

Natural Convection Heat Transfer Enhancement Using Cooling Pipes in the Heat Generating Debris Bed



Vidhyasagar Jhade, Anil Kumar Sharma, D. Ponraju, B. K. Nashine and P. Selvaraj

Abstract The whole core meltdown scenario is considered as a beyond design basis accident with a probability of occurrence less than 10^{-6} per reactor year. To prevent and mitigate such a hypothetical severe accident, in fast breeder reactors, research has been focused on accommodating the destroyed core debris within the primary containment boundary. An in-vessel core catcher is provided to receive the fuel debris arising out of core meltdown and disperses it uniformly, thus enabling safe and adequate heat transfer by natural convection. The present study is focused on the thermal hydraulic analysis of in-vessel core catcher. A 3-D numerical analysis has been carried out in the lower plenum of the fast reactor. Turbulence is modeled using the standard $k-\varepsilon$ turbulent model. The Boussinesq approximation is assumed for liquid sodium. The heat source is assumed to have spread on the heat shield plate and has a total volume of 5.12 m^3 with inbuilt decay heat source. The mathematical model is validated with the available benchmark experimental results in the literature. The existing design of core catcher plate is modified by providing cooling pipes in the top collection plate with different configurations to assess the cooling capability of the debris by natural convection. The temperature and velocity contour are obtained to observe the flow field established above the heat source in the sodium pool. It has been found that new design of core catcher improves the natural circulation of sodium toward the center of CC and more than $50 \text{ }^\circ\text{C}$ temperature decrement is observed in upper heat shield plate.

Keywords Natural convection · Boussinesq approximation · Core catcher · Severe accident

Nomenclature

g Gravitational acceleration (m/s^2)
 T Temperature, k
 u, v, w Velocity along r, θ and z direction in m/s

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Greek Symbol

β Isobaric cubical expansion coefficient of fluid, K^{-1}
 ρ and ρ_0 Density (kg/m^3) at T and T_0 temperature

1 Introduction

Whole core meltdown scenario in nuclear reactors is considered as a beyond design basis event (BDBE) with a probability of occurrence less than 10^{-6} /reactor year. After the Fukushima Dai-Ichi accident, it has gained more interest from researchers and scientists around the world. Melting of core occurs due to failure of cooling system to remove heat generated in the core. The excess temperature in core is essentially due to loss of coolant flow, i.e., unprotected loss of flow accident (ULOFA) or increase in the core power, i.e., unprotected transient overpower accident (UTOPA) [1]. UTOFA or ULOFA initiates the melting of subassembly (SA). The molten fuel along with the liquid sodium will fragment and is expected to settle at the bottom of the main vessel in the absence of any melt retention arrangement. This fragmented core debris constantly generates heat because of decay of fission products. The core debris will damage the integrity [2] when it comes in contact with the main vessel. To avoid such event, a core retention assembly called core catcher (CC) is placed below the grid plate. A chimney along with top heat shield plate (HSP) and core catcher plate all together is named as core catcher. It retains the core debris and enhances the decay heat removal by natural convection. The CC can be in-vessel or ex-vessel. Ex-vessel CC, where debris is collected and transfers outside the main vessel but within the containment building. A separate cooling system is provided for ex-vessel type CC [3, 4] which is extensively used in water-cooled nuclear reactors. In-vessel CCs are used in liquid metal cooled fast breeder reactors (LMFBR). In a sodium-cooled fast reactor (SFR), in-vessel CC is a favorable choice because sodium has a tendency to react violently with water and air. The CC for Indian Prototype Fast Breeder Reactor (PFBR) which has a total 500 MWe capacity is designed to take care of the mechanical load of all 181 SA and thermal load of 7 SA.

Hung [5] carried out the comprehensive numerical study to examine the decay heat removal capacity without any active heat removal mechanism. They have concluded that a passive air cooling system is capable to remove the decay heat by conduction, convection, and radiation. They have implemented the extended liner in the inner vessel. It prevents the downward flow from partition to the core area and improved the convective heat transfer. However, modification in pool geometry will change the entire reactor vessel design and economically it is not beneficial. Alternatively, the modification in CC would be a more favorable approach such as two different design of chimney of CC used by Sharma et al. [6] or multi-layer CC plate concept for SFRs suggested by Sudha et al. [7]. It is essential to note that

material compatibility with liquid sodium has to be evaluated along with the manufacturing feasibility for the entire life of the reactor.

To ensure the sufficient cooling during operation and shutdown condition, multiple sources of the power supply are incorporated in SFR. However, inherent passive safety during core meltdown situation has been studied by Verma et al. [8], under varying number of decay heat exchangers. They have proposed that relocation of core debris at the gap between the core-periphery and inner vessel reduces the thermal load on the CC plate. Also, concluded that integrity of inner vessel will not be hampered even when half of the core debris settled in the gap. This thermal load can also be reduced when, rather than distributing the entire core debris on a single plate, use of multiple plates could be advantageous. Sharma et al. [9] show that using multiple plates increases the thermal load carrying capacity of core catcher. It was assumed in their study that the heat load is distributed uniformly in all plates. Essentially, it is not possible for the debris to settle equally on all plates. The passage needs to be provided so that the debris can flow down the plate as proposed in a numerical study of Rakhi et al. [10]. Also, it has been concluded in their study that multiple trays improve the natural circulation in lower plenum. However, providing such opening will make the upper heat shield plate (HSP) annular. Additional support is needed for each annular plate and that increases the complexity in the lower plenum. To overcome such complexity and provide more realistic design, a new concept of core catcher is presented in the current study as shown in Fig. 1. Hollow pipes have been protruded at the top of HSP, which are closed from the top, and liquid sodium flows inside this pipes. Three-dimensional simulations have been carried out for the lower plenum of a reactor to evaluate the change in the coolability of core catcher under core disruptive accident. The results obtained from the present analysis have been compared with existing design.

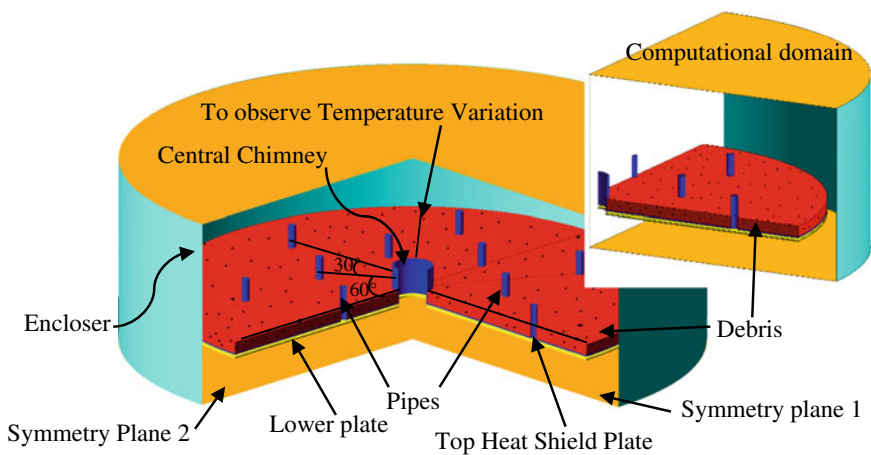


Fig. 1 Physical model of CC assembly

2 Mathematical Modeling

For the present numerical analysis, the 1/4th sector of complete lower plenum has been considered as the computational domain of interest. The domain has taken all the important components of the lower plenum of reactor viz. HSP, chimney, lower tray, etc. The material used for core catcher assembly is SS316LN. Important properties of SS316LN, debris and liquid sodium are shown in Table 1.

Following are the assumptions considered during the analysis-

1. Boussinesq's approximation is assumed to hold good for liquid sodium and variation in density with temperature is solely important for producing buoyancy effect.
2. All other physical properties, except density, are assumed to be invariant.
3. Liquid sodium is considered as viscous, Newtonian, and incompressible.

2.1 Physical Mode

The physical model is shown in Fig. 1, comprises an enclosure whose diameter is 7.7 m and height 2.5 m. Pipes are extruded on a top HSP at the radial distance of 1.263 m for inner, and 2.256 m for the outer row from the center. Each row has six pipes, whose internal diameter is 100 mm, at an angle of 60° while the angle between inner and outer rows pipe is 30°. The thickness of upper HSP and the lower plate is 20 mm, and they are separated by a distance 30 mm. The height of pipes is considered equal to chimney height, i.e., 480 mm.

2.2 Governing Equations

A three-dimensional mass, momentum, and energy equation [11] along with equation for turbulence kinetic energy (k) and dissipation rate (ϵ) [12]

Boussinesq equation for calculating density

$$(\rho - \rho_0) \cong -\rho_0 \beta g (T - T_0)$$

Table 1 Properties of material used in the model

Material	ρ (kg/m ³)	C_p (J/kg K)	K (W/m K)	μ (kg/m s)	β (K ⁻¹)
SS316LN	7749.5	576.5	21.15	–	–
Debris	6158.3	743.23	33.735	–	–
Liquid sodium	766.76	1259.4	65.1	2.35×10^{-4}	2.9183×10^{-4}

2.3 *Boundary Conditions*

1. Adiabatic wall with no-slip boundary condition for the top and bottom of enclosure

$$Q = 0; u = v = w = 0$$

2. Isothermal along with no-slip boundary condition was imposed at the peripheral wall of enclosure

$$T_{\text{wall}} = 673 \text{ K}; u = v = w = 0$$

3. Constant heat generation per unit volume of debris.

$$\ddot{q} = 5 \text{ MW}/5.12 \text{ m}^3$$

Initial condition $u = v = w = 0$ and $T_0 = 673 \text{ K}$.

3 *Methodology*

For the present numerical simulation, a commercial CFD code FLUENT is used to solve transient governing equations. Finite volume method is used for the discretization of governing equations. The SIMPLE algorithm for pressure-velocity coupling has been considered. The second-order upwind method is used for pressure term while the first order is used for convection term. The solution is assumed to converge when the residual of continuity and momentum fall down to 10^{-4} whereas for energy it is 10^{-6} . The Boussinesq approximation is used to consider the change in density of liquid sodium.

3.1 *Grid Independence Test*

To have a solution, which is independent of grid size, a grid independence test was performed. The three different types of grids 1,00,745, 1,36,578, and 1,48,404 have been exercised for the test and variation of velocity was plotted at the vertical center axis of a chimney as depicted in Fig. 2. From the plot, it can be seen that variation of velocity is insignificant after 1,36,578 nodes grid. Therefore, 1,36,578 size grid has been chosen for further analysis.

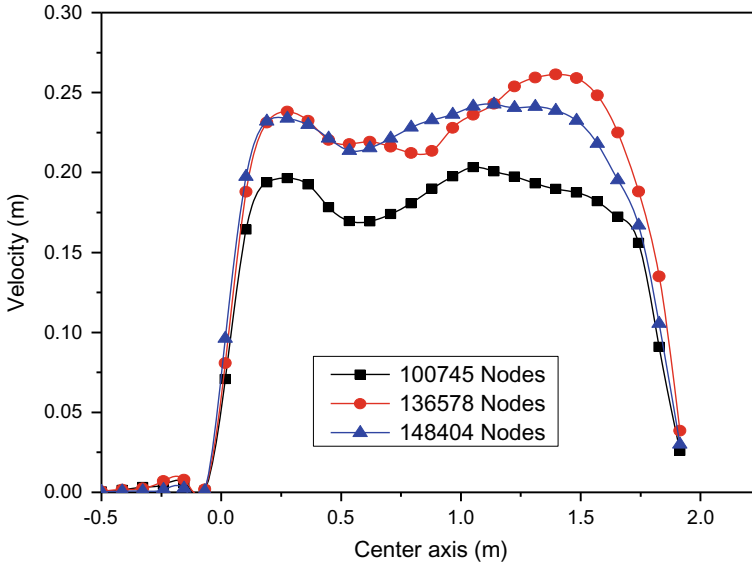


Fig. 2 Grid independence test

3.2 Validation

The numerical model used for the present study has been validated with experimental result of PATH experimental facility [13]. PATH facility is a 1:4 scale water model of the PFBR and is exclusively dedicated to post-accident thermal-hydraulic experiment. An 18 kW heat load is imposed on the top heat shield plate and variation of temperature along the symmetry axis was plotted after 2 h as shown in Fig. 3. From the graph it can be seen that the numerical results provide good agreement with the experimental data.

4 Results and Discussion

The present work is focused on the three-dimensional (3D) numerical analysis of turbulent natural convection in the lower plenum of the PFBR. The objective of the present numerical study is to provide more realistic fluid flow characteristic and heat transfer phenomena in a modified design of core catcher. Results and plots are taken when the steady state attained and temperature of CC plate reached the maximum. The temperature contour and velocity vectors for the existing CC design have been presented in Fig. 4. It has been found through the analysis that when there are no pipes protruded in the top plate, liquid sodium gets heated and a large anti-clockwise vortex was formed above the debris bed. It has also revealed from

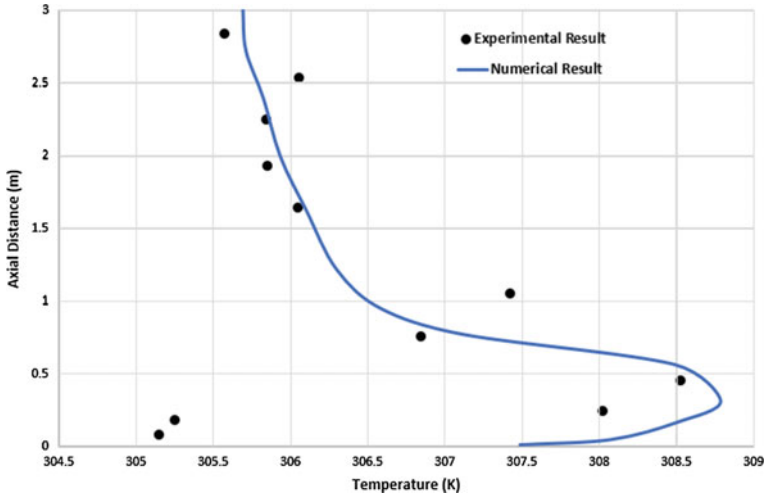


Fig. 3 Validation of numerical result

temperature contour that region below the lower tray has not observed any significant changes in the temperature. The fluid is stagnated in this region and the change in temperature is very marginal.

Providing the pipes at regular interval on the upper plate improves the heat transfer by natural convection around the pipes. This can be seen in the temperature contour as depicted in Fig. 5. A change in temperature contour around the pipes can easily be noticed along with the change in temperature at a lower region below the plate. A velocity vector at the symmetry plane shows the enhanced natural circulation and increase in velocity of liquid sodium to 0.459 m/s as depicted in Fig. 6. Circulation of sodium inside the pipes can also be seen in this figure, in which both the pipes have similar zone inside them. The sodium enters from the bottom of pipe, gets heated, and rises to upward. This sodium transfers the heat to the upper pool sodium through conduction from pipes. The authors have also observed that due to

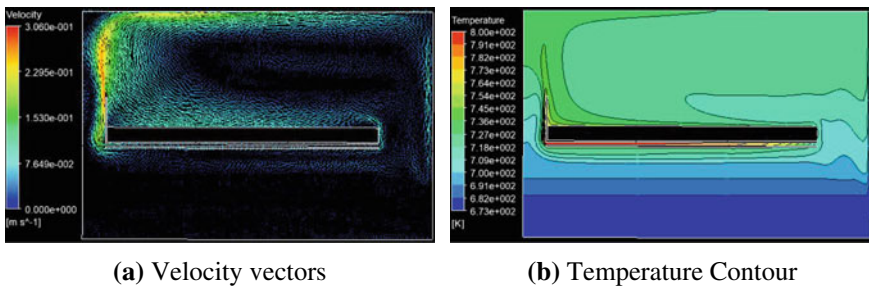


Fig. 4 Velocityvectors and temperature contour for existing CC

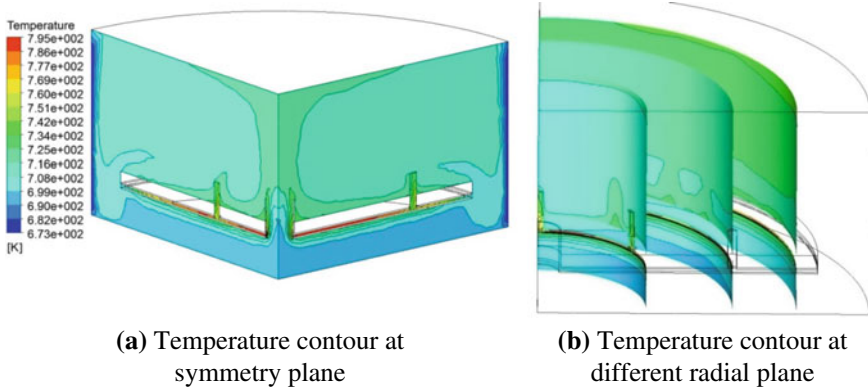


Fig. 5 Temperature contour for present analysis

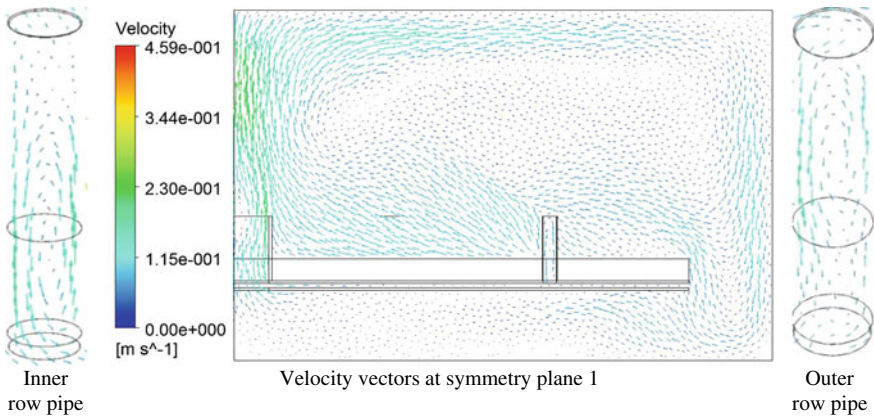


Fig. 6 Velocity vectors with pipe

the chimney and inner row pipes, the temperature on top HSP is less toward a center of chimney compared to the peripheral side. This can be seen by plotting temperature variation on the top HSP. Figure 7 shows the temperature variation on top HSP for both designs of CC assembly. It has been also found that the area weighted average temperature of upper plate decreases to 786.2 K, compared to existing design where it was 843 K. The present study shows the improvement over existing design in terms of coolability.

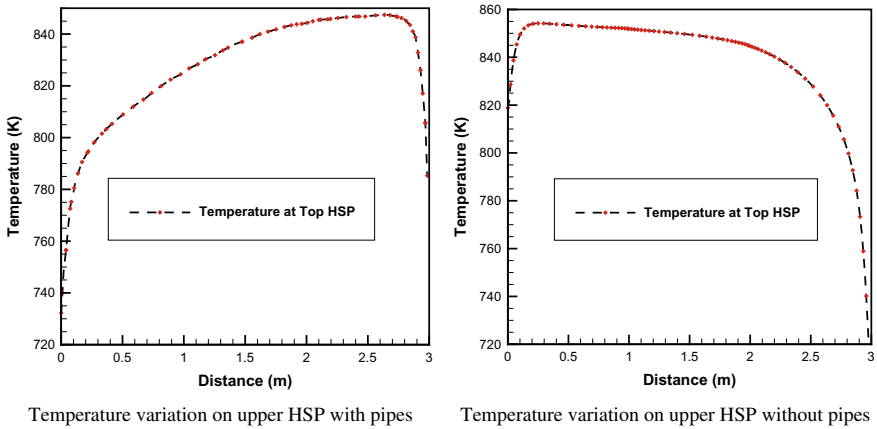


Fig. 7 Variation of temperature on upper HSP for both the cases

5 Conclusion

A transient numerical analysis was carried out on a 3D model of core catcher with pipes at the top of HSP. Natural convection in lower plenum of LMFBR has been analyzed to assess the coolability of the new design of CCP under whole core meltdown scenario. The $k-\epsilon$ turbulence model has been used for the simulation, and the governing equations are discretized using finite volume scheme. The current study has revealed that using pipe at the top plate will enhance the natural circulation of liquid sodium. The results obtained from the study have been compared with existing design. The area weighted average temperature at the upper plate is found out to be 786.1 K. The present study shows decrease in temperature in HSP of more than 50 °C over existing CCP design. A variation of temperature shows improved natural convection toward chimney side than the periphery of the plate. The circulation of sodium inside the pipes increases the heat transfer from debris to upper pool sodium. The present numerical analysis provides the basis to further extend present work toward optimum core catcher plate design for future SFR.

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