze due to heat loss to the header and the plug.

In the case of sodium freezing in the header, the sodium instead of draining to transfer tank will spill over

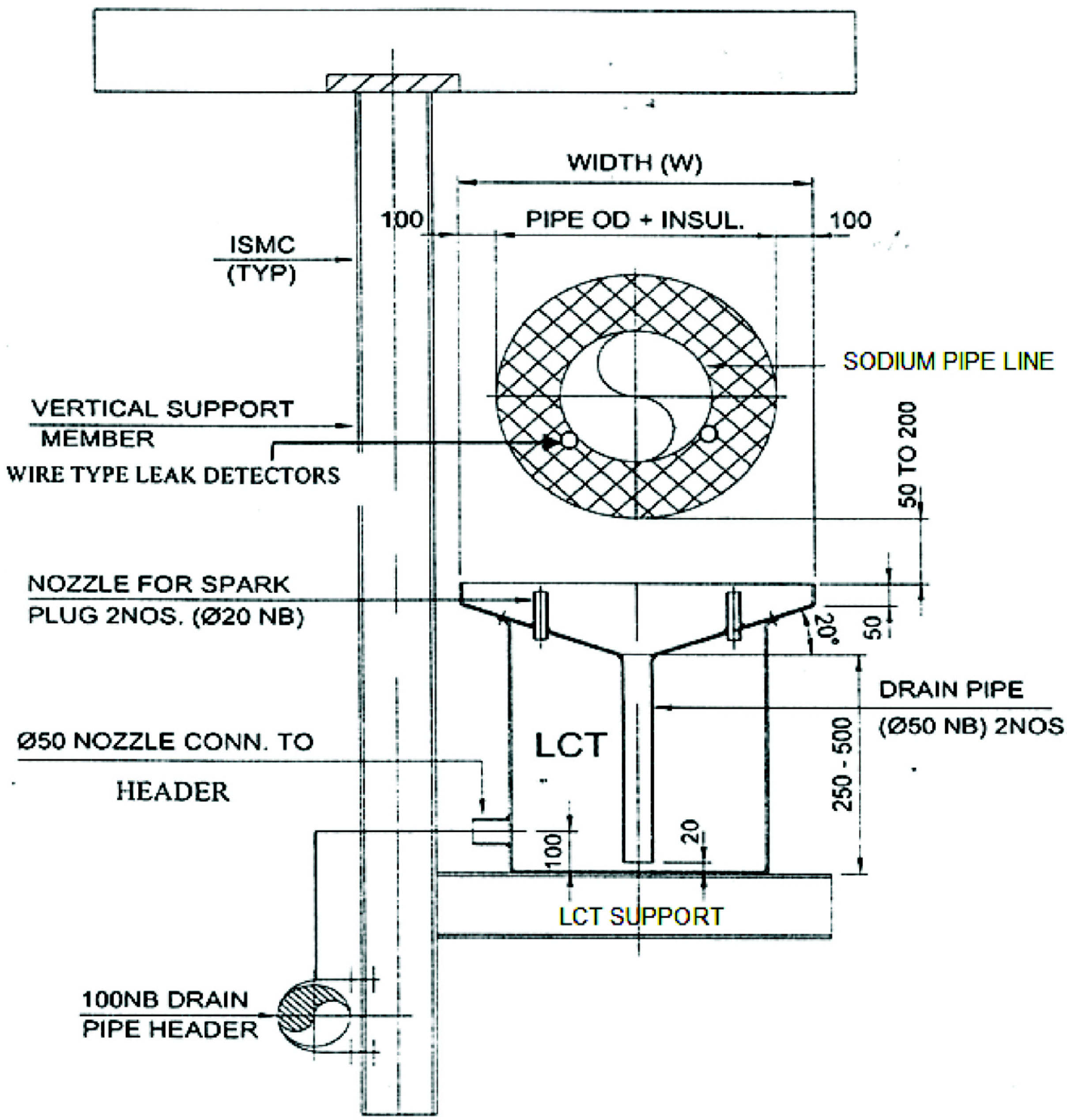


Fig. 1. Arrangement of leak collection tray

the LCT, which is to be avoided. Temperature evolution in sodium depends on the thickness of the header, its diameter, thickness of the fusible plug and its heat capacity.

Computational heat transfer analysis has been carried out to predict the temperature evolution in the header system of 100 NB schedule - 40 and schedule - 10 pipe lines with woods metal fusible plug. The temperature of the leaking sodium has been varied systematically from 150°C – 350°C to investigate the risk of sodium solidification and understand the stages of melting propagation of fusible plug. The physical model of the system is shown in Fig. 2.

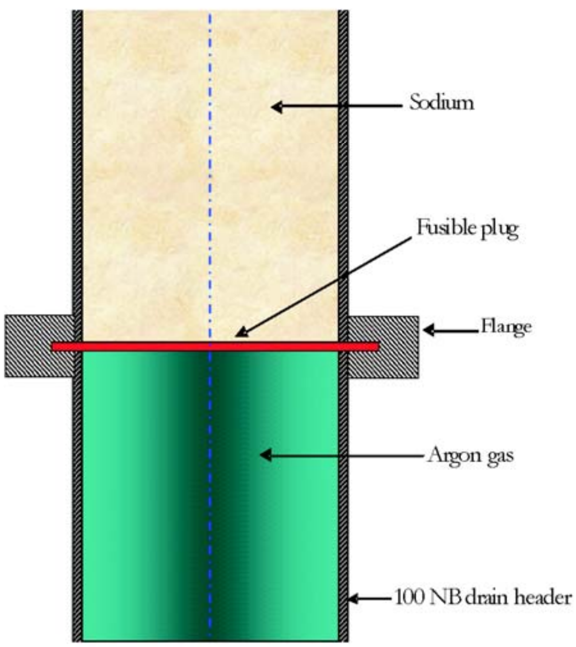


Fig. 2. Physical model of the system

II. RESULTS AND DISCUSSION

Heat transfer analyses are carried out to investigate the desired thickness of woods metal fusible plug to perform it duties without solidification of sodium in the pipe line. A well insulted 100 NB Sch 40 pipe with bottom disk of woods metal is taken as physical domain. Simulations are carried out to time required for sodium to reach the solidification temperature. The critical parameters of the study are the pipe thickness of 3 mm and 6 mm, nominal diameter of the pipe 100 mm, 200 mm and 300 mm with initial temperature of sodium varied from 150°C to 350°C and of steel at 30°C. Analytical solution of the heat equation for melting:

A. Assumptions

- Disk is approximated as semi-infinite media in which there is 1-D heat condition
- Solid and liquid layer remains at fusion temperature throughout melting
- Constant thermo physical properties

B. Governing equation

At the interface of liquid and solid rate of heat conduction into solid must be balanced by the latent heat released at interface per unit surface area.

Thickness of the disk ‘S’ decreases with time‘t’

$$\rho\, h_{sf} \frac{dS}{dt} = q_{cond}$$

$$q_{cond} = \frac{k\,(T_f - T_i)}{(\pi \alpha t)^{1/2}}$$

where

T_f = Fusion temperature of woods metal, K

T_i = Initial uniform temperature, K

α = thermal diffusivity, m^2/s

ρ = Density, kg/m^3

h_{sf} = Latent heat of fusion of woods metal, J/kg

Time required to melt woods-metal plug of different thicknesses obtained by solving the above equation are given in Table 1.

Table 1. Time required to melt woods metal plug of different thicknesses

Thickness, mm	Time, s
1	1
2	5
3	11
4	19
5	30
6	43
7	59
8	77
9	97
10	120

III. NUMERICAL ANALYSIS

A. Analysis with 100 NB Sch 40 pipe with 6 mm fusible plug of Woods metal

In this case the initial conditions are taken as t = 0 s, $T_{Na} = 150°C$, $T_{SS} = 30°C$ $T_{plug} = 30°C$ and thermal insulation also at 30°C with outer surface exposed to ambient of convective heat transfer coefficient, $h = 5\ {}^{W}\!/_{m^2}\,K$. It is found that the sodium temperature was well below the 100°C within initial 5 s, whereas the analytical solution of the time to melt the plug is about 43 s. entire heat capacity of sodium was used to increase the thermal capacity of steel pipe. Hence this option was ruled out. Similar results also predicted by bulk sodium and steel calculation as follows.

The bulk temperature of steel and sodium is calculated for different combinations of pipe as follows.

$$T_B = \frac{(mc_p)_{Na}\,T_{Na-\mathrm{Intial}} + (mc_p)_{SS}\,T_{SS-\mathrm{Intial}}}{(mc_p)_{Na} + (mc_p)_{SS}}$$

From this it is obvious the bulk temperature of sodium and steel remains well below the solidification limit of the sodium for the 100 NB Sch 40 pipe. Hence, other option of reduced thickness with same diameter is envisaged to reduce the heat capacity of the pipe material so that the bulk temperature is increased above the solidification temperature. From these tables it was concluded that the 100 NB Sch 10 pipe is sufficient to have bulk temperature $> 100°C$. Hence, it is selected for further analysis.

B. Analysis with 100 NB Sch 10 pipe with 6 mm fusible plug of Woods metal

As discussed above, the lowest possible temperature for the leaking sodium is 150°C. When this sodium flows in the header, the equilibrium temperature of the sodium and the header is 112°C. Thus the initial temperature for sodium (T_{Na}) and header (T_{CS}) is $112°C$ and the plug temperature (T_{plug}) is 30°C. With 25 mm thick mineral wool insulation on the outer surface of the header, the external natural convective heat transfer coefficient on the insulation surface is $5\ W/m^2\,K$. In this case the additional steel flange to hold the fusible plug also considered with extended pipe, which is filled with argon gas. The conduction through argon gas also considered to realize the actual case of heat transfer process. The temperature variation with time on the top and bottom surfaces (Bot) of fusible plug is depicted in Fig. 3.

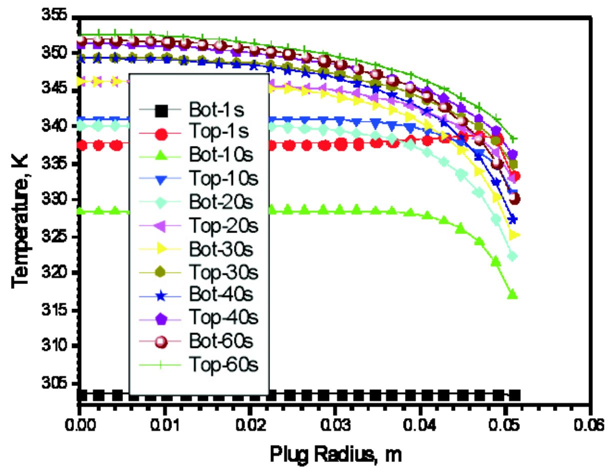


Fig. 3 Variation of temperature on inner and outer surfaces of woods metal fusible plug at different time intervals (T_{INTIAL} Na, CS = 112°C)

Latent heat of melting of woods metal is taken account for calculation purposes. It is clear from this figure that the entire thickness takes around 40 s to melt, which is much closed to the analytical value obtained from solution of the governing equation of the heat.

Fig. 4 shows the transient evolution of the sodium and fusible plug bottom region temperatures just above the center of the fusible plug. It is clear from these figures that the sodium temperature falls much below the solidification temperature of sodium (98°C). Time taken for at least 3 cm radius of the fusible plug to melt completely is estimated as 40 s and by this time solidified sodium of 9 cm is found to occur over the plug and continuing to grow. It is also important to notice that the sodium temperature just above the fusible plug is at least 20°C lesser than its melting point and its evolution has become flat, indicating that with any amount of time (read with any amount of further sodium arrival at 112°C above the sodium column) the sodium plug formed will not re-melt.

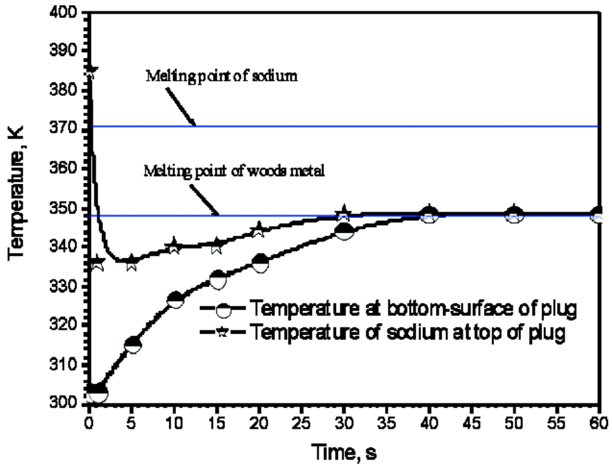
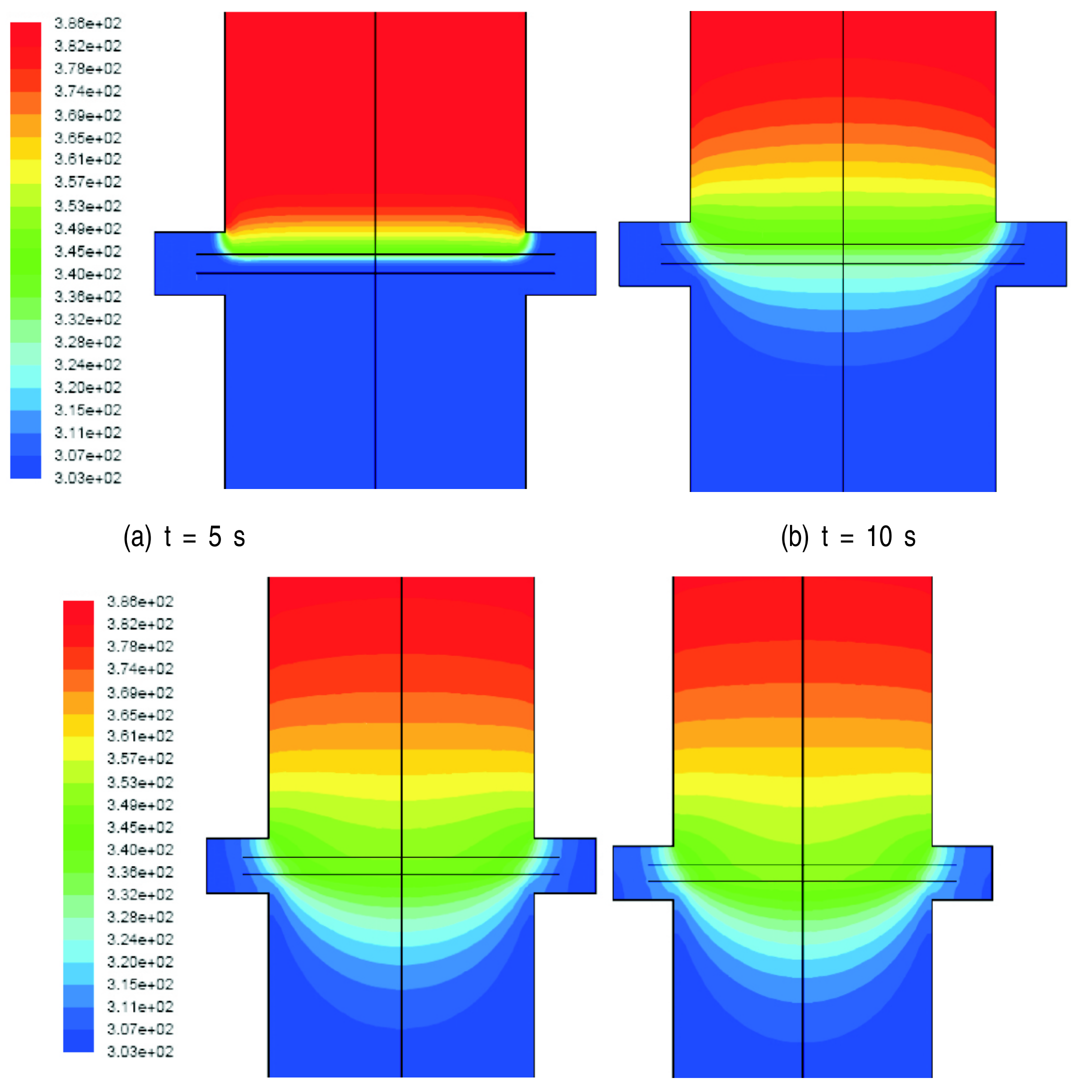


Fig. 4. Sodium and plug temperature at the plug center

Isotherms obtained at different time intervals are depicted in Figs 5 (a-d). It is also clear from these figures that the sodium temperature falls below the solidification temperature within the melting process of the plug. Hence it may be highlighted from this study that the sodium may plug the pipe line before it fuses the plug.

Now new option to overcome this problem, the reduction in thickness of plug is envisaged to reduce the heat capacity of plug and hence avoiding sodium to reach below solidification temperature. The results are highlighted in the next paragraph.



(a) t = 5 s (b) t = 10 s

(c) t = 30 s (d) t = 40 s

Fig. 5. Isotherms in the pipe line (Temperature scale in K)

C. Analysis with 100 NB Sch 10 pipe with 3 mm fusible plug of Woods metal

To find out the solidification process of the sodium during that period, the isotherms are plotted for the two time steps and are presented in Fig. 6 (a-b). It was found that the sodium temperature falls to 85°C during melting. However, the thickness of the layer in which the solidification starts reduces to just 10 mm. In all theses cases studied above the solidification process of the sodium is not considered for analysis proposes. The temperature variation on the plug surfaces at different time intervals are given in Fig. 7. It can be seen that the plug takes 10 s to melt, which is again very close to the analytical obtained time period. Hence, in the final simulations the fusion of woods metal plug and solidification of the sodium with all possible heat transfer paths has been considered and results are highlighted in next paragraph.

Variation of the temperature on top and bottom surface of the woods metal fusible plug of and isotherms at different time intervals are depicted in Figs. 8 and 9 respectively. It is evident from these

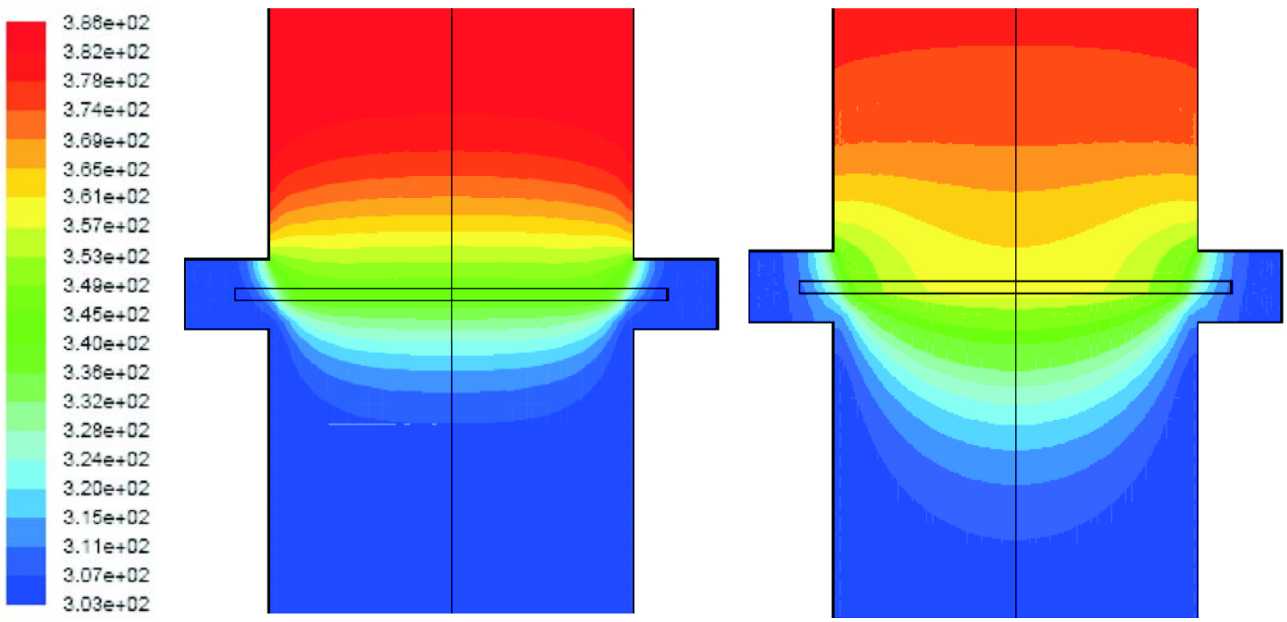


Fig. 6. Isotherms in the pipe line (Temperature scale in K)

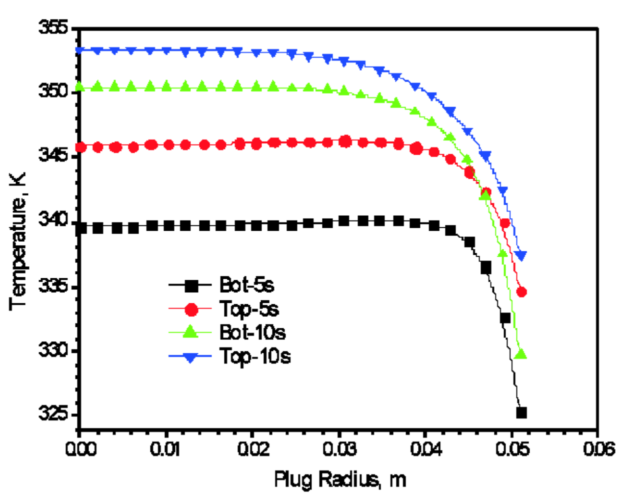


Fig. 7. Variation of temperature on inner and outer surfaces of woods metal fusible plug of 3 mm at different time intervals (T_{INTIAL} Na, CS = 112°C)

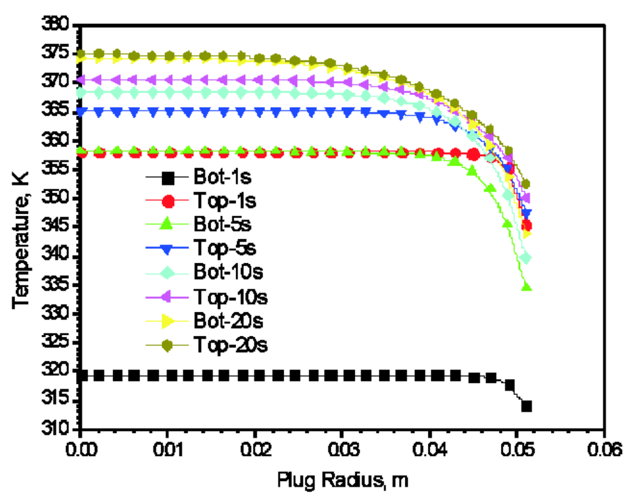
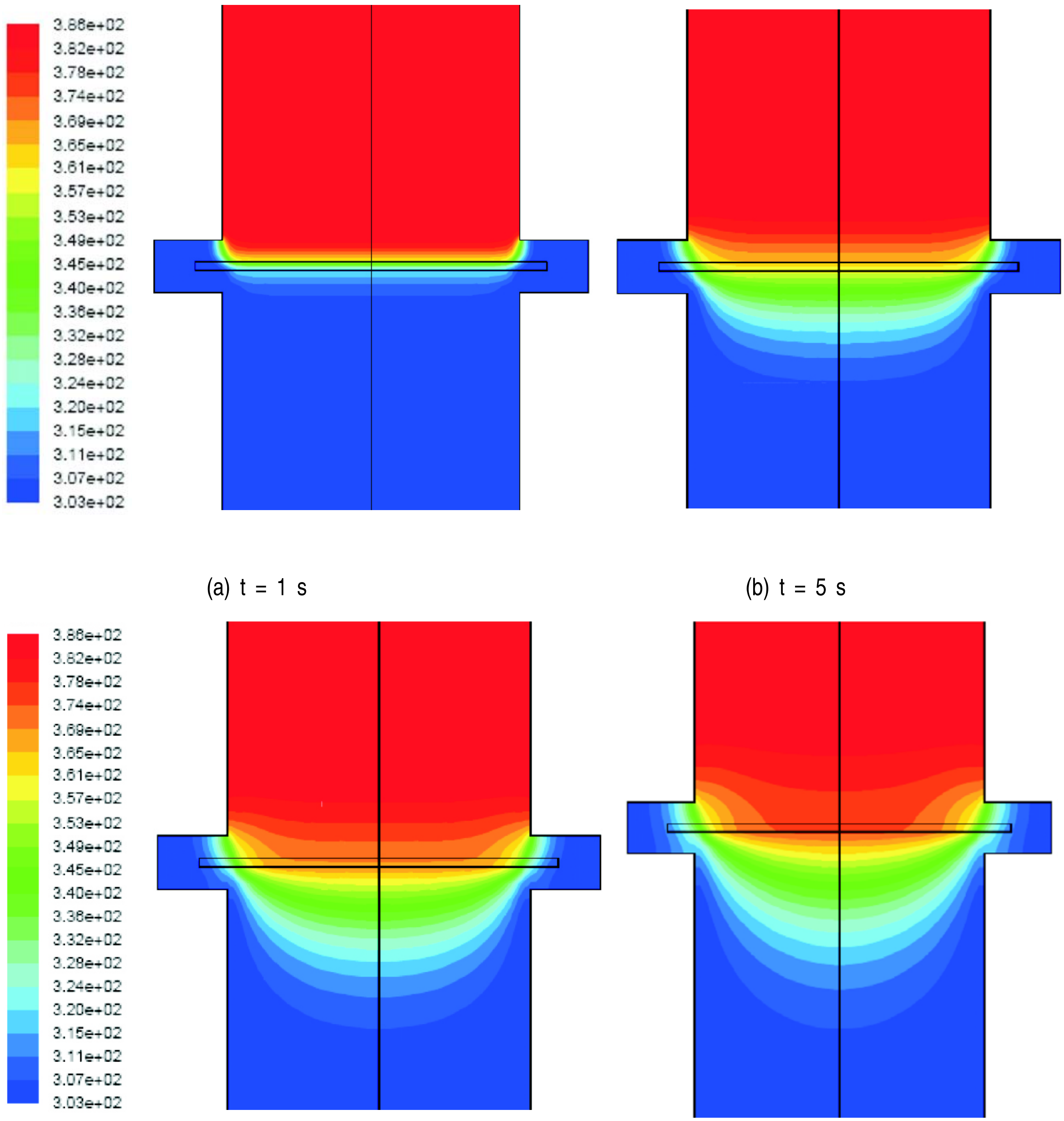


Fig. 8. Variation of temperature on inner and outer surfaces of woods metal fusible plug of 3 mm at different time intervals (T_{INTIAL} Na, CS = 112°C)



(a) t = 1 s (b) t = 5 s

(c) t = 10 s (d) t = 20 s

Fig. 9. Isotherms in the pipe line (Temperature scale in K)

figures that within 5s, the fusible plug will melt and the same time the sodium temperature within the 3 mm layer will start solidifying at interface of plug. However, it can be seen that if at all plug does not fuse up to 10 s also, the sodium temperature in the adjacent layer will again rise and will be in the liquid state and hence the sodium will eventually drain to storage tank without plugging into the drain pipe.

IV. CONCLUSION

Transient thermal analyses have been carried out to arrive at the suitable thickness of the woods metal fusible plug required in the header – transfer tank junction, for effective melting of the fusible plug and complete draining of the leaked sodium. Numerical results obtained are compared with analytical solution for fusion time of the woods metal disk and found to be in very good agreement. Different combinations of pipe sizes with different thickness of woods metal fusible plug are studied. It is found that the 100 NB Sch 10 pipe with glass wool insulation of 25 mm on it having 3 mm fusible plug is sufficient for complete trouble free draining of the leaked sodium.

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