DESIGN OPTIMIZATION OF FLOW DISTRIBUTION DEVICE IN BOTTOM HEADER OF IHX FOR FUTURE INDIAN FBR

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Abstract

The next generation commercial fast breeder reactors in India are in design phase. Design optimization of nuclear components is important task with respect to its safe operation and economy consideration. Intermediate heat exchanger (IHX) is a typical shell and tube type heat exchanger, in which primary sodium in shell side exchanges heat with secondary sodium in the tube side. Primary sodium flows shell side from top to bottom through inlet and outlet window. Secondary sodium enters the IHX through central tube and flows downward into the bottom header before it enters ~3900 tubes. Secondary sodium flows upward through tubes and extract heat from primary sodium. Primary sodium flows as crossflow near inlet and outlet windows and axial in remaining length of tubes. Peripheral tubes extract higher heat compared to inner rows. Therefore, it is recommended to allow 30% higher flow of secondary sodium in 7 outer peripheral rows of tubes to achieve a nearly uniform secondary sodium outlet temperature. Towards this a simplified design of flow distribution device was conceptualized. The main purpose of this device is to divert the flow to outer rows of tube. With the present motivation, a three-dimensional CFD study of the bottom header of IHX of FBRs have been carried out to explore the ways to simplify the design of FDD. Parametric studies have been carried out to achieve the desired flow distribution. The effect of conical diffuser and vertical baffle inside bottom header of IHX is quantified.

1. INTRODUCTION

Prototype Fast Breeder Reactor (PFBR) is a 500 MWe pool type liquid sodium cooled nuclear reactor presently under commissioning at Kalpakkam, India [1]. The design for next generation higher capacity Fast Breeder Reactors 1&2 (FBR1&2) is under progress [2]. Design optimization for nuclear components, is important task with respect to its safe operation and economy consideration. The intermediate heat exchangers (IHX) of FBR 1&2 are typical shell and tube type counter flow heat exchanger. Primary and secondary sodium exchanges heat across the tube walls of IHX. Primary sodium enters the shell side of IHX through an inlet window at the top and exits through an outlet window located at the bottom. The secondary sodium enters IHX from top into a central tube known as down comer and flows downward into an inlet plenum called as bottom header. Secondary sodium takes 180^o turn after impingement on the surface of bottom header and enters the 25 rows of tubes. Secondary sodium flow upward through these tubes before it enters header at the top. There are 3900 tubes arranged in circular pitch surrounding the central down comer in 25 rows. Secondary sodium extracts heat from primary sodium across the tube walls, while it flows upward. However, primary sodium flows as crossflow near the inlet and outlet window and axially in the remaining length. The heat exchanged by various tubes of IHX is not the same due to the following reasons: (a) cross flow of primary sodium at the inlet and outlet window regions because of which inner rows sees lower temperature primary sodium, and (b) primary sodium flow near the inner rows in less when compared to outer rows. Consequently, temperature of secondary sodium at the outlet of various row of tubes is not the same resulting in thermal loading of tube sheet and other structures of IHX. Since the secondary sodium flowing in the outer rows receive significantly large heat compared to the inner rows, temperature of secondary sodium at the outlet of various tubes can be made more uniform by admitting more flow through the outer rows of tubes. This is possible by increasing the hydraulic resistance of inner rows compared to the outer rows. A desirable option is to introduce a flow distribution device (FDD) in the bottom header to accomplish the required flow zoning. Based on a simplified 1 – D network model it is recommended that outer 7 rows of tubes in IHX should have 30% more flow rate compared to the 18 inner rows. In the available literature, researchers have investigated the heat transfer aspect of the IHX for various application including those of nuclear reactors, viz., Mochizuki and Tokano [3], Patankar and Spalding [4], and Gajapathy et.al. [5]. However, it is observed that there is no exclusive investigation carried out for the hydraulics of sodium flow in the bottom header of IHX. With the present motivation, a three-dimensional CFD study of the bottom header of IHX of FBRs have been carried out to explore the ways to simplify the design of FDD. Parametric studies have been carried out to achieve the desired flow distribution. The effect of conical diffuser and vertical baffle inside bottom header of IHX is quantified, which makes the objective of the paper.

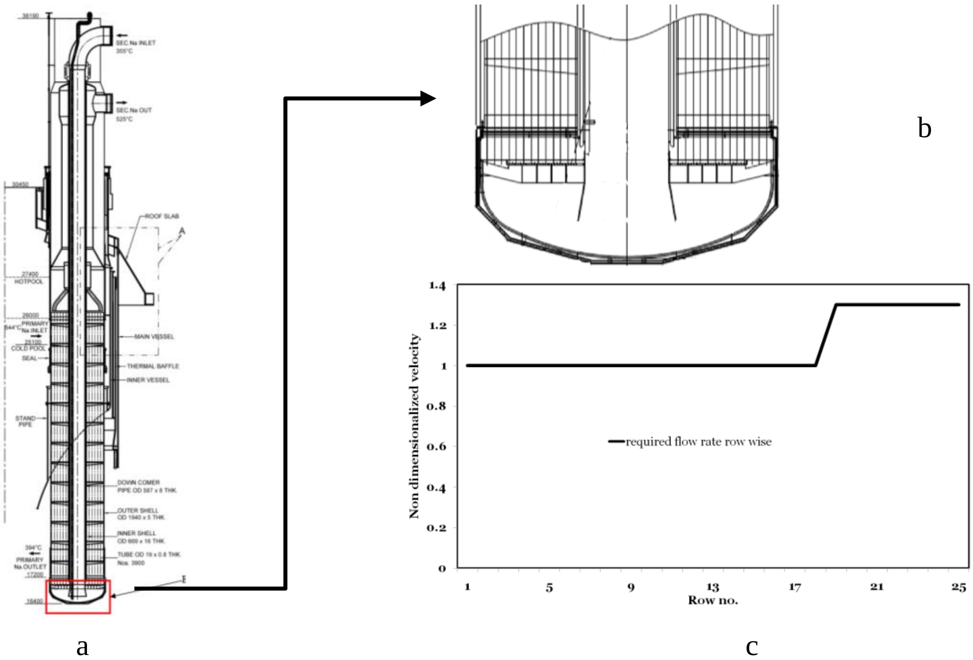

FIGURE 1: (a) Schematic of IHX and (b) bottom header of FBR1&2 (c) Desired flow distribution in the 25 rows

2. COMPUTATIONAL METHODOLOGY

The tubes of the IHX are arranged in a circular pitch, with 84 tubes in the first row. A 30° sector model of the IHX bottom header is considered for the analysis. The complete axial length of IHX tubes is modeled, and the outlet boundary condition is specified at the top of the tubes, as shown in Fig.2. The mass flow rate of secondary sodium entering the domain under consideration is 144 kg/s. Thus, a uniform velocity of ~ 8 m/s is imposed as an inlet boundary condition at the top of the down comer. Zero-gauge pressure is specified at the exit of all the tubes modeled. No - slip boundary condition is imposed over all the walls. Symmetric planes of the 30° sector are specified as symmetry boundary conditions. Steady state incompressible flow of sodium is considered in the present study. Density and dynamic viscosity of sodium are considered as constant at 848 kg/m^3 and 2.64 x 10^{-4} kg/ms respectively. High Re $k - \varepsilon$ turbulence model with standard wall function is used to consider the effect of turbulence on fluid flow. ANSYS FLUENT 19.2 is used to carry out the simulation. The 3D steady state incompressible flow of sodium is governed by fundamental equations of conservation of mass and momentum. Energy equation is not solved as the temperature field is not resolved. Finer mesh with the hexahedral cell (y^+ value maintained between ~30-300) is generated near most walls to capture the near-wall effect accurately. The total mesh count is approximately 1.2 million.

3. RESULTS AND DISCUSSION

Initially numerical simulations of the IHX bottom header without conical diffuser were conducted to analyse its influence. The predicted pressure distribution in the header shows high pressure below the downcomer at the header wall attributed to stagnated sodium jet from the downcomer. Velocity distribution in non dimensionalized form (a ratio of tube velocity (v_t) and downcomer velocity (v_{dc})) through 25 rows is shown in Fig. 3a. The conical diffuser helps in the smooth expansion of the jet and thereby reducing the regions of sharp velocity interfaces. Subsequently, simulations were carried out with the conical diffuser and a vertical baffle considered right below the tube sheet located radially after the 18th row. Parametric studies were carried out by considering different lengths for the vertical baffle, viz., 22.5 mm, 45.0 mm, 90.0 mm, 135.0 mm, 185.0 mm, 225.0 mm, and 265.0 mm. As the baffle length increases, flow distribution among the tubes approaches closer to the desired one (Fig. 3b). The sodium flow gets restricted physically due to the vertical baffle, leading to flow recirculation at the baffle location and behind it. Flow distribution predicted for the cases with baffle lengths 185.0 mm, 225.0 mm, and 265.0 mm are very close to the desired flow distribution. It is recommended to consider the baffle height of 225 mm.

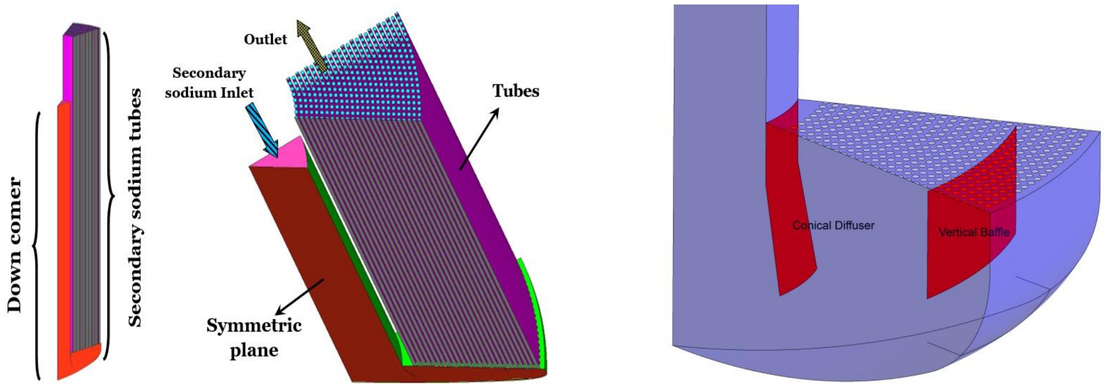

FIGURE 2: Computational domain with boundary conditions

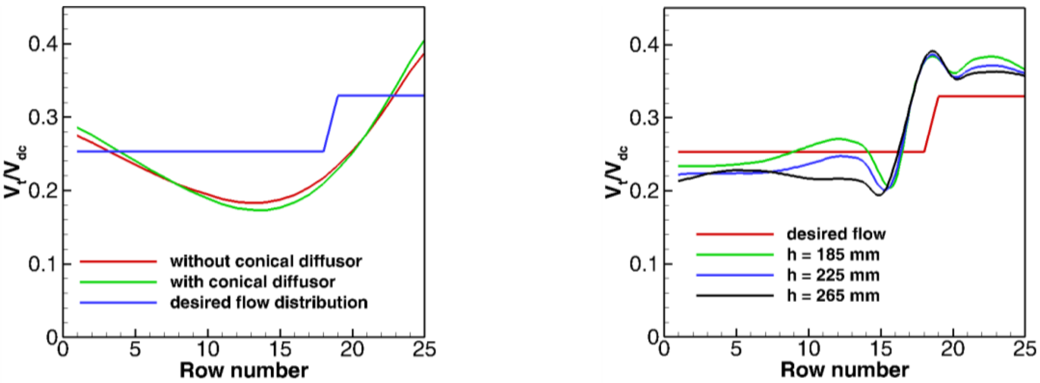

FIGURE 3: Velocity distribution through tube rows (a) without conical diffuser (b) for different baffle height

4. CONCLUSION

Three-dimensional CFD study of the bottom header of IHX of FBRs have been carried out to explore the ways to simplify the design of FDD. Parametric studies have been carried out to achieve the desired flow distribution. The effect of conical diffuser and vertical baffle inside bottom header of IHX is quantified. A vertical baffle of 225 mm height (located 12 mm below the tube sheet) provided after the 18th row rendered a flow distribution very close to the desired one. With this arrangement, the average absolute deviation between the flow distribution achieved and the desired one is ~ 10 %.

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