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Effect of geometric factors on performance of a sodium to air heat exchanger in a fast breeder reactor

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ABSTRACT

Prototype fast breeder reactor (PFBR) has a safety grade decay heat removal system whose performance depends on the effective functioning of natural convection heat exchangers called sodium to air heat exchangers. The development of Representative Elementary Volume (REV) model for the sodium to air heat exchanger is necessary to envisage its design and to study the effect of various factors for continuous improvement in design. With a Representative Elementary Volume, the hydrodynamic and heat transfer characteristics of the heat exchanger was studied and the results agree well with experimental data. The effect of longitudinal pitch and transverse pitch on the heat exchanger performance has been studied and an improvement of 22% in heat transfer is predicted.

1. Introduction

A sodium cooled, pool type, prototype fast breeder reactor (PFBR) has a safety grade decay heat removal (SGDHR) system, which is a passive circuit and is used to remove the decay heat from the reactor core after its shutdown. SGDHR system is a completely passive system except dampers on the airside. SGDHR system of a 500 MW_e PFBR consists of 4 independent loops of each 8 MW heat removal capacity. Each SGDHR loop consists of sodium-sodium heat exchanger (DHX) dipped in hot pool, sodium to air heat exchanger placed outside the reactor containment building at an higher elevation, an expansion tank, associated piping, air dampers and a stack. Sodium air heat exchanger placed outside the reactor containment, is a natural convection type heat exchanger. The current interest is to enhance its performance by improving its effectiveness by which a reduction in heat transfer area can be achieved.

The complexity of cross flow heat exchangers stems from their geometrical configuration, the physical phenomena present in the transfer of heat, and the large number of variables involved in their operation. As a consequence of such complexity, no analytical solutions entirely based on first-principles approach are available; most calculations are based on empirical information from the manufacturers of these equipments and, presently, the vast majority of the analyses for predicting their behavior include assumptions and conditions that are not consistent with the phenomena occurring in them under actual states of operation. The shortcomings in the current approach thus lead, in many cases, to unsatisfactory predictions of the heat transfer with errors that can be sometimes of the order of 25–30% or even higher. Since the heat exchanger performance is very often a key factor in the overall thermal system design, constant improvements in their modeling and simulation are definitely needed to increase the accuracy of their predictions and, consequently, to improve the reliability and efficiency of thermal systems for the specific application.

Yang et al. (2014) reviewed the CFD's effectiveness in prediction of heat transfer in a shell and tube heat exchanger when the four different modeling methods called unit model, periodic model, porous model and whole model are applied. Mahmood et al. (2012) reviewed CFD applications in various heat exchangers design with the collection of journals published from year 1986 to 2011. The most of the studies are related to plate heat exchangers and new types of heat exchangers. The available literatures have been categorized into four namely (i) flow maldistribution analysis (ii) pressure drop analysis (iii) Thermal analysis (iv) design optimization studies. Authors have concluded that easily accessible general purpose CFD commercial software can fulfill the requirements of CFD analysis of various heat exchangers with

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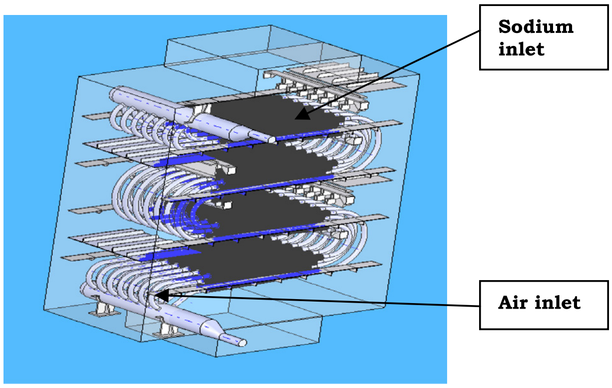

Fig. 1. Skeleton model of sodium to air heat exchanger.

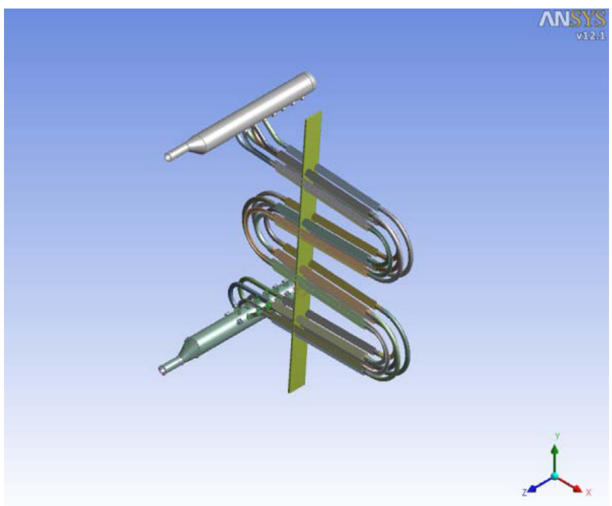

Fig. 2. One tube bundle with REV.

deviation up to 36% in some exceptional cases when compared to the experimental studies. Yongqing et al. (2011) modeled half of the shell side of a new type of shell and tube heat exchanger for analyzing the effect of tube support structure over shell side flow characteristics and heat transfer characteristics. Velocity distribution in shell side along with convection heat transfer coefficient values for 5 flow fluxes where equivalent Reynolds number was less than 15,000 in shell-side of H-shape heat exchanger has been reported.

Mochizuki and Takano (2009) derived the empirical correlations applicable to the design of commercial scale sodium air heat exchangers from the experiments conducted in three facilities. Authors have compared the heat transfer coefficients with earlier correlations and found that the agreement was good.

Table 2
Sodium temperature in different pipes.

Pipes	Temperature (K)	Pipes	Temperature (K)
1	603.7	7	699.2
2	597.5	8	697.7
3	594.9	9	695.8
4	646.4	10	742.8
5	648.0	11	745.0
6	648.9	12	747.1

Mohammadi et al. (2009) divided the shell side of E type shell and tube heat exchanger into 6 zones for the analysis of the effect of baffle orientation over flow and heat transfer characteristics. A shell side gain factor and performance factor has been introduced to analyze and compare the different cases when the shell side fluids were changed. Zhang et al. (2009a,b) has reported the shortcomings of modeling and analyzing shell side flow and heat transfer characteristics with porous medium and distributed resistance concept with a detailed literature survey support. Sunden (2007) reviewed CFD's effectiveness for analysis of single phase flows. The review starts with generalized form of governing equations, the basics of finite volume method, procedure for solution of the momentum equations, available turbulence models and continues with useful notes about CFD's effectiveness like Nusselt number predictions in turbulence region were 50% more than experimental one in certain cases which demands the careful application of CFD in a given application for reduced error percentage. Sahin et al. (2007) considered two fins with half fin thickness including flow path for analysis of fin inclination angle (0–30°) influence over a commercial fin and tube heat exchanger performance in laminar region. When the inclination was increased from 0° to 30°, it was found out that the increase in inclination angle decreased the fin spacing which has resulted in increase in velocity and the rate of heat transfer. The net increase in total heat transfer was 105% maximum, at 30° inclination.

Dirkse et al. (2006) created CFD model for a natural convection shell and tube heat exchanger with baffles. The feature of complex geometry had been simplified considerably resulting in an almost two dimensional mesh with only 30,000 quadrilateral mesh cells. Mon and Gross (2004) modeled a flow domain with half fin and half air path having three and five row of tubes and analyzed the effect of fin spacing on hydrodynamic and thermal characteristics of annular finned tube heat exchangers with the aid of FLUENT. The authors found good agreement in heat transfer results whereas the pressure drop results were found to exceed by more than 50%.

It is evident from the literature that the hydrodynamic and heat transfer characteristics are expected to change whenever a change in pitch, fin spacing, etc. is implemented. It necessitates the numerical flow visualization in conjugate heat transfer condition of each configuration of heat exchanger which helps to further improve its design. Most of the work reported is in the field of new types of heat exchangers with simplified flow domain reasonably. It is also clear that the domain with more number of fins and bundles in a

Table 1
Geometric dimensions of REV.

Sl. No.	Geometry of Representative Elementary Volume	Dimensions (mm)	Sl. No.	Geometry of Representative Elementary Volume	Dimensions (mm)
1	Length of shell side	159	7	Fin pitch	5.08
2	Breadth of the shell side	15.24	8	Height of the fin	12.5
3	Height of the shell side	2384.5	9	Number of fins per tube	3
4	Tube diameter	38.1	10	Number of rows	12 (each row having one and half pipes)
5	Thickness of each fin	1.22			
6	Diameter of the fin	63.1			