RADIATIVE HEAT TRANSFER MODEL DEVELOPMENT FOR INDIAN PHWR FUEL BUNDLE

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Abstract:

During the normal operation of the Pressurized Heavy Water Reactor (PHWR), fuel bundle is cooled through sufficient flow of heavy water. In certain postulated accident scenario, the coolant flow may cease and the fuel bundles may expose to steam and heat up as it continues to produce decay heat even after the reactor is shutdown. Under such condition, the fuel pins in the bundle would radiate heat to the enclosing tube called Pressure Tube. To model and analyze such scenario, an integral thermal-hydraulic code, PRABHAVINI, is being developed at BARC. A radiation heat transfer model was developed for the code based on the radiosity method and accounting for the anisotropic effect arising due to large/curve surfaces. Verification of the model was carried out using finite element package ANSYS. A detailed 2D finite element modeling and simulation of the radiative heat exchange in the channel was also carried out in ANSYS postulating a typical accident condition. Results of the simulation indicate that the assumption of uniform radiosity around the fuel rod may significantly affect the average surface temperature of the fuel.

Index Terms:PHWR channel, Radiation in fuel bundle, Anisotropic correction, ANSYS radiation model

I. INTRODUCTION

During the normal operation of the PHWR, the coolant passes through the fuel bundles in a horizontal channel, gaining heat through the convective mode and maintains the fuel temperature. In certain postulated accident scenario such as loss of coolant accident along with the failure to activate emergency core cooling system, the channel would be devoid of coolant flow and the fuel bundle would be exposed to steam. Under such situation the only dominant mode of heat rejection is the radiation heat transfer from the fuel bundle to the surrounding Pressure Tube enclosure.

A radiation heat transfer model based on Radiosity Matrix Method was developed for an integral thermal-hydraulics code PRABHAVINI. This code is being developed at Bhabha Atomic Research Centre (BARC) to address the severe accident phenomena in PHWRs. The code does not evaluate circumferential temperature gradient in the fuel pins. It assumes a uniform temperature and uniform flux around the fuel pin surface. The radiation model based on this assumption has the advantage of reduced computational cost but overestimates the heat transfer due to isotropic reflection. In reality there could be large temperature gradient for some fuel pins due to bounding geometry and boundary conditions. For such cases, dividing the surfaces into smaller elements would improve the prediction substantially but this may not be always feasible to implement in system codes. Andersen [1] developed a semi-empirical method to address the non-uniform radiosity in the conventional radiation model through an anisotropic correction factor. A further improvement in the correction factor suggested by Tien et al.[2] was implement in the model. Verification of this model was carried out with Finite Element (FE) package ANSYS. A detailed 2D FE modeling and analysis of the channel which includes fuel bundle, PT and CT was also carried out in ANSYS for a typical accident condition where in the radiative exchange plays the dominant role. It is observed that large temperature gradient can develop in the outer pins of the PHWR fuel bundle which warrants judicious use of the conventional radiation model in system code.

II. DESCRIPTION OF PHWR CHANNEL

The Primary Heat Transport (PHT) system of a typical 220 MWe Indian PHWR consists of 306 horizontal reactor channels submerged inside calandria vessel filled with moderator. Each reactor channel is connected to a common inlet and outlet header and consists of two concentric tubes, the PT and the CT, and the fuel bundles placed horizontally inside the PT (Fig.1). The pressure tube acts as a pressure boundary for the PHT system through which coolant at high pressure flows axially over the fuel bundles. The gap between PT and CT is maintained through four garter springs. During normal reactor operation, this gap essentially reduces the radial heat loss from the core to the moderator.

A 19 pin fuel bundle of 0.5 m length consists of three rings of pins generating heat in the ratio of 1: 1.1: 1.33 from inner to outer ring. The pins are arranged in the combination of triangular and square pitches as shown in Fig.2.

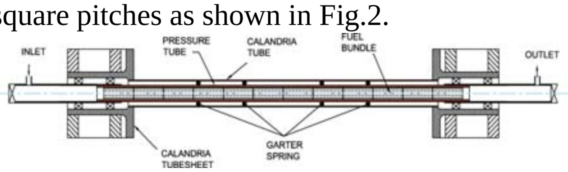

Fig.1 PHWR reactor channel

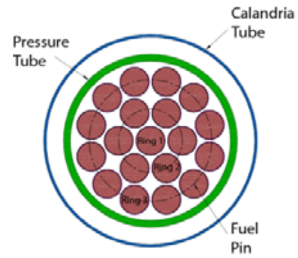

Fig.2 Fuel bundle configuration

III. RADIATION MODEL DEVELOPMENT

The PHWR fuel bundle along with the pressure tube is idealized as four sided enclosure filled with transparent medium. Three sides represent the pin surfaces at each ring and the fourth one represents the PT surface. The surfaces are considered gray and diffuse. For a planer surface at uniform temperature, radiosity (reflected plus emitted radiation) may be considered uniform in all direction referred as isotropic radiation. But for large and curved surfaces like PT and fuel pins, part of the reflected radiation would travel back to the origin surface of the incident radiation. This is taken into account through anisotropic correction factor proposed by Andersen [1] and Tien [2]. The formulation described below is adopted from Sohal [3].

In the anisotropy correction method, it is assumed that for each fuel rod i a fraction $(1-\mu_i)$ of the incident radiation I_i is reflected isotropically and the rest μ_i is reflected back to the source rod j. The isotropic part of the radiosity, J_i^I, from the surface i is given as

$$J_i^I = \epsilon_i \sigma T_i^4 + (1-\mu_i)(1-\epsilon_i)I_i \qquad (1)$$

And the anisotropic part which is reflected back to the originating surface j is given as

$$J_{ij}^A = \mu_i(1-\epsilon_i)I_{ij} \qquad (2)$$

where I_{ij} is the incident radiation to surface i from surface j

$$I_{ij} = \frac{1}{A_i}\left[J_j^I A_j F_{ji} + J_{ji}^A A_j\right] \qquad (3)$$

Using above equations and view factor reciprocity relation, following equation for radiosity, J_i^I, may be obtained.

$$\sum_{j=1}^{n}\left\{\left[1-\sum_{k=1}^{n}\frac{(1-\mu_i)(1-\epsilon_i)\mu_k(1-\epsilon_k)F_{ik}}{1-\mu_i(1-\epsilon_i)\mu_k(1-\epsilon_k)}\right]\delta_{ij} - \frac{(1-\mu_i)(1-\epsilon_i)F_{ij}}{1-\mu_i(1-\epsilon_i)\mu_j(1-\epsilon_j)}\right\}J_j^I = \epsilon_i\sigma T_i^4 \qquad (4)$$

Where, δ_{ij} is given as

$$\delta_{ij} = \begin{cases}1, & for\ i=j\\ 0, & for\ i\neq j\end{cases}$$

Equation (4) can be written for each of the 'n' surfaces of the enclosure giving 'n' simultaneous equations. It can be expressed in the Matrix form as

$$[C_{ij}^1][J_i^I] = [\sigma T_i^4] \quad (5)$$

Where,

$$C_{ij}^1 = \left[1 - \sum_{k=1}^{n} \frac{(1-\mu_i)(1-\epsilon_i)\mu_k(1-\epsilon_k)F_{ik}}{1-\mu_i(1-\epsilon_i)\mu_k(1-\epsilon_k)}\right]\delta_{ij} - \frac{(1-\mu_i)(1-\epsilon_i)F_{ij}}{1-\mu_i(1-\epsilon_i)\mu_j(1-\epsilon_j)} \quad (6)$$

For known values of T_i, the radiosities J_i^I are obtained through Gauss-Seidel method.

The net radiation heat flux from the surface i can be calculated from the radiosity and the incident radiation as below

$$q_i = \left(J_i^I + \sum_{j=1}^{n} J_{ij}^A\right) - I_i$$

$$q_i = \frac{\epsilon_i}{(1-\mu_i)(1-\epsilon_i)}\{\sigma T_i^4[1-\mu_i(1-\epsilon_i)] - J_i^I\} \quad (7)$$

For surfaces where net heat fluxes are prescribed,

$$[C_{ij}^2][J_i^I] = \left[\frac{q_i(1-\mu_i)(1-\epsilon_i)}{1-\mu_i(1-\epsilon_i)}\right] \quad (8)$$

$$C_{ij}^2 = \left[1 - \sum_{k=1}^{n} \frac{(1-\mu_i)(1-\epsilon_i)\mu_k(1-\epsilon_k)F_{ik}}{1-\mu_i(1-\epsilon_i)\mu_k(1-\epsilon_k)} - \frac{\epsilon_i}{(1-\mu_i(1-\epsilon_i)}\right]\delta_{ij} - \frac{(1-\mu_i)(1-\epsilon_i)F_{ij}}{1-\mu_i(1-\epsilon_i)\mu_j(1-\epsilon_j)} \quad (9)$$

Based on Tien et al.[2] recommendation, anisotropic factor μ of 0.5 for the fuel rods and 0.15 for the enclosure tube (PT) were used.

The view factors F for the 19 pin fuel bundle were calculated by Hottel's cross-string method

$$F = \begin{bmatrix} 0.0 & 0.9577 & 0.0367 & 5.64\times10^{-3} \\ 0.1596 & 0.3357 & 0.4918 & 0.0129 \\ 3.0587\times10^{-3} & 0.2459 & 0.3301 & 0.4209 \\ 1.0399\times10^{-3} & 0.0143 & 0.9313 & 0.0534 \end{bmatrix}$$

IV. Verification Analysis

A. Single Pin Enclosure

In this exercise, a single pin generating heat enclosed in a concentric tube was analyzed. The temperature of the tube was maintained constant. Both the pin and the tube were assumed to have the same material properties and emissivity. Problem definition, the boundary conditions and the corresponding FE model in ANSYS is shown in Fig.3. The surface temperature of the fuel rod is evaluated through steady state analysis in ANSYS. Comparison of the predicted temperature is shown in Table 1. Here the radiosity around the pin is uniform and hence anisotropic factor is assumed zero in the model prediction.

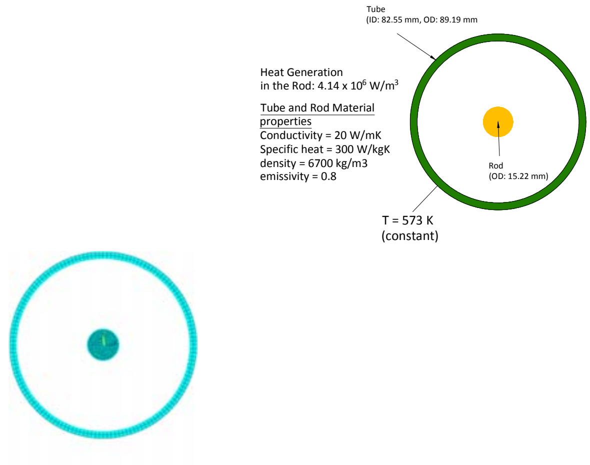

Fig.3 Problem definition and meshing

Table 1 Results of the analysis

	Analytical	ANSYS	PRABHAVINI
Pin surface temperature	827 K	827.75 K	827 K

B. PHWR fuel bundle

Radiative heat exchange in PHWR 19 pin fuel bundle with the PT enclosure was analyzed using PRABHAVINI and ANSYS code. Detail of the model is shown in Fig.4. It is assumed that the fuel bundle is exposed to the non-participating medium steam. The bundle is generating decay heat of 8.9 kW with radial power factor of 1: 1.1: 1.33. PT is maintained at a temperature of 1275 K.

In the radiation model, the heat fluxes on the enclosure surfaces (the inner, the middle and the outer pins) were prescribed based on the power generation and area. Using (5) for the pins and (8) for the PT, coefficient matrix was formulated. The matrix was then solved for isotropic radiosity J_i^I and the surface temperatures of the fuel pins were calculated using (7). The predicted temperatures are shown in Table 2.

The FE meshing of the fuel, the clad and the PT in ANSYS is shown in Fig.5. PLANE55 element was used for the solid components for temperature calculation and a surface element SURF251 was used for radiation heat flux calculation. Each pin generates heat based on the radial power factor. At the interface of the fuel and the clad, temperature continuity is assumed. A steady state solution was obtained for the imposed PT temperature.

The temperature distribution obtained from ANSYS solution is shown in Fig.6. The circumferential temperature profile for the pins shown in Fig.7, Fig.8 and Fig.9 indicate large temperature gradient along the pin surface. Average temperatures calculated from the ANSYS results are shown in Table 2. The differences in the predicted temperature between the model and the ANSYS can be attributed to the non-uniform local view factor effects which introduce significant two-dimensional non-uniformity in the temperatures and heat fluxes in the FE model. In the conventional model, the assumption of uniform radiosity and uniform temperature around the pin surfaces overestimate the transfer of heat and reduce the surface temperature.

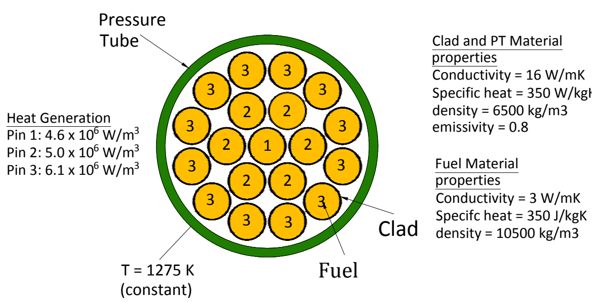

Fig.4 Problem definition

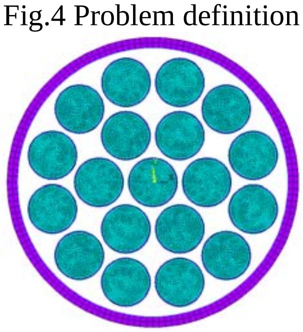

Fig.5 Meshing of the fuel bundle and PT

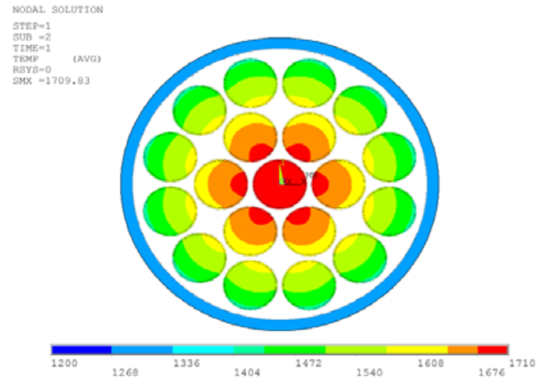

Fig.6 Channel temperature distribution

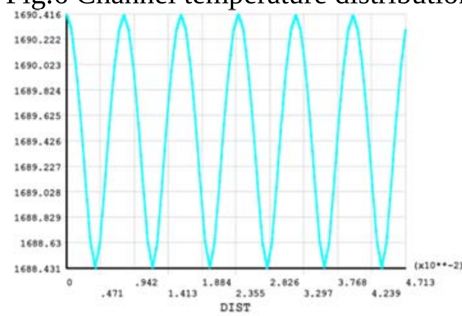

Fig.7 Center pin circumferential temperature

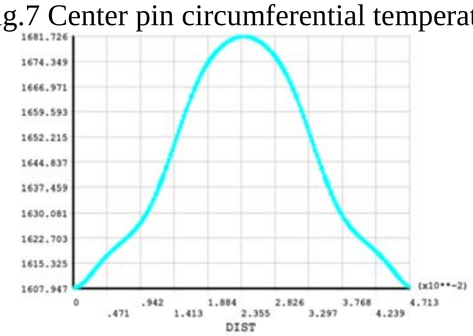

Fig.8 Middle pin circumferential temperature

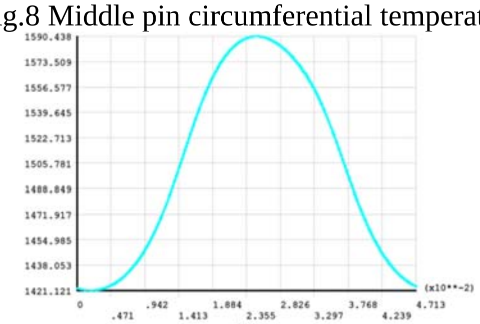

Fig.8 Outer pin circumferential temperature

Table 2: Surface temperature predictions

	PRABHAVINI		ANSYS
	Isotropic radiation	With Anisotropic correction	
Centre pin surface temperature	1508.0 K	1530.0 K	1689.5 K
Middle pin surface temperature	1490.6 K	1509.0 K	1643.0 K
Outer pin Surface temperature	1440.3 K	1448.6 K	1506.0 K
PT temperature (imposed condition)	1275.0 K	1275.0 K	1275.0 K

V. CONCLUSION

A radiation exchange model was developed for PRABAHVINI code based on the formulation of anisotropic correction factor. The model accounts for non-uniform reflected radiation and found to predict improved fuel surface temperature compared to the conventional isotropic radiosity method. A detailed analysis of PHWR fuel bundle performed with ANSYS indicates large circumferential temperature gradient and non-uniform heat fluxes around the surface of the fuel pins, consequently, higher surface temperature is predicted. In spite of the limitations, the conventional method of lumping fuel surfaces is widely and successfully used in system codes for simulating radiation specifically in reactor core with large number of rods e.g. in Pressurized Heavy Water reactors. In such configuration non-uniformity mainly exists at the peripheral rods and its influence is less felt away from the bounding surface.

REFERENCES

[1] Andersen, J. G. M., and Tien, C. L.,"Radiation heat transfer in a BWR fuel bundle under LOCA conditions", Fluid Flow and Heat Transfer Over Rod or Tube Bundles, p. 197, American Society of Mechanical Engineers, New York, 1979.

[2] Tien, C. L., Sanchez, R. A., Mandell, D. A. and McDaniel, C. T., (1979), "Surface Radiative Exchange in Rod Bundles", Trans. ASME, J. Heat Transfer, 101, 378, 1979.

[3] Manohar S. Sohal, "A Radiation Heat Transfer Model for the SCDAP Code", Nuclear Technology, Vol. 75, pp. 196-204, 1986.