Thermal Hydraulic Analysis of Multi-pass Heat Exchanger using a FDM Based Network Model

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ARTICLE INFO

Received : 20 June 2019
Revised : 23 September 2019
Accepted : 01 October 2019

Keywords:

Network model, Finite Difference method, Multi-pass heat exchanger, Nuclear reactor

ABSTRACT

In order to analyze the performance of a multi-pass shell and tube type heat exchanger used for decay heat removal operation in fast breeder reactor, a computer code has been developed using network model. The model is based on 1-D finite difference method (FDM) formulations. The transient momentum and continuity equations are solved simultaneously to obtain pressure field and flow rates, viz., inlet flow over a distributed inlet window, cross flow between radial zones, and axial flows along the length. Intermixing between radial zones is modeled using cross flow. Transient energy equation is solved to obtain temperatures. The heat transfer capacity of the heat exchanger is estimated as 8.93 MW when the hot pool is at 547 °C. Natural circulation flow rate of primary sodium is found to be 46.3 kg/s. The results are compared with the CFD results and a reasonable agreement is found. A transient study is also carried out and the results are given in this paper.

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1. Introduction

Post shutdown decay heat removal from nuclear reactor core is carried out using Safety Grade Decay Heat Removal System (SGDHRS) (Fig. 1). This is a passive circuit which removes heat directly from the hot pool. It consists of three coupled natural circulation loops. The design capacity is 8 MW/circuit. Each circuit consists of a Decay Heat Exchanger (DHX) coupled to Air cooled Heat Exchanger (AHX) by an intermediate sodium circuit.

DHX is a 'U' tube type heat exchanger with two passes on tube side and one pass on shell side. Since the flow is multi-pass on tube side, the conventional one-dimensional (1-D) modeling of heat exchanger needs to be modified. Since the inlet is distributed over a length, the heat transfer and pressure drop correlations available in literature for heat exchangers with single inlet and single outlet cannot be used directly. Generally, CFD is used for modeling this special kind of heat exchangers. But CFD models are computational intensive and hence difficult to use for transient and parametric studies. Hence, an attempt has been made to model the behaviour of shell side fluid flow using 1-D formulations. The 1-D model takes less computational time and can be easily used for transient and parametric studies to optimize the design. The 1-D model can also be coupled easily with the existing plant dynamics codes. Towards this, a network model based on Finite Difference Method is developed and the thermal hydraulic performance of DHX is studied. The results of this model are compared with the CFD results. A transient study is also

Fig. 1 Schematic of Safety Grade Decay Heat Removal Circuit

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carried out and various performance parameters, viz., flow rate and temperature evolution in DHX are investigated.

1.1 Literature survey

FDM is one of the oldest numerical method used for heat transfer and fluid flow analysis. It has been used to study various real life scenarios, viz., ground water flow in porous media [1], charge of particles in an accelerator [2], water waves and currents [3], etc. The present authors studied coupled natural convection loops in Decay Heat Removal (DHR) systems of Fast Breeder Reactors, where various components of the DHR system viz., heat exchangers, intermediate circuit, stack etc., are modeled using FDM formulations [4]. Integrated finite difference method is used to analyze more complicated domains, viz., flow in multidimensional heterogeneous systems [1], steady state and transient temperature distributions in multi-dimensional systems [5]. Recently, Generalized FDM (GFDM) is developed, and Li and Liu [6] proposed the main objective of the GFDM method is to approximate the spatial derivatives of a differentiable function in terms of its values at some randomly distributed nodes. GFDM uses meshless methods and thus suitable for any geometry of the domain and has been used to solve, 2-D shallow water equations [7], sloshing phenomena in a wave tank [8], the Poisson's equation on irregular 2D domains [9] etc.

Many studies have been carried out using network model methodology for investigating flow distribution in manifolded solar Collectors. In Jones and Lior [10], flow distribution through a typical system consisting of two manifolds connected by a number of parallel riser tubes have been investigated. Wang and Ju [11] studied flow profile by solving mass and momentum balance equations at every segment of the header system and compared the results with experiment. A. Acrivos et. al. [12] studied division of fluid stream into parts by a manifold, where the flow field is analyzed by solving 1-D conservation equations. At present, the authors used the network model with FDM formulation to study the multi-pass heat exchanger.

2. Description and Modeling Details

DHX is a shell and tube type heat exchanger as shown in Fig. 2. The inner legs of the 'U' tubes are arranged in five central rows and the outer legs are arranged in two outer rows. The outer rows of tubes are supported by four anti-vibration belts along the length. At the same axial locations, the inner rows of tubes are supported by baffle plates. The intermediate sodium enters the tubes at inner legs and flows downwards. At the bottom, it takes 180° turn and flows upwards in the outer legs. This makes the inner region to behave like co-current heat exchanger and outer region to behave like counter-current heat exchanger. Primary sodium from hot pool enters the shell side of DHX through the inlet window (top porous

shell), flows over the tubes and exits to the hot pool through the bottom outlet window.

2.1 Network Model

Towards analyzing the thermal hydraulics of DHX, a 1-D network model with multiple inlets is developed using finite difference method. In this model, shell side of the DHX is divided into two radial zones of equal cross-sectional area. The multiple inlet points are distributed over inlet window length and the flow rates at each inlet point is calculated by solving momentum equation. Number of inlet points are taken as a parameter. The computational domain is discretized into convenient number of nodes in the axial direction. Figures 3a and 3b show the schematic of the network model used. The model consists of three types of axial segments, viz., inlet window segments representing entry of primary sodium, middle segments, and outlet window segment. At each inlet elevation, the hot sodium entering from the inlet window mixes with sodium in the outer region. Part of this sodium goes to inner zone and the rest flows downwards with mixed mean temperature.

Intermediate sodium in tube side

Fig. 3a Schematic of DHX

Fig. 2 Schematic of Decay Heat Exchanger

Fig. 3b Network model

The flow in each segment of the circuit is calculated based on the pressure difference between two end points of the segment, pressure drop experienced by the flow in the segment and the buoyancy head developed in that segment. Cross flow between the inner and outer zones is calculated based on the pressures at the adjacent nodes and the pressure drop in the flow path. Mixing is considered and mixed mean temperature is calculated at each control volume which is further used for estimation of heat transfer.

The unsteady momentum equation and continuity equation are solved simultaneously to obtain flow rates ($\dot{m}$) at each segment and pressures at each node. The momentum equation for segment between nodes i and o is given as below:

$$\left(\frac{L}{A_c}\right) \frac{d\dot{m}_{io}}{dt} = P_i - P_o - K_{io} \left| \dot{m}_{io} \right| \dot{m}_{io} + \sum_i^0 \rho g \Delta z$$

Where L is distance between two nodes i and o , A_c is the flow area, t is time, P is pressure, ρ is density of sodium, g is gravity, Δz is elevation difference between the two nodes. K_{io} is the coefficient of pressure drop between two nodes ' i ' and ' o ', and is estimated as, $K=k/(2\rho A_c^2)$, where A_c : flow area, ρ : density of fluid, k : pressure drop coefficient estimated using various correlations describe in next section. Total number of continuity and momentum equations for ' n ' segments in axial direction is: $5n+n1+4$, where $n1$ is number of segments in inlet window. The momentum equation is solved using semi-implicit scheme.

Using the evaluated flow field, the transient energy equation is solved for each segment as given below.

$$\left(M_1 C_p \right)_j \frac{dT_{ij}}{dt} = \left(\dot{m}_1 C_p \right) (T_{li} - T_{li+1}) + (UA)_j (\bar{T}_3 - \bar{T}_1) \left. \begin{array}{l} \bar{T}_3 = fT_{3i} + (1-f)T_{3i+1} \\ \bar{T}_1 = fT_{1i} + (1-f)T_{1i+1} \\ T_{1j} = T_{li+1}, \text{ if } \dot{m}_1 > 0 \text{ else } T_{1j} = T_{li} \end{array} \right\} \text{ for } i=1:N,$$

Where T is temperature, the subscripts 1, and 3 represent the intermediate sodium in inner rows of tubes, and primary sodium respectively. M_1 : is the mass of fluid (sodium) at a node, C_p : specific heat of fluid, U : overall heat transfer coefficient, A : surface area of heat transfer. In the above equation, ' f ' is a weighting factor used to obtain the mean temperature difference between shell side and tube side, and it is estimated based on the flow rate ratio and flow configuration as given in the reference [13].

The energy equation is solved using semi implicit scheme. For outer zone tubes, the energy equation is similar to that used for inner tube taking into account the direction of intermediate sodium flow. The thermal inertia of sodium and tube material is considered in the analysis. The tube thermal inertia is distributed equally between shell side and tube side sodium. The heat transfer coefficient in each segment is calculated based on the flow in that segment. The shell side and tube side Nusselt numbers are calculated using the following correlations [14].

For shell side: $Nu=6+0.006Pe$, $30 < Pe < 4000$, $1.2 < p/d < 1.75$

For tube side: $Nu=4.82+0.0185Pe^{0.827}$, $50 < Pe < 13100$

2.2 Estimation of Pressure Drop Coefficients

The pressure drop coefficient at inlet and outlet window is estimated using following correlations for porous plate as given in the reference [15].

$$k = \left[\left\{ 0.608 \beta (1 - \beta^{2.6}) \left(1 + \left(\frac{\Delta t}{d_h} \right)^{3.5} \right) + \beta^{3.6} \right\}^{-1} - 1 \right]^2,$$

Where β is porosity, Δt is thickness of porous plate, d_h is hydraulic diameter of holes in the inlet window.

The correlation used for evaluating pressure drop coefficient for baffle plate is same as that used for porous plate. For ferrule belts the correlation used is given below [16].

$$k = \left(\zeta_\phi + \varepsilon_0^{-Re} \zeta_0 + \lambda \frac{l}{d_h} \right) \frac{1}{f^2},$$

for $l/d_h > 0.015$, Where, l is the height of the ferrules, d_h is the hydraulic diameter at the belt location.

The cross flow pressure drop for tube bundle is calculated using correlation given below [4].

$$k = \psi A Re_{av}^{-0.27} (z_r + 1) + \Delta \zeta_r,$$

Where Re_{av} is based on the average inter-tube velocity, z_r is the number of rows of tubes. Description of all other parameters are given in the reference.

Friction pressure drop in pipes and tubes are calculated using the Blasius correlation. A 20 % uncertainty margin is taken in calculation of pressure drop coefficients.

3. Results and Discussion

The hot pool temperature is taken as 547 °C. The intermediate sodium inlet temperature and flow rate are taken as constant and the values are 266 °C and 32.26 kg/s respectively. The intermediate sodium flow is assumed to be distributed uniformly among the tubes. Number of nodes in the axial direction are taken as 77 (grid size: 0.04m). The geometrical data of the heat exchanger is given in table 1.

Table 1: Dimensions of the heat exchanger

Parameter	Value
Shell outer/inner diameter	0.58/0.564 m
Tube outer/inner diameter	25.4/23 mm
Length of tubes	3.25 m
Number of tubes	90
Height of inlet perforations	1.76 m

In the present analysis, 45 number of inlet points are taken which is equal to the total number of rows of holes at the inlet window. Heat transfer capacity estimated is 8.93 MW. Heat transfer in inner zone (~59 %) is found to be more than that in outer zone. Figure 4a shows the axial temperature distribution in primary and secondary sodium in both inner and outer zones and tubes. Intermediate sodium temperature in inner rows of tubes increases from top to bottom and in outer rows of tubes temperature increases from bottom to top. It can be seen that the increase in temperature of intermediate sodium is more in inner rows of tubes. Primary sodium temperature reduces from top to bottom and the temperature profile is seen to be smooth except the three kinks, which are due to baffle plates and belts. At the locations of baffle plates in the inner zone, a reduction in temperature is observed due to the heat transfer from primary sodium at low flow rate. For outer zone the reduction in temperature is due to the mixing with low temperature sodium coming from the inner zone. It is also found that heat transfer at inlet window length is ~80% of total heat transfer. The difference in primary sodium

Fig. 4a Variation of temperature of DHX along the height

outlet temperatures between the two zones is found to be 15 °C. Since the flow is taking place under natural circulation, estimation of buoyancy head is important for flow prediction and is estimated using the temperature profile as shown in the figure.

Figure 4b shows the distribution of heat sink per meter length in DHX. From the figure it can be seen that, maximum heat transfer takes place at the top of the DHX. Heat transfer rate reduces from top to bottom. The minimum heat transfer is seen to be at the bottom of DHX. There are three kinks as shown in the figure which represents reduction in heat sink capacity due to the baffle plates and belts. At this location, primary sodium from inner zone migrates to the outer zone (will be discussed in next section). Due to this migration, the enthalpy content of the inner zone reduces which results in a reduction of heat transfer capacity. Whereas, in the case of outer zone, the reduction in temperature results in a decrease in heat transfer capacity. From the figure it is found that, the heat transfer taking place at inlet window region constitutes major part of (~80%) the total heat transfer and thus shows the importance of modeling the inlet window region accurately.

Primary sodium flow rate is estimated as 46.3 kg/s. Flow distribution at inlet window is shown in Fig. 4c. For inlet flow rates and cross flow

Fig. 4b Distribution of heat sink (avg.), per m length

Fig. 4c Flow profile in shell side of DHX

rates, radial inward direction is represented as negative. The radial flow distribution along the length of inlet window is found to be of parabolic profile. Maximum inlet flow rate is seen at the top of the inlet window. Reverse flow in the inlet window is found near two locations. One is at the tube support belt location, which offers higher resistance for primary sodium flow and hence sodium comes out of the DHX. Reverse flow is estimated at the bottom of inlet window due to high pressure. This is because a higher heat transfer (~80%) at inlet window region results in lower primary sodium temperature at the bottom of inlet window, which creates a high pressure region. It can be seen from the figure that flow migration from inner zone to outer zone and vice-versa is taking place near the belt location. This is due to fact that, the baffle plate located in the inner zone provides a higher flow resistance path compared to the outer zone leading to flow migration to outer zone. Below the baffle plate a low pressure region is created which drives the sodium to flow into inner zone. The outward and inward migration of primary sodium from one zone to another zone observed at the belt locations enhances mixing between the two zones.

3.1 Grid Independence Study

A grid independent study is carried out by changing the number of nodes in axial direction in the range of 10 – 77 and is shown in Fig. 5. It is found that beyond 70 nodes, the change in heat transfer capacity is insignificant (< 0.1%). Thus, the chosen grid size is found to be adequate.

Fig. 5 Change in heat transfer capacity in the DHX with no. of nodes

3.2 Comparison with CFD Results

CFD analysis was carried out using a sector model of the DHX using commercial CFD code as given in the reference [17]. The results obtained from CFD study are compared with the present network model and is presented in the Table 2. It is found that the network model results are quite close to the CFD results and difference in heat transfer capacity is ~1.5%. Maximum difference in outlet temperatures of sodium in tube side and shell side is found to be < 5 °C. Comparison of sodium temperature variation within the tubes is shown in Fig. 6a and a good agreement can be seen from the figure.

Table 2: Comparison of CFD model and network model

Parameters	CFD Result	Network model result	Percentage deviation
Capacity of heat transfer	8.80 MW	8.93 MW	1.5
Outlet temperature of primary sodium in inner zone and outer zone	395.5 °C 418.4 °C	398.2 °C 413.6 °C	0.68 1.14
Outlet temperature of intermediate sodium	482.2 °C	483.2 °C	0.21
Total flow rate of primary sodium	44.3 kg/s	46.3 kg/s	4.5

Fig. 6a Comparison of temperature profile within tubes obtained from Network model and CFD study

3.3 Transient analysis

A transient analysis is carried out using the network model. A step change in flow rate of intermediate sodium (30 % to 100 % at 100 s) is given as transient boundary condition. Evolution of primary sodium flow rate is shown in Fig. 6b. From the figure it is found that, primary sodium flow takes ~30 s to reach the full flow rate.

Evolution of outlet temperatures of DHX is also depicted in the figure. It is also found that, the outlet temperatures of intermediate sodium and primary sodium takes ~30-40 s to reach the final value.

Fig. 6b Evolution of flow rates and outlet temperatures of tube and shell side in DHX

4. Conclusions

Thermal hydraulic analysis of multi-pass sodium-sodium heat exchanger (DHX) is carried out using network model. The heat transfer capacity and natural circulation flow rates of primary sodium are estimated. The radial flow distribution along the length of the inlet window is found to be of parabolic profile and the flow rate at the top most inlet point is found to be maximum. Flow migration from inner zone to outer zone at the tube support belts is predicted. Presence of tube support belts in shell side of DHX is found to enhance mixing of sodium between two zones. A transient study is carried out and the evolution of primary sodium flow rate and outlet temperatures of DHX are estimated. The network model results are found to be in reasonable agreement with CFD results. Thus, the network model is a promising option which can be utilized for thermal hydraulic analysis, viz., transient studies and parametric studies with less computational resources and in less time but still maintaining a reasonable accuracy compared to CFD codes.

Acknowledgement

The authors acknowledge the CFD work carried out by the project student Mr. Sathyajith Raj, Amrita University, which helped in verification of the Network model.

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