Thermal Analysis of Intermediate Heat Exchanger in a Pool Type Fast Breeder Reactor

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Abstract: Intermediate heat exchanger (IHX) in a pool-type liquid metal cooled fast breeder reactor is an important heat exchanging component as it transfer heat from the radioactive primary sodium in the pool to the non-radioactive secondary sodium. The secondary sodium ultimately heats up water in a steam Generator (SG) to produce the steam for power generation. Intermediate heat exchanger is a sodium to sodium heat exchanger and is modeled using COMSOL multiphysics code. The code estimates the temperature and velocity distribution of primary sodium in the shell side.

Keywords: Intermediate heat exchanger (IHX), Fast breeder reactor (FBR), COMSOL.

1. Introduction

Fast Reactors would be an important and inevitable source of energy for sustained growth of nuclear power in India. In India, a pool type liquid metal cooled Fast Breeder Reactor [PFBR] is under construction at Kalpakkam. PFBR is a 1250MWt and 500MWe liquid sodium cooled fast breeder reactor. In PFBR the entire primary circuit is immersed in a pool of liquid sodium, which is used as a coolant and hence it comes under pool type reactor. The pool is divided into hot pool and cold pool by an inner vessel (Fig1). The inner vessel consists of two cylindrical shells of different diameters joined by a conical shell called redan. In the primary sodium system, the nuclear heat generated in the core is removed by primary sodium circulated by primary pumps through grid plate. The hot primary sodium emerging from the core mixes with a hot sodium pool and penetrates the intermediate heat exchanger (IHX) through its inlet window (Fig.1). In the secondary sodium system, the primary sodium flowing in the shell side of the IHX exchanges heat with the secondary sodium flowing in the tube side. The cool primary sodium comes out of the IHX through the outlet window and mixes with cold sodium pool. The sodium temperature of 544 ^{0}C in the hot pool is reduced to 394 ^{0}C after the heat exchange. The secondary sodium enters the IHX at the top and flows downwards through a central pipe (Down Comer) (Fig. 2) at a temperature of 355 ^{0}C. On reaching the bottom, the secondary flow is reversed upwards through the tubes. After the bundle, the hot secondary sodium at 525 ^{0}C is collected in an annular pipe which leaves the IHX through a lateral outlet nozzle. In the steam–water system, the secondary sodium exchanges heat with water in a once through steam generator (SG) to produce superheated steam for power generation. The IHX also acts as an intermediate boundary between the highly radioactive primary sodium circulating through the reactor core and the non-radioactive secondary sodium. The IHX is supported on the roof slab (Fig. 1), which is maintained at 95 ^{0}C and is freely hanging from the top. The lower part of the IHX is in the cold sodium pool of the reactor vessel.

This paper focus is to predict primary sodium flow and temperature distributions inside the IHX using COMSOL.

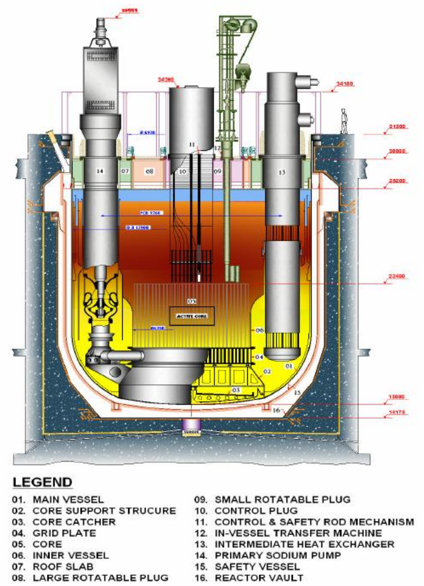


Figure.1.PFBR reactor assembly

1.1 Main characteristics of IHX

The total thermal power generated in the reactor core is exchanged by four IHX in the reactor vessel. IHX is a shell and tube vertical counter flow heat exchanger with primary sodium on the shell side and secondary sodium on the tube side. The tubes are arranged in circumferential rows around the secondary sodium down comer between the top and bottom tube sheets. The tubes encounter cross flow of primary sodium in the inlet and outlet window regions.

Total thermal power of reactor	1250 MW (t)
Thermal capacity of each IHX	315 MW (t)
Primary sodium inlet flow	1650 kg/s
Primary sodium inlet temperature	544 ^{0}C
Primary sodium outlet temperature	394 ^{0}C
ΔT between primary sodium inlet and outlet	150 ^{0}C
Secondary sodium inlet flow	1450 kg/s
Secondary sodium inlet temperature	355 ^{0}C
Secondary sodium outlet temperature	525 ^{0}C
ΔT between secondary sodium inlet and outlet	170 ^{0}C
Inlet and outlet windows height	900mm
Heat exchanging tubes OD and thickness	19 and 0.8mm
Total number of tubes	3600
Radial pitch of the rows	25mm
Circumferential pitch	26.2mm
Heat transfer length	7.5 m
Heat Transfer Area [Based on tube OD]	1612m^2
Shell diameter (Cylindrical IHX)	1850 mm/5thk
Down Comer Outer/Inner diameter	580/547mm
Number of tube rows (Cylindrical IHX)	25

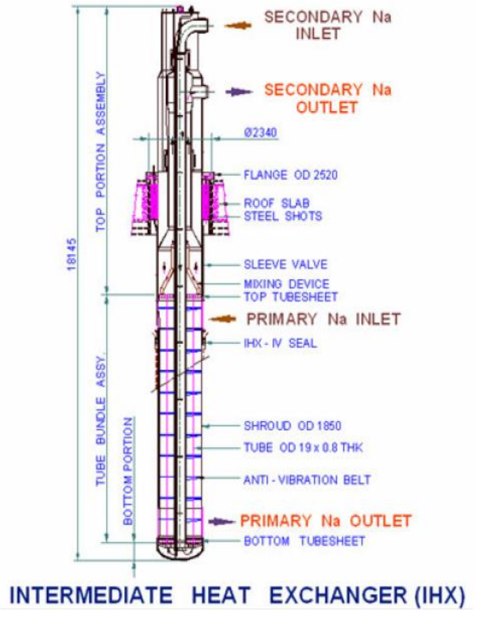


Figure.2. Schematic of IHX

2. Mathematical modeling

In IHX, the tubes are arranged in rows and they are symmetrical in the circumferential directions. Hence, a 2D axi-symmetric analysis of the tube bundle is carried out using COMSOL Multiphysics code. In this computer code continuity equation, momentum equation and energy equation where solved simultaneously to obtain pressure, velocity and temperature distribution of primary sodium inside the IHX. It is difficult to model each and every tube in the simulation for large equipment like IHX, which comprises of 3600 tubes in a tight pitch. To circumvent this difficulty, the secondary sodium is modeled as heat sink in the energy equation of the primary sodium and tube bundle is modeled by porous body formulation.

From the law of conservation of mass, the general conservation form of the continuity equation for compressible fluid is given below

$$\frac{\partial \rho}{\partial t} + \nabla.\rho v = 0 \qquad (1)$$

For incompressible fluid,

$$\nabla.v = 0 \qquad (2)$$

From the law of conservation of momentum, the brinkman equation for flow of fluid in porous media is given below

$$\frac{\rho}{\varepsilon_p}\frac{\partial u}{\partial t} + \frac{\mu}{\varepsilon_p}\nabla^2 \mathrm{u} = -\nabla.p - \frac{\mu}{k_p}u + F \qquad (3)$$

Where μ the dynamic viscosities of the fluid (in kg/(m · s)), **u** is the velocity vector (m/s), ρ is the density of the fluid (kg/m^3), p is the pressure (Pa), ε_p is the porosity and k_p is the permeability of the porous medium (m^2). Second term in the right hand side represents linear matrix drag. Influence of gravity and other body forces can be accounted for via the force term **F** (kg/(m2·s2)). This term can be also use for accommodating non-linear matrix drag term.

From the law of conservation of energy, the general form of conduction convection equation is given below

$$\rho C_p\left(\frac{\partial T}{\partial t} + u.\nabla T\right) = \nabla.(k\nabla T) + Q \qquad (4)$$

Where T is the temperature (K) , k is the thermal conductivity (W/(m.K)) , Cp is the specific heat capacity (J/(kg.K)) and Q (W/m^3) account for heat sink or heat generation term in the equation.

2.1 Calculation of non-linear matrix drag in radial and axial flow direction.

The flow resistance coefficient ‘K’ for turbulent cross flow over bundle of smooth-wall tubes is given by (Idelchik, 1966),

$$\Delta p = \frac{K\rho U^2}{2} \qquad (5)$$

Where

$K=A*Re^{-0.27}*(Z+1)$
$A=3.2 + (4.6-2.7((S1-d)/(S2'-d)))(2.0-S1/d)$
$S2'= (0.25S1^2+S2^2)^{0.5}$
Δp, pressure drop (Pa)
U, primary sodium velocity at the inlet window (m/s)
Re, Reynolds number ((U*ρ*d)/μ)
Z, is the Number of tubes over the tube depth
d, is the tube outer diameter (m)
S1, S2 and S2’ are the circumferential, radial and transverse pitch distance between the tubes, respectively.
For the axial flow, the friction factor ’f’ is calculated from (Idelchik,1966)

$$\Delta p = \frac{\rho f L V^2}{2D_{eq}} \qquad (6)$$

Where,

$f= 0.11((\varepsilon/d)+(68/Re))^{0.25}$
f, friction coefficient
ε, roughness of tubes (m)
L, axial length (m)
V, average interfacial axial velocity (m/s)
Deq, hydraulic diameter of the shell side of IHX
Re, Reynolds number ((Deq*ρ*V)/μ)

2.2 Calculation volumetric heat sink.

The volumetric heat sink ’Q’ is calculated using

$$Q = \frac{Power\ of\ the\ reactor}{No.of\ IHX * IHX\ Volume}$$

Where,

Q is the heat sink in W/m^3.

Note: In COMSOL Negative sign has to be applied since heat is removed from the system

2.3 Boundary condition

The Schematic of computational model and boundary conditions is presented in Fig.3.

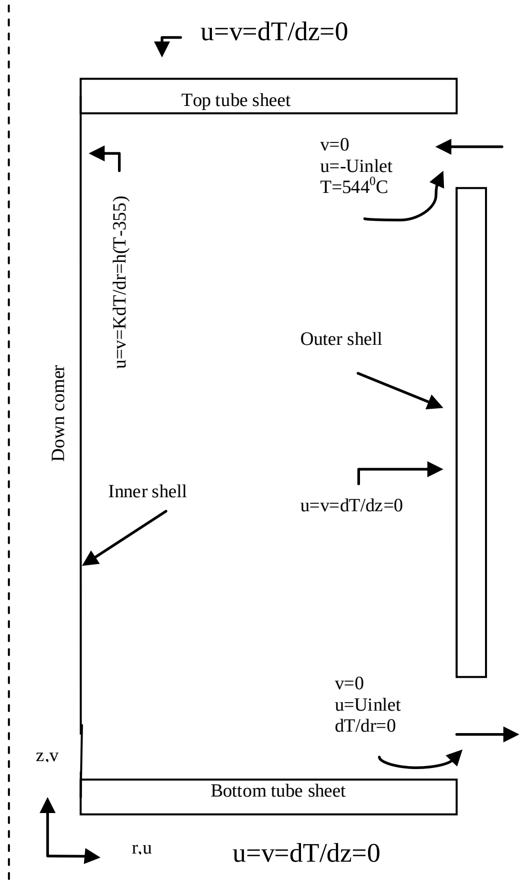


Figure.3. Boundary conditions for IHX.

3. Results

Primary sodium temperature distribution in the IHX is shown in Fig.4. Radial temperature variation of primary sodium at different elevation is shown in Fig.5. It is seen that there is much more temperature variation of primary sodium along the radial direction towards IHX inlet as compare to IHX outlet. Mean outlet temperature of primary sodium at different time obtained using COMSOL code along with outlet temperature of primary sodium obtained using one dimensional IHX code at different time is shown in Fig.6. Mean outlet temperature of primary sodium obtained from the one dimensional code written for IHX showed good agreement with the result obtained from the COMSOL model.

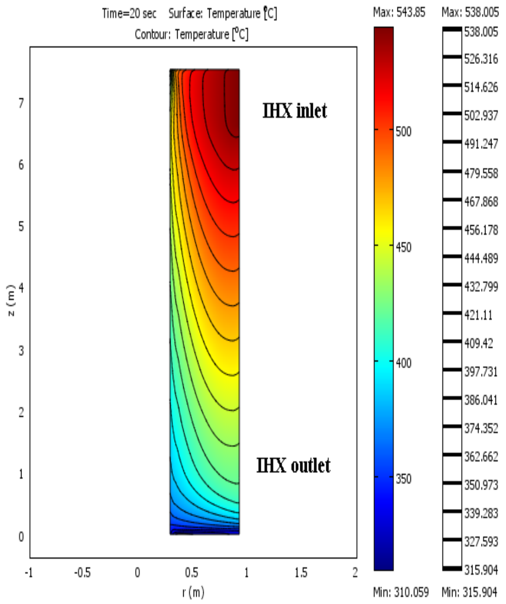


Figure .4.Temperature distribution of primary sodium in IHX.

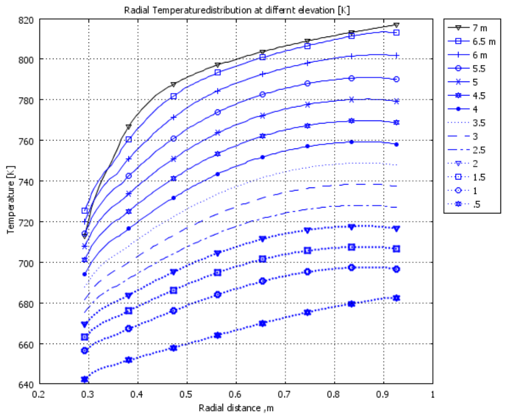


Figure.5. Radial temperature distribution of primary Sodium at different elevation.

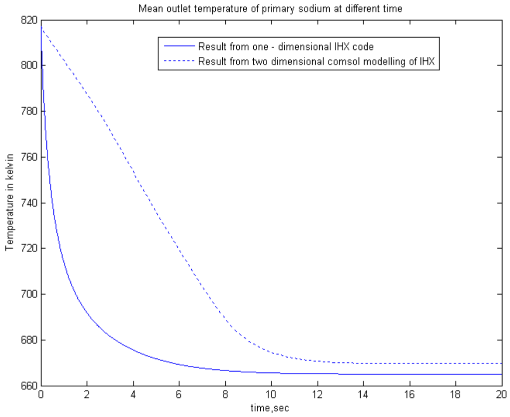


Figure.6. Primary sodium outlet temperature at different time interval.

Primary sodium flow distribution inside the IHX in 2-D is shown in Fig.7. Radial velocity variation of primary sodium at different elevation is shown in Fig.8. It is seen that there is little velocity variation along radial direction between inlet and outlet window of IHX. It is also seen that velocity is constant in the region between inlet and out window of IHX which signifies that there is good mixing of primary sodium.

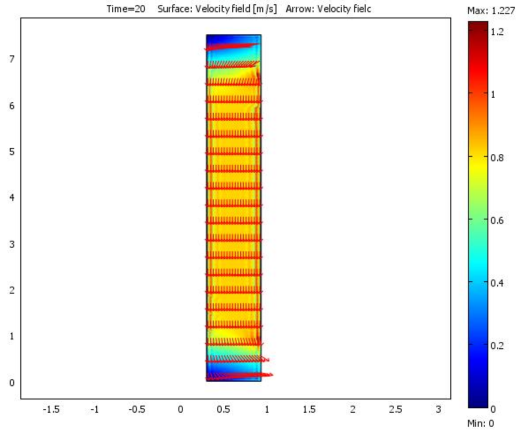
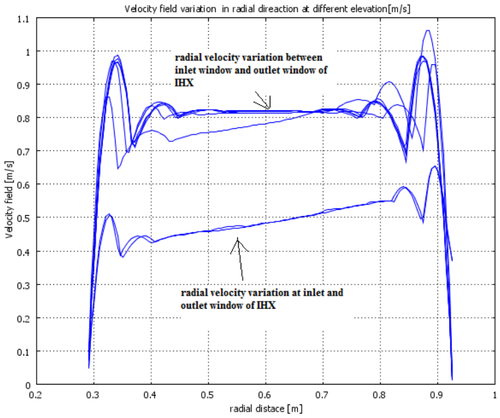


Figure.7.Velocity field in IHX tube bundle during normal operating conditions.



4. Conclusions

- COMSOL Thermal and hydraulic investigation of IHX carried out using COMSOL code have helped to verify the results got from the one-dimensional code written for IHX.
- Primary sodium Temperature distribution obtained from the COMSOL code will be useful in predicting the outlet temperature of secondary sodium from each tube of the

IHX. This will help in further verification of the one dimensional code.

8. References

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