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Cellular Convection in Vertical Annuli at roof slab of Fast Breeder Reactor (FBR)

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Abstract: In the pool type Fast Breeder Reactors the roof structure is penetrated by a number of pumps and heat exchangers which are cylindrical in shape. Argon gas in reactor is sandwiched between the free surface of sodium and the roof structure and can flow in the annular space between the components and roof structure forming a thermosyphon. These thermosyphons not only transport heat from sodium to roof structure, but also result in cellular convection in vertical annuli resulting in circumferential temperature asymmetry of the penetrating component. There is need to know the temperature asymmetry as it can cause tilting of the components. Experiments were carried out in an annulus model to predict the circumferential temperature difference. Three-dimensional CFD analysis was carried out using COMSOL 3.4 and PHOENICS 3.2 and the results compared with the experimental data. This paper describes the experimental details and the theoretical analysis carried out in COMSOL and PHOENICS.

Keywords: Fast reactors, sodium, annuli, upper closure, circumferential temperature difference, Rayleigh number

1. Introduction

In Fast Breeder Reactors, many mechanical components such as Pump, Intermediate Heat Exchanger (IHX), Rotating plugs, etc. penetrate the top closure of the reactor with argon as cover gas above free sodium level at 803 K. These penetrations form vertical annular gaps, which are open at the bottom to hot cover gas and closed at the top (Fig. 1). The top closure is cooled by air through an external circuit to maintain its temperature at 393 K to minimize sodium deposition in the annuli (melting point of sodium~370K). Due to the temperature differences between the top closure and bottom entrance of annulus, there is natural convection of argon gas in the annuli. As the hot gas moves up it loses heat to the annuli wall, becomes denser and starts coming down and exits through another circumferential location (Fig. 1). This phenomenon result in setting up of natural convection cells in the annulus and is also referred to as Cellular Convection. This type of phenomena is noticed even for annuli filled with liquids such as water[1] and Sodium[2]. This results in non-uniform circumferential temperature distribution in the penetrating component, leading to deflection due to uneven expansion and impacting their functional requirement.

This type of phenomenon has also been encountered in the sodium cooled Fast Breeder Test Reactor (FBTR), Kalpakkam. Tilting of the reactor vessel by about 8 mm occurred due to a circumferential temperature difference of 80 K in the rotating plug annuli[3]. If the tilt is more than 10 mm, it would affect movement of control rods. Experiments were carried out in an annulus model to predict the circumferential temperature difference. If the circumferential temperature difference is exceeding the acceptable limits, the annulus gap can be changed / cooling the can be provided accordingly to meet the acceptable values. A two dimensional analysis for annulus model for PHENIX Fast Breeder Reactor annulus model has been carried out[4]. Their analysis involves two codes, one dealing with convection in the annuli coupled to another conduction code for the wall. Three-dimensional CFD analysis was carried out using COMSOL 3.4 and PHOENICS 3.2 and the results compared with the experimental data.

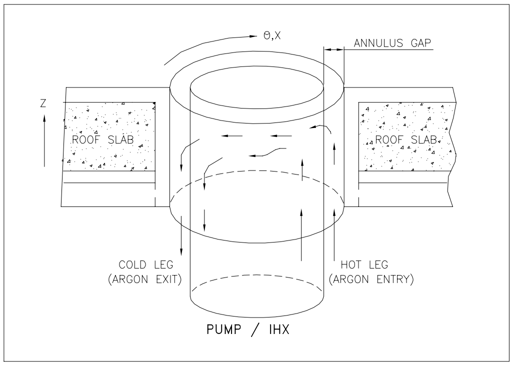

Fig.1 Natural Convection of argon in annulus

2. Experiments carried out

The experiments were carried out in the test vessel without sodium. The test vessel with hot plate was kept at the sodium level as shown in Fig. 2. The temperature of bottom plate was maintained at 803K equal to sodium temperature. The upper vessel annulus height is 1000mm and the upper vessel can be dismantled into inner and outer shell. The upper vessel simulates the penetration of a pump/intermediate heat exchanger. To achieve different axial temperature difference in the annulus wall, a surface heater has been put in the top of upper vessel outer shell. Eight numbers of thermocouples are distributed radially at each height. The argon cover gas pressure inside the test vessel is maintained at 100 millibar above atmosphere as in the reactor. Fibre glass wool insulation is provided over the circumference of the upper and lower vessel and upper vessel inner shell to minimize the heat loss. Fig. 3 shows the circumferential temperature distribution at the bottom of the annuli for a bottom plate temperature of 803 K at different axial temperature difference. The increase in circumferential temperature difference increases the natural circulation.

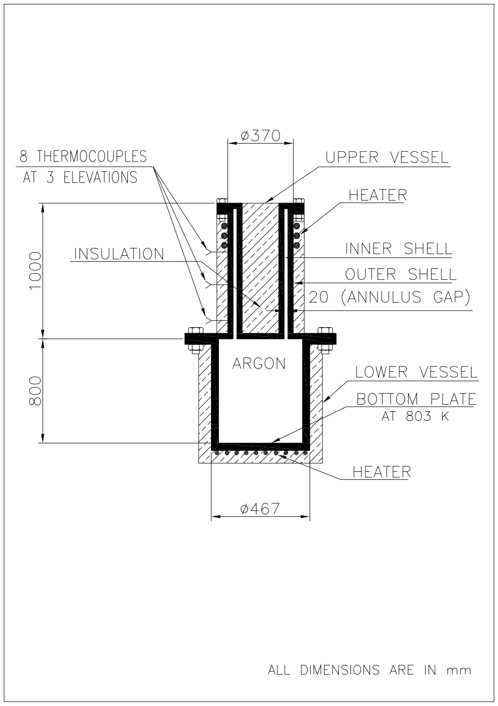

Fig. 2 Experimental set up

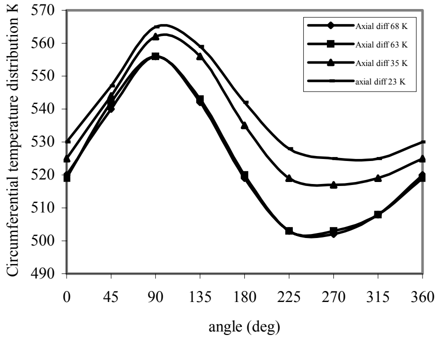

Fig. 3 Circumferential temperature distribution at the bottom of annuli for heated plate at 803K at different axial temperature difference

3. Numerical Model

The numerical solves the continuity, Navier-stokes and energy equation for argon in three-dimensions taking the temperature as a boundary conditions for heated plate temperature of 803K. Boussinesq approximation was used to account for buoyancy effects in the momentum equation. The governing equations are given below:

Conservation of mass:

$$\nabla.\bar{u} = 0$$

$$\bar{u} = (u, v, w)$$

Conservation of momentum with boussinesq approximation:

$$\nabla.\left(\bar{u}\bar{u}\right) = \gamma\nabla^2\bar{u} - \nabla P + g\beta\left(\Delta T\right)\delta_{i3}$$

$$\delta_{i3} = 0 \text{ (if } i \neq 3\text{)}$$

$$= 1 \text{ (if } i = 3\text{)}$$

Conservation of energy:

$$\nabla.\left(\bar{u}T\right) = \frac{k}{\rho C_p}\nabla^2 T + \frac{Q_v}{\rho C_p}$$

For simulating turbulence, the k-ε model proposed by Launder and Spalding (1974) is employed. The transport equations for k and ε are:

$$\nabla \quad (\bar{u}\,k) = (\bar{u}_k \;\nabla^2 k) + S_k$$

$$\nabla \quad (\bar{u}\,\varepsilon) = (\bar{u}_\varepsilon \;\nabla^2 \varepsilon) + S_\varepsilon$$

Where,

$$\nabla = \left(\hat{i}\frac{\partial}{\partial X}, \hat{j}\frac{\partial}{\partial Y}, \hat{k}\frac{\partial}{\partial Z}\right)$$

$$\nabla^2 = \left(\frac{\partial^2}{\partial X^2} + \frac{\partial^2}{\partial Y^2} + \frac{\partial^2}{\partial Z^2} \right)$$

$$u_t = \frac{C_\mu k^2}{\varepsilon}$$

where C_μ is considered as 0.09.

$$\alpha_t = \frac{u_t}{\Pr_t}$$

$\Pr_t$ is taken to be 1 as the enhancement in the heat transfer due to turbulence would be in the same as the enhancement in the momentum transport.

The upper vessel inner shell was assumed as adiabatic. The boundary conditions are as shown in Table 1. The heat transferred to the outer annulus wall is by convection, and is dissipated to the surrounding by conduction through wall and convection to atmosphere air outside the insulation cladding. Since the annular gap area facing the heat source at the bottom is relatively less and annulus wall are at the temperature of about 373 K, radiation was not considered in the thermal hydraulic analysis.

3.1 Use of PHOENICS

Computational Fluid Dynamic analysis for annulus model was carried out using the computer code PHOENICS Ver. 3.2. The ratio of annulus gap to its radius is small and thereby the curvature effects are negligible. Hence the flow analysis is carried out in developed space of Cartesian coordinate in x,y and z plane as shown in Fig. 4. A grid pattern of 100*19*129 was considered. The developed space represents the annulus, the boundary conditions on the left and right sides of the slab is imposed with cyclic boundary conditions. Boussinesq approximation was used to account for buoyancy effects in the momentum equation. The k-epsolon model has been used to solve the model

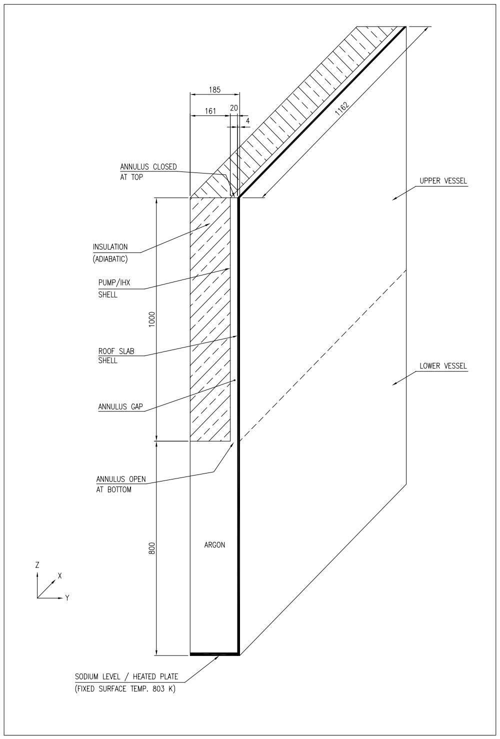

Fig. 4 Developed space of annulus and test section for PHOENICS model

3.2 Use of COMSOL Multiphysics

Three-dimensional CFD analysis was carried out using COMSOL 3.4. The analysis was carried out in 3D polar cylindrical coordinate in r,z and θ as shown in Fig. 5. In COMSOL multiphysics, combined model of weekly compressible Navier-Stokes and general heat transfer model has been used to simulate the experimental setup. In COMSOL free mesh option has been used and it is termed as unstructured mesh, using triangular elements. The solver used in this simulation was the stationary BICGSTab linear system solver.

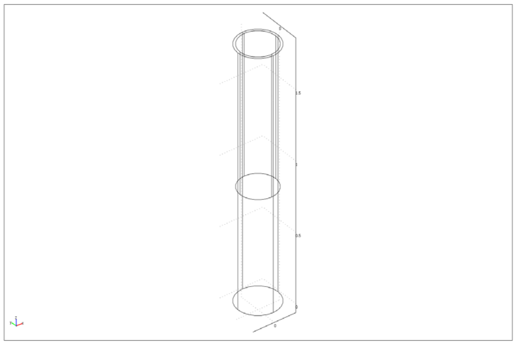

Fig. 5 Physical geometry of COMSOL model

The results of velocity profile obtained from COMSOL at angle 0 deg and angle 180 deg as shown in Fig 6 (a) & 6 (b) respectively. The natural convection occurs has been seen clearly that argon gas rises at one end at high temperature and losses heat at the top, as the density reduces and it falls at the other end. Fig 7 shows the temperature profile at the entrance of annulus. Hot argon enters at one end (Red) and the cold argon exits at the other end (Blue).

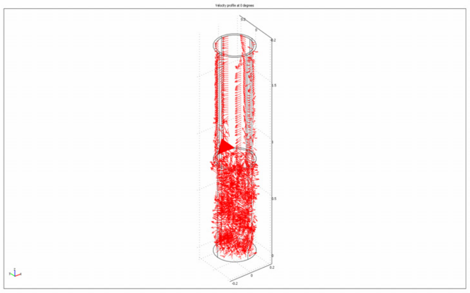

Fig 6 (a) Velocity profile at angle 0 deg.

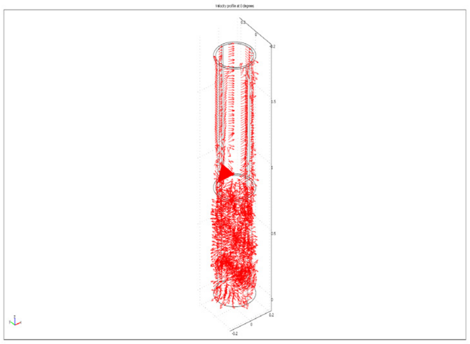

Fig 6 (b) Velocity profile at angle 180 deg

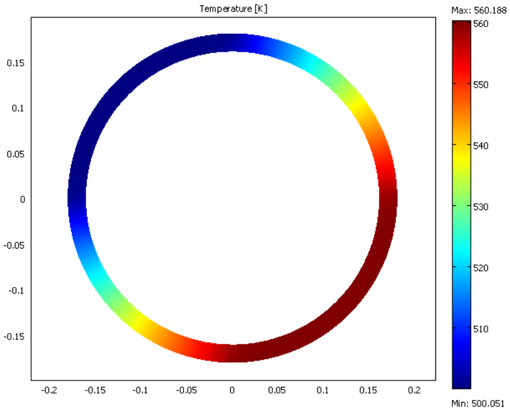

Fig 7 Temperature profile at the entrance of annulus (Z=0.8m)

4. Results compared with experimental and CFD analysis using PHOENICS & COMSOL

The circumferential temperature difference for the axial temperature of 68K has been compared with experimental and analytical results as shown in Fig. 8.

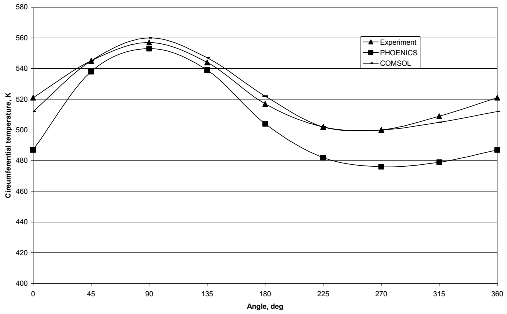

Fig. 8 shows the Comparison of experimental with CFD analysis results for circumferential temperature distribution at the bottom of the annuli for the axial temperature difference of 68K.

For an axial temperature difference of 68K, the maximum circumferential temperature difference obtained by experiment was 57K. The maximum circumferential differences estimated by analysis using PHOENICS & COMSOL are 77K and 60K respectively. Considering the uncertainty in the experiments and assumptions in the theoretical analysis, the comparison is satisfactory. The results predicted by COMSOL is more close to the experimental result

5. Conclusions

Experiments on the circumferential temperature difference in vertical annuli, open at the bottom and closed at the top, have been studied for application to sodium cooled FBR. Analysis with COMSOL and PHOENICS code has been carried out. It is felt that modeling using COMSOL multiphysics is easy and computational time is less compared to PHOENICS and the results are also close to experimental results. It is felt that the future estimation of circumferential temperature difference for other components in the roof slab can be carried by using COMSOL modeling and the results found to be conservative.

6. References

1. Vijayan, P.K., et al., Studies on Natural convection in vertical annuli heated from below, *Proceedings of 8th International heat transfer conference, SanFransisco,California,USA*, Vol.4, 1986
2. Timo, D.P., 1954. Free convection in narrow vertical sodium annuli KAPL-1082, Knolls Atomic power laboratory, Scenectady, New York .
3. Srinivasan, G., et al., Thermo-mechanical behaviour of FBTR reactor vessel due to natural convection in the cover gas space, *Fourth International conference on Liquid metal engineering and technology*, Vol. 1, 1998
4. Goldstein, S., Joly, J., Thermal analysis of Penetrations of a LMFBR. *Fifth SMIRT*, 1979
5. Hemanath.M.G., et al., Cellular convection in vertical annuli of Fast Breeder Reactors, *Annuls of Nuclear Energy Journal*, 2007

7. Appendix

Table 1: Boundary conditions used for CFD

No.	Geometry	Boundary Conditions
1	Heat source	Fixed surface temperature, 803 K
2	Annulus outer shell	Heat loss to atmosphere through wall and insulation
3	Top plate	Adiabatic
4	Annulus inner shell	Adiabatic