NUMERICAL INVESTIGATION FOR THE EFFECT OF GUIDE PANEL ON HEAT TRANSFER FROM STEEL CONTAINMENT

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ABSTRACT

Steel containment of nuclear reactor is surrounded by thick RCC concrete structure. In the annulus gap formed between the steel containment and RCC structure, a guide panel is provided to enhance the heat transfer from the steel containment during accident conditions. The effect of guide panel and its distance from steel containment on heat transfer is required to be studied. Therefore, a typical steel containment of nuclear reactor along with RCC structure and guide panel has been modelled using COMSOL code. Steady state analysis has been carried out to study the significance of guide panel (with and without guide panel) on heat transfer from containment. The effect of location of guide panel on heat transfer was also carried out for two different distances from steel containment.

INTRODUCTION

In nuclear reactor, containment is the last barrier for the release of radioactivity during severe accident conditions. Worldwide containments are designed to withstand the pressures postulated for design basis accidents (like Loss of Coolant Accident / Main Steam Line Break accident), while keeping in view of minimizing the escape of radioactive species and also for the external hazards such as flood, tornado, airplane crash etc [1].

Containment material could be concrete or steel or steel lined concrete, however each type has its own merits and demerits [2]. Double containment made up of concrete material is generally preferred as it provides both leak tightness and shielding, however it is difficult to remove the energy released into containment, for longer period of time, during severe accident conditions due to low thermal conductivity of concrete.

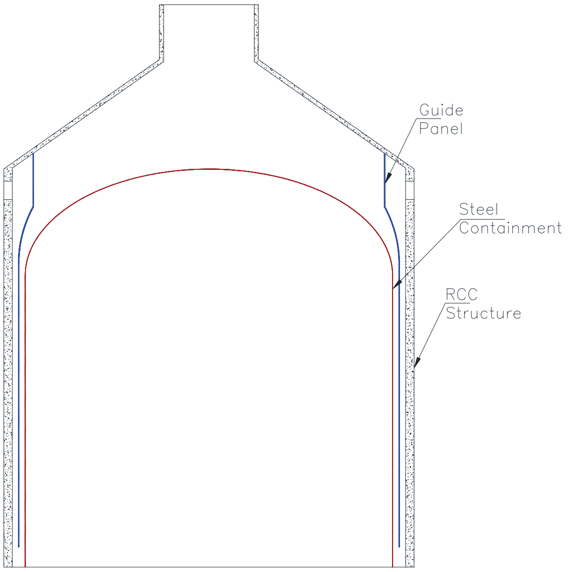

Fig.1 : Schematic diagram of Steel Containment and RCC structure

Steel containments have high load bearing capacity and high degree of leak tightness at higher pressures. To take the advantage of both, new containments are designed with steel containment surrounded by a thick RCC concrete structure (outer containment) for providing biological radiation shield for neutrons and gamma radiation. In case of Loss of Coolant Accident / Main Steam Line Break accident / severe accident, heat can be removed from containment in passive means [3]. For this, a guide panel is provided, in the annular gap between the steel and outer containment, to increase the heat transfer from the steel containment. The heat transfer from the containment is depends upon annulus air flow through the gap between steel containment and guide panel. Hence the effect of annulus air gap on heat removal rate has been studied for a typical steel containment (Fig.1).

NUMERICAL INVESTIGATION

In case of Loss of Coolant Accident / Main Steam Line Break accident, high enthalpy steam is released into the containment which causes rise in containment pressure and temperature. The steel containment temperature also rises due to high thermal conductivity of steel and it transfers heat to the annulus gap air by natural convection. An opening is kept at the top of RCC structure, through which air flows into the annulus gap and takes the heat from steel containment surface and flows out through the top of RCC structure. A guide panel is kept in the annulus to ensure the flow of air over maximum length of steel containment. Since the heat sink is atmosphere, heat transfer from steel containment takes place by passive means. The heat transfer from the containment is depends upon annulus air flow through the gap between steel containment and guide panel. Hence the effect of annulus air gap on heat removal rate has been studied for a typical steel containment using Finite Element based Multi-physics Code COMSOL 4.0.

NUMERICAL METHODOLOGY:

(i) Governing equations

Based on the Navier-stokes time averaged equations and using Bousssinesq approximation for Reynolds stresses, differential equations governing viscous turbulent flow field can be written as

$$div(\rho \boldsymbol{u}) = 0 \tag{1}$$

$$div(\rho \boldsymbol{u} u) = div(\mu_{eff}\, grad u) - \frac{\partial p}{\partial x} + f_x \tag{2}$$

$$div(\rho \boldsymbol{u} v) = div(\mu_{eff}\, grad v) - \frac{\partial p}{\partial y} + f_y \tag{3}$$

where ρ is the fluid density, μ_{eff} the effective viscosity, $\boldsymbol{u}$ the mean flow velocity field, p the pressure and u, v are the mean components of flow field in the x and y directions, respectively. The terms f_x , f_y denote body forces for the unit volume of fluid. The turbulence is modelled by the two equation $k-\varepsilon$ model which is easily implemented and has a wide application in engineering problems.

In the current case, the only body force is acting in y direction due to the buoyancy effect induced by variation of density of fluid i.e. air because of thermal gradients. Thus, the problem is quite complex in nature because of strong momentum-energy coupling.

(ii) Computational domain and boundary conditions

To simplify the problem, the current case is solved as 2-D axisymmetric problem with the typical computational domain along with applied boundary conditions are shown in Fig 2. Since the velocity field develops only because of buoyancy, the direction of flow is not known a priori. For such scenarios, open boundary conditions are most suitable in which fluid can both enter and leave the domain on boundaries with this type of condition.

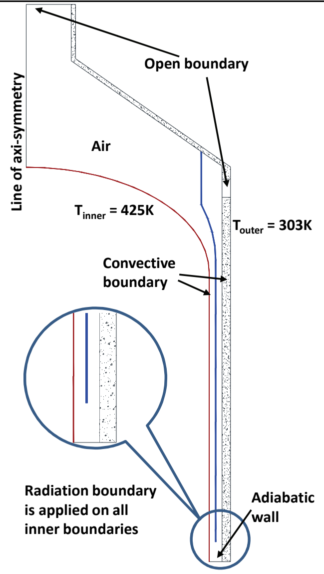

Fig.2 : Computational domain of steel containment.

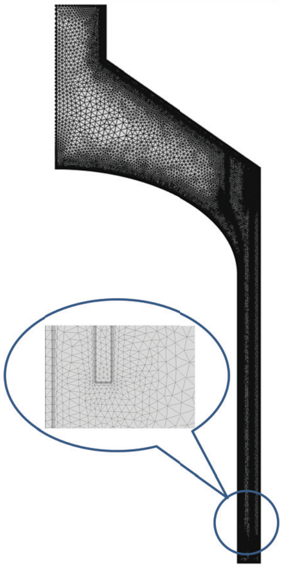

Fig.3 : Grid arrangement with boundary layer

Because of the complex geometry, unstructured grids with appropriate boundary layers (Fig.3) have been employed to adequately capture momentum and thermal gradients. The total mesh count is approx. 50,000 elements. Conjugate heat transfer module with K-epsilon turbulence model and radiative heat transfer has been used. Although complete accident analysis is transient in nature, in this work, steady state analysis was carried out to study the effects of guide panel. Therefore, the peak temperature and condensation heat transfer coefficient was given as the boundary condition at the inside surface of steel containment. At the outside surface of concrete structure, heat transfer takes place by convection. The problem was solved on an 8 noded Xeon server and it takes almost 4 hours to solve a single case.

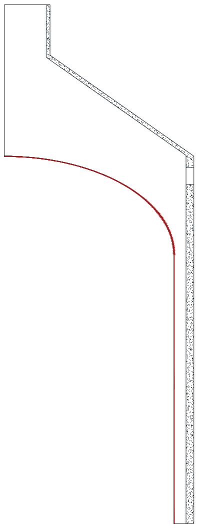

Fig.4 : Arrangement without guide panel

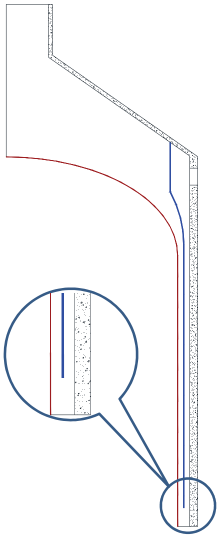

Fig.5 : Arrangement with guide panel located in the middle of annulus gap

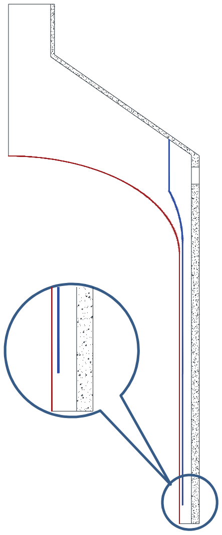

Fig.6 : Arrangement with guide panel in the annulus gap located near the steel containment

RESULTS AND DISCUSSION

To study the importance of guide panel and effect of location of guide panel analysis has been carried out for three cases, which are (i) without guide panel (Fig.4), (ii) With Guide panel located in the middle of annulus gap (Fig.5) and (iii) With Guide panel in the annulus gap located near the steel containment (Fig.6).

Case-1 : Without Guide panel

Figure 7 and 10 show the temperature contour plot and velocity vector plot for the case without guide panel. From these figures it may be observed that maximum temperature has gone up to 423K but the rise in average outlet temperature of air at the stack is 313.14K only. The observed peak velocity at the outlet of stack is around 4m/s but the average velocity is around 2.87m/s. Total mass flow rate of air through the steel containment by way of natural convection is around 257.5kg/s and the heat removal rate is around 2.6MW.

In this case, the air only removes the heat from the top portion (dome region) of the steel containment. Heat removal from the perimeter wall of steel containment takes place through the outer concrete wall. The temperature in annulus gap also rises because of formation of air pocket takes place and air circulation within the pocket ensures the uniform temperature of air in the gap. Air flow, in this case, takes shortest route. Thus the heat from steel containment wall surface is transferred to concrete wall and from that heat is convected out to atmosphere. Therefore the wall temperature at the bottom of the concrete wall goes very high up to 403K at inside surface and at outer surface wall temperature goes up to 330K. In this case the concrete wall temperature exceeds the permissible limit of 333K for concrete structures. Beyond this temperature the concrete loses it water which leads to loss of strength.

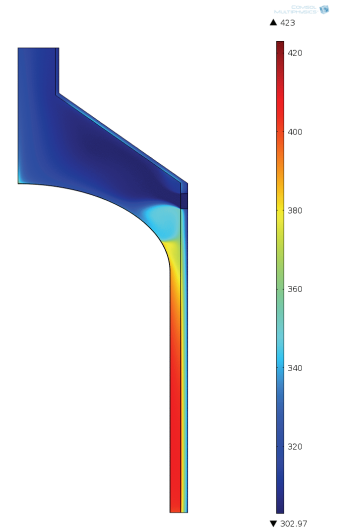

Fig.7 : Temperature contour plot for case-1

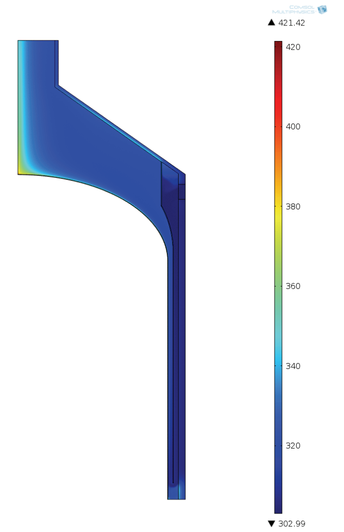

Fig.8 : Temperature contour plot for case-2

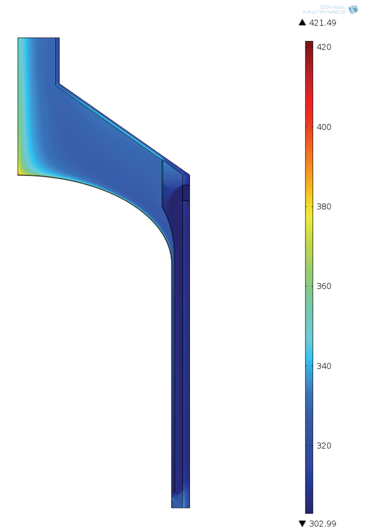

Fig.9 : Temperature contour plot for case-3

Case-2 : With Guide panel in the middle of annulus gap

Figure 8 and 11 show the temperature contour plot and velocity vector plot for the case with guide panel located in the middle of annulus gap. From these figures it may be observed that maximum temperature has gone up to 421.29K and the rise in average outlet temperature of air at the stack is 329.4K. The observed peak velocity from the contour plot is around 7.1m/s but the average velocity of air at the outlet of stack is around 4.34m/s. Total mass flow rate of air through the steel containment by way of natural convection is around 389.4kg/s and the heat removal rate is around 10.3MW.

Since the guide panel is provided between the steel containment and concrete wall, air flow is allowed to flow over the full height of the steel containment, therefore the flow takes longer route than the previous case. Heat from the steel containment is transferred to the air between the containment and guide panel, which rises up due to buoyancy. As the air flows up, it creates the low pressure at the bottom, which draws the air from the top of concrete wall through the gap between the guide panel and concrete wall. Therefore, the air flows from top to bottom along the concrete wall side and rises up along the steel containment side and after taking heat it exits through the stack. In this case no air pockets formation takes place and passively the heat from the steel containment is removed. The guide panel also receives heat from the steel containment through radiation, which in turn gives the heat to fresh downward flowing air. The wall temperature at the bottom of the concrete wall goes up to 337.5K at inside surface and at outer surface wall temperature goes up to 313K.

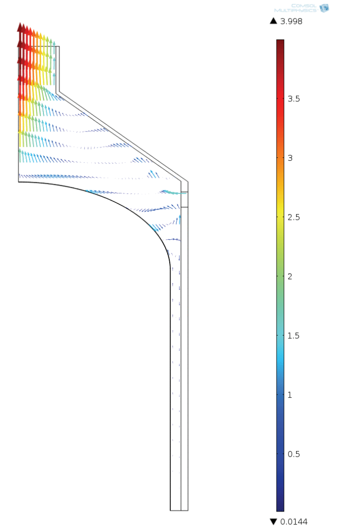

Fig.10: Velocity vector plot for case-1

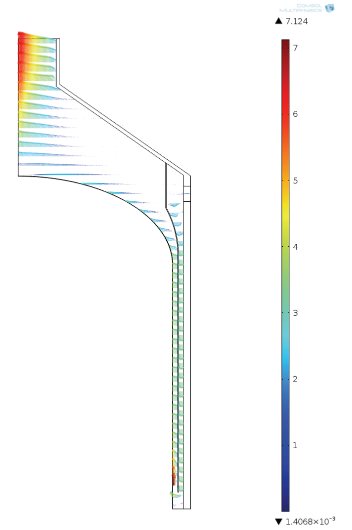

Fig.11: Velocity vector plot for case-2

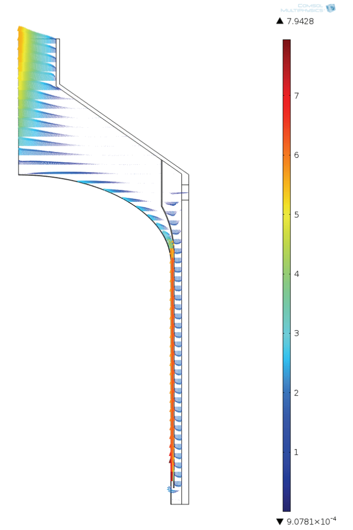

Fig.12: Velocity vector plot for case-3

Case-3: With Guide panel in the annulus gap near the steel containment

Figure 9 and 12 show the temperature contour plot and velocity vector plot for the case with guide panel located near to steel containment at a distance 1/4th of annulus gap between steel containment and concrete wall. From these figures it may be observed that maximum temperature has gone up to 421.49K and the rise in average outlet temperature of air at the stack is 335.9K. The observed peak velocity from the contour plot is around 7.94m/s but the average velocity of air at the outlet of stack is around 3.65m/s. Total mass flow rate of air through the steel containment by way of natural convection is around 327.3kg/s and the heat removal rate is around 10.78MW.

In this case, the effect of the guide panel location on heat transfer can be observed from the temperature and velocity contour plots. The velocity has been increased as the air flow area is decreased which results in increase in exit temperature. However, the heat removal rate is marginally higher than previous case. The wall temperature at the bottom of the concrete wall goes up to 338.6K at inside surface and at outer surface wall temperature goes up to 313.5K.

CONCLUSION

One of the merits of using steel containment is that it can be cooled passively by providing the guide panel in the annulus gap between steel containment and RCC structure. From this study, the guide panel allows the air to pass over the full length of the steel containment and also transfers heat to air by receiving the heat from the steel containment through radiation. In this way, the guide panel provides enhanced heat removal passively by 4 times than when guide panel is not provided. It also helps in avoiding the formation of local air pockets which leads to increase in concrete temperature. The effect of location of guide panel (i.e. gap between steel containment and guide panel) on the heat transfer has been studied for two cases, however the heat removal rate for both the cases are almost same.

REFERENCES

[1] S.S.Bajaj,2002,"CONTAINMENT SYSTEMS FOR INDIAN PHWRS", 1st National Conference on Nuclear Reactor Safety, November 25-27, 2002, Mumbai INDIA

[2] Adolf WALSER, 1980,"AN OVERVIEW OF REACTOR CONTAINMENT STRUCTURES", Nuclear Engineering and Design 61 (1980) 113-122.

[3] T.L. Schulz, 2006,"Westinghouse AP1000 advanced passive plant", Nuclear Engineering and Design 236 (2006) 1547–1557.