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Three dimensional analysis of natural convection in a narrow vertical annulus closed at top and opened at bottom

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ABSTRACT

Natural convection flow and heat transfer in a narrow vertical annulus located centrally above a reservoir has been studied. The fluid in the reservoir is heated up by a hot, isothermal bottom end wall. The flow characteristics has been analysed by observing flow topologies and contours of temperature. Results are presented for Rayleigh numbers in the interval [2000–20000]. The flow consist of steady, periodic and quasi periodic regimes. The stream trace plot in each case is found to contain correct number of singularities of different types, which is required for satisfying the Hunts criterion. The annulus geometry selected for the study is a simplified model of the narrow annulus of a typical nuclear reactor design. The variation of circumferential temperature obtained from the study provides a relevant data for the design of nuclear reactors and similar systems.

1. Introduction

Concentric annular passages having relatively small radial gaps, with full or partial opening at one of the end faces and an air tight sealing at the other end face, find application in a variety of engineering systems, such as chambers in process equipments, vessels in nuclear reactors, and several others. Often, natural convection heat transfer by a fluid medium through partially opened annular spaces is complex due to the occurrence of multiple modes of flow as a consequence of changes in the operating conditions. This pose challenges in design, analysis, optimization and operation of systems involving this phenomenon.

A motivation for the present investigation is a typical natural convection heat transfer problem existing in liquid sodium-cooled pool type Fast Breeder Reactors (FBR). Fig. 1 shows the cross sectional view of a pool type fast breeder reactor vessel. It consists of a vertical reactor vessel having a sealed concrete cover (called roof slab) at the top. Certain number of cylindrical shell structures containing devices for performing specific tasks related to the operation and safety of the reactors are passing through the roof slab into the reactor vessel while a small portion remains on the top of roof slab to facilitate control. The gap between the shell and the opening provided in the roof slab is kept sufficiently small to allow proper insertion and alignment of the shell. Top end of the annular gaps is sealed, whereas the bottom is open to the hot Argon gas maintained above a pool of hot sodium stored in the reactor vessel. The region above the free surface of the sodium pool together with the annular gap forms an enclosed space. The cooling of the roof slab generate buoyancy force to cause natural convection flow and heat transfer from the hot sodium pool.

A review of the literature in natural convection flow and heat transfer in annulus shows that the first pioneering numerical investigation of natural convection in a vertical cylindrical annulus is done by Davis and Thomas [1]. The two dimensional N-S equation was solved using vorticity - stream function formulation for an axisymmetric geometry. They have established the capability of simulations in predicting the flow and heat transfer characteristics in the annulus by comparing their results with reported experimental results. They concluded that Nusselt number is a function of Prandtl number, radius ratio, aspect ratio and Rayleigh number. Kumar and Kalam [2] studied the effect of diameter ratio on heat transfer from an annulus. They have found that Nusselt number is a function of radius ratio raised by a function of 'r', rather than a constant value as proposed by Davis and Thomas [1]. Mohanthy and Dubey [3] have reported experimental and numerical investigations of buoyancy induced flow, through a vertical annulus, with a uniformly heated inner cylinder wall and an adiabatic outer cylinder wall for different values of radius ratio. By comparing the results of experimental and numerical studies it is observed that the calculated values of height of the wall required to induce a desired flow rate, temperature of the rod and temperature of the fluid are over predicted. They attributed this discrepancy to the entry loss, variation in physical properties and Boussinesq approximation used to model the density variation. However the calculated value of Nusselt number

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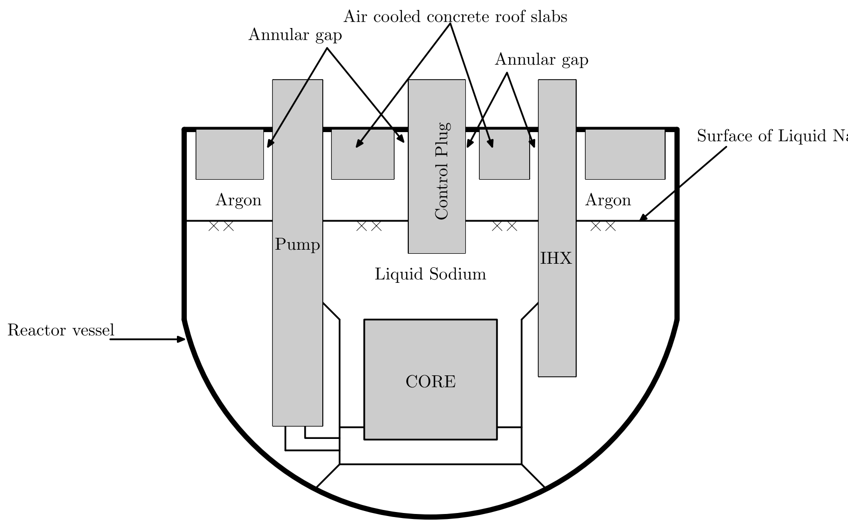

Fig. 1. Schematic showing the annular gap regions of a pool type fast breeder reactor.

averaged along the length of the cylinder has agreed well with experimental data. Nobari et al. [4] have studied the flow and heat transfer characteristics in a curved annular pipe. The continuity, Navier Stokes and energy equations have been discretised using second order accurate central difference scheme. The effect of Reynolds number, Prandtl number, aspect ratio and curvature on the flow and temperature variation in the developing and fully developed region have been studied in detail and two major flow field patterns have been identified based on maximum axial velocity. They also observed that the friction coefficient and Nusselt number are functions of Reynolds number and wall curvature. Rodríguez et al. [5] have numerically studied natural convection in the laminar range in a vertical storage tank considering an axisymmetric geometry. They have presented the transient evolution of flow using velocity vector plots. Natural convection in a square enclosure, in the turbulent regime has been studied numerically by Sharma et al. [6]. Results have been presented for both steady and transient cases, by solving the two dimensional form of Navier Stokes equation. Turbulence has been modeled using Reynold's averaging. The dependence of Nusselt number for two boundary conditions viz iso-thermal and iso-flux have been reported.

Natural convection flow through a vertical annular passage fully opened at the top and bottom has been studied numerically by El-Shaarawi and Sarhan [7]. They have determined the geometrical parameters required for fully developed flow in the annulus. Another important investigation on natural convection through open-ended vertical annulus is performed by Halder [8]. In this study buoyancy induced flow and heat transfer taking place in open-ended 7-rod bundles of two different arrangements are analysed. Natural convection in enclosures having partial openings has been investigated by a number of researchers [9–12]. The numerical investigation by Chan and Tien [9] have compared the results of heat transfer from a flat plate and a shallow cavity. They observed that a shallower cavity can approach the asymptotic heat transfer behavior of flat plate only at higher values of Ra. Desrayaud [11] have numerically investigated the effect of partial openings on heat transfer to a cold wall, the openings being connected to an infinite hot reservoir. They have developed correlations to predict the mean Nusselt number of cold wall as a function of Ra. Bilgen and Oztop [12] have numerically investigated heat transfer characteristics of a partially open square cavity at various inclinations. They have identified for a given Ra that the heat transfer can be controlled by controlling the size and position of the openings and inclination of the cavity. A detailed review of the boundary conditions employed for the solution of natural convection in cavities with openings is given in Ref. [13].

Goldstein et al. [14] have presented a numerical method to predict the convection flow fields in the gap left by penetrations of heat exchanges in FBR concrete top shield. They have predicted the formation of two convective cells in the annular gap region. Yamakawa et al. [15] have presented flow characteristics and circumferential temperature variation for both experimental and numerical analysis of the natural convection of gas in a narrow vertical annuli of a liquid metal fast breeder reactor. The simulation was done in the θ-z coordinates by neglecting the variables in the radial direction and results matching with experiments were obtained. Hemanth et al. [16] studied temperature variations from experimental and numerical investigations of flow through a narrow vertical annular gap of a prototype fast breeder reactor for typical temperature conditions. The actual geometry of the annulus has been simplified to a rectangular slot, which is justified due to the smaller radial gap.

Lal and Kumar [17] performed a detailed study of natural convection in a vertical annulus for different values of percentage gap ratios as well as Rayleigh numbers. Correlations for Nusselt number and volume flow rate in terms of Rayleigh number and percentage gap ratio are reported. This study was two-dimensional axisymmetric and a possible circumferential motion of the fluid medium is ignored. Investigations in Refs. [15] and [16] show that tangential motion is important as it cause a detrimental temperature variations along the circumference of the shell. A numerical simulation of natural convection of argon gas in a vertical annulus of extremely small annular gap of $(0.5 - 2\%)$ is reported by Dinesh and Mahendra [18], for two geometrical configurations. Both the configurations considered only a small volume of the sodium pool. Clearly, volume of the pool can influence the characteristics of natural convection flow and heat transfer in the annulus. The simulation revealed the occurrence of a pair of convective rolls. They have reported a linear fit for circumferential temperature difference in terms of axial temperature difference.

The properties of fluid occupying the annular gap is capable of influencing the flow and heat transfer. A number of contemporary research have been dedicated for such studies. Nanofluids enhance the heat transfer and a few related literature are also discussed here. Alawi et al. [19] have conducted a numerical study on a two dimensional annulus geometry with a nanofluid in the annular gap. The effect of Ra, hydraulic radius ratio and angle of orientation of the closed system on the heat transfer has been analysed. It is found that the average Nusselt number is enhanced with increase in Ra, orientation angle and hydraulic radius ratio. Entropy generation associated with a shear thinning nanofluid in a two dimensional, inclined cavity has been simulated using FDLBM (Finite Difference Lattice Boltzmann Method) by Kefayati and Sidik [20] by considering the Buongiorno's model. The entropy generation due to fluid friction, heat transfer and mass transfer are