RADIATION HEAT TRANSFER CODE DEVELOPMENT IN NUCLEAR POWER PLANT

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ABSTRACT: PRABHAVINI is the integrated code under development at Reactor Safety Division, BARC. The code aims to simulate degradation of PHWR under a Postulated Initiating Event such as Loss of Coolant Accident arising from high energy pipe break along with failure of Emergency Core Cooling System. Under such postulation the nuclear fuel bundles are devoid of coolant, tend to get heated up. The nuclear fuel bundles are housed in Pressure Tube which is again housed in Calandria Tube. Under postulated accident conditions, due to loss of cooling, the fuel bundle temperature rises and the radiation heat transfer to the Pressure Tube becomes dominant as compared to convective heat transfer. Rise in the fuel bundle temperature also causes deformation of the fuel pins changing the overall geometry of the fuel bundle. The radiation heat transfer from the fuel bundle to the Pressure Tube thus varies with time as not only the fuel temperatures but also the view factors amongst fuel pins change as accident progresses. It is therefore necessary to calculate radiation heat fluxes taking into account the change in view factors.

NOMENCLATURE

A	**Area, m²**
A_c	**Cross-sectional area, m_2**
D	**Diameter, m**
G	**Gravitational acceleration, m/s2**
h	**Convective heat transfer coefficient, W/m2k; planks constant**
J	**Radiosity, W/m2**
k	**Thermal conductivity, W/mk**
L	**Characteristic length, m**
P	**Perimeter, m**
Q	**Heat transfer rate, W**
T	**Temperature, k**
t	**Time, s**
V	**Volume,m3**
ν	**Sp. Volume m3/kg**
α	**Absorptivity**
ρ	**Reflectivity**
τ	**Transmissivity**
ε, Є	**Emissivity**
λ	**Wavelength, µm**
σ	**Stefansboltzmann's constant**

INTRODUCTION

PHWR is a horizontal pressure-tube type reactor, with the several parallel reactor channels. The fuel bundles are housed inside Pressure Tube (PT) which in turn is housed in Calandria Tube (CT).There are two kinds of PHWRs[1-2] in India. The small 220MWe PHWR based power plants are more in number as of today as compared large 540MWe PHWR. In addition, design of 700MWe PHWR is in progress.

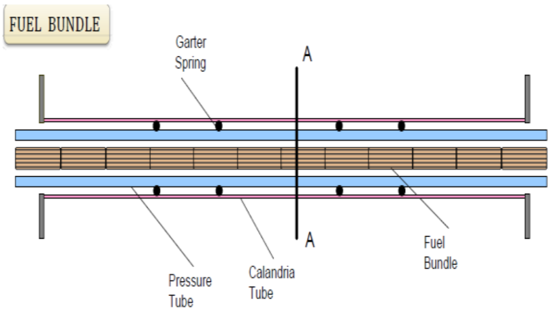

Figure 1: SCHEMATIC OF A PHWR REACTOR CHANNEL

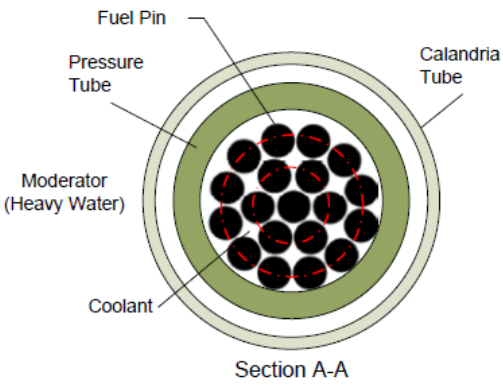

Figure 2: CROSS SECTIONAL VIEW OF A PHWR REACTOR CHANNEL

Under a Postulated Initiating Event such as Loss of Coolant Accident arising from high energy pipe break along with failure of Emergency Core Cooling System the nuclear fuel bundles are devoid of coolant and it tends to get heated up. The nuclear fuel bundles are housed in Pressure Tube which is again housed in Calandria Tube. Under postulated accident conditions, due to loss of cooling, the fuel bundle temperature rises and the radiation heat transfer to the Pressure Tube becomes dominant as compared to convective heat transfer. Rise in the fuel bundle temperature also causes deformation of the fuel pins changing the overall geometry of the fuel bundle. The radiation heat transfer from the fuel bundle to the Pressure Tube thus varies with time as not only the fuel temperatures but also the view factors amongst fuel pins change as accident progresses.

THE VIEW FACTORS [3]

Radiation heat transfer between surfaces depends on the orientation of the surfaces relative to each other as well as their radiation properties and temperatures. View factor (or shape factor) is a purely geometrical parameter that accounts for the effects of orientation on radiation between surfaces.

In view factor calculations, we assume uniform radiation in all directions throughout the surface, i.e., surfaces are isothermal and diffuse. Also the medium between two surfaces does not absorb, emit, or scatter radiation.

Note the following:

- The view factor ranges between zero and one.
- $F_i \rightarrow j$ or F_{ij} = the fraction of the radiation leaving surface i that strikes surface j directly.
- $F_{ij} = 0$ Indicates that two surfaces do not see each other directly.
- $F_{ij} = 1$, *i* indicates that the surface *j* completely surrounds surface *i*.
- The radiation that strikes a surface does not need to be absorbed by that surface.

Fii is the fraction of radiation leaving surface i that strikes itself directly. $F_{ii} = 0$ for plane or convex surfaces, and $F_{ii} \neq 0$ for concave surfaces (Figure 3).

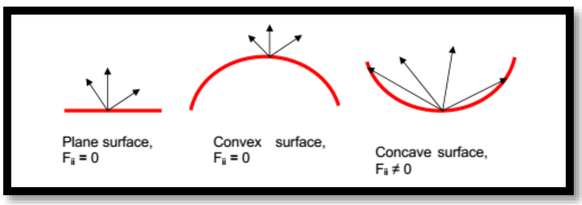

Figure 3: VIEW FACTOR BETWEEN SURFACE AND ITSELF

METHOD FOR CALCULATION OF VIEW FACTORS

The Crossed-String Method [3]

Geometries such as channels and ducts that are very long in one direction can be considered two-dimensional (since radiation through end surfaces can be neglected). The view factor between their surfaces can be determined by cross string method developed by H. C. Hottel, as follows:

$$F_{i\rightarrow j}=\frac{\sum(\text{Crossed Strings})-\sum(\text{Uncrossed Strings})}{2*(\text{string on surface i})}$$

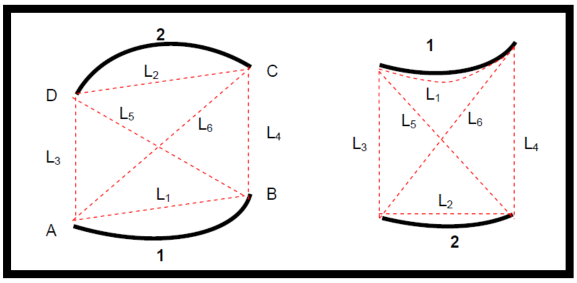

Figure 4: CROSS STRING METHOD

$$F_{12}=\frac{(L_5+L_6)-(L_3+L_4)}{2L_1} \qquad (1)$$

CALCULATION OF VIEW FACTORS FOR 37 PIN CONFIGURATIONS

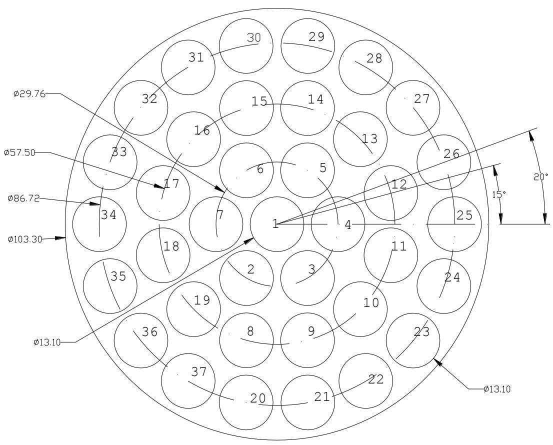

Figure 5: FUEL PIN STRUCTURE FOR 37 PIN ARRANGEMENT

The View Factors for 37 pin configuration is determined in different steps with respect to the individual pins. Each fuel pin is of constant diameter of 13.1mm. The fuel pins are arranged in a particular manner. The fuel pins (2, 3, 4, 5, 6 and 7) are placed at a distance of 14.8mm w.r.t fuel pin 1. The fuel pins (8, 9, 10…, 18 and 19) are placed at a distance of 28.75mm w.r.t fuel pin 1 and the fuel pins (20, 21, 22… 37) are placed at a distance of 43.30mm w.r.t fuel pin 1. These pin structure is enclosed in the pressure tube (PT) having ID= 103.3mm, OD= 112.06mm. The PT is enclosed inside the Calandria Tube (CT) having ID= 128.7mm.

The View Factor is determined using the formulae-

$$F_{ij}=\frac{1}{2\pi}\left\{\begin{array}{l}\pi+\sqrt{[C^2-(R+1)^2]}-\sqrt{[C^2-(R-1)}\\ +(R-1)\cos^{-1}\left[\left(\frac{R}{C}\right)-\left(\frac{1}{C}\right)\right]-(R+1)\cos^{-1}\left[\right.\end{array}\right. \quad (4)$$

where

r1= radius of pin-1

r2= radius of pin-2

d= distance between the pins

S= center to center distance of the fuel pins

R= ratio of the radius of the two pins.

C= 1+R+S

RESULTS

The model is simulated under COMSOL for different geometry configurations and the results obtained were validated. The model imported is provided with the global boundary conditions for the 'Heat Transfer in Solids' where we select the mode of heat transfer as surface to surface radiation. The model is made of zirconium alloy, whose material properties are provided as user input, thermal conductivity of material (k)= 12.767 W/mK, density of the material (ρ) = 6560 kg/m^3, specific heat at constant pressure (C_p) = 285.66 J/kgK, and the surface emissivity of the material is 0.5. The initial value of temperature considered is 293.15K. The solution obtained is time dependent and the equation used to solve is $-n.(k\nabla T)=qo$ where the inward heat flux considered is q_o = 0 W/m^2.

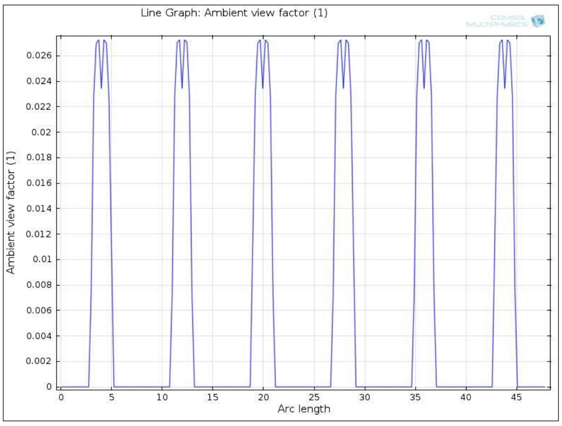

Figure 6: VIEW FACTOR PLOT FOR FUEL PIN 1 IN 19 PIN ARRANGEMENTS

The above graph is plotted for the view factor against the arc length which is exposed in the reactor channel. The peaks in the above graph represent the open space where the radiation is been exposed to the ambient for the specified arc length, and as the arc length increases, there is obstruction to the emitting radiation by the surrounded fuel pins. Thus the view factor drops to a nearest value zero.

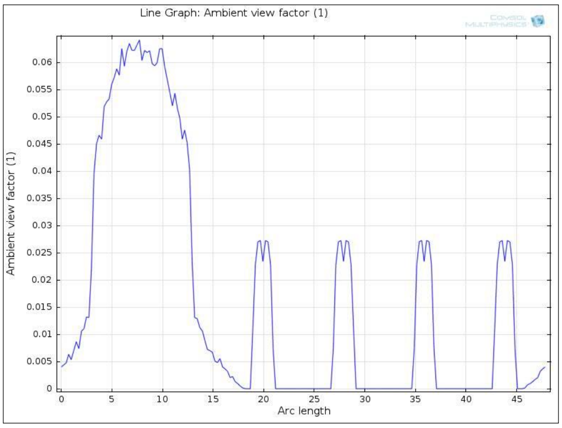

Figure 7: VIEW FACTOR PLOT FOR FUEL PIN 1 BY REMOVING PIN 2

VARIATION IN VIEW FACTORS WITH PRESSURE TUBE BALLOONING

Table 1: VIEW FACTORS FOR DIFFERENT PTDIAMETERS FOR 37 PIN CONFIGURATIONS

PT Dia (mm)	F_{38-1}	F_{38-2}	F_{38-8}	F_{38-20}	F_{38-38}
103.3	1.06E-03	2.28E-03	1.02E-02	5.13E-02	1.02E-01
106.3	1.03E-03	2.22E-03	9.92E-03	4.99E-02	1.27E-01
109.3	9.98E-04	2.15E-03	9.65E-03	4.85E-02	1.51E-01
112.3	9.72E-04	2.10E-03	9.39E-03	4.72E-02	1.74E-01
115.3	9.46E-04	2.04E-03	9.15E-03	4.60E-02	1.95E-01
118.3	9.22E-04	1.99E-03	8.91E-03	4.48E-02	2.16E-01
119.9	9.10E-04	1.96E-03	8.79E-03	4.42E-02	2.26E-01

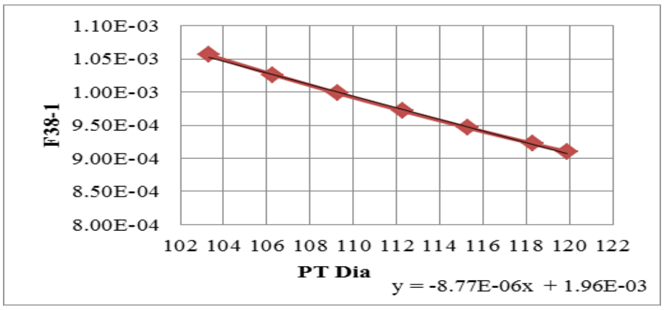

Fig. 8: Plot for F_{38-1} for variation in pressure tube diameter

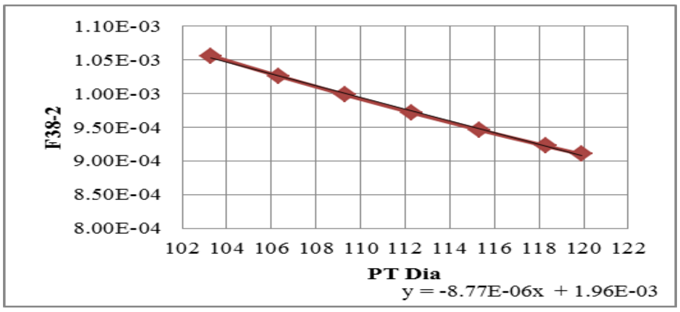

Fig. 9: Plot for F_{38-2} for variation in pressure tube diameter

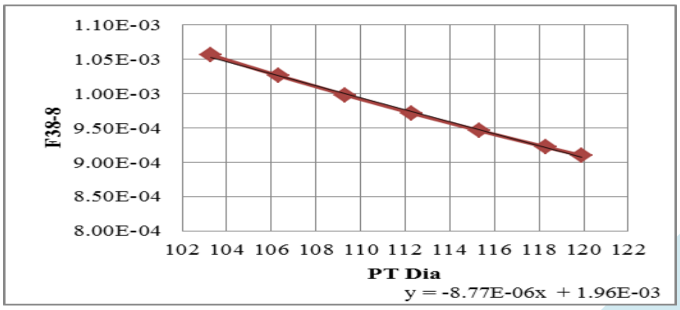

Fig. 10: Plot for F_{38-8} for variation in pressure tube diameter

CONCLUSION

The calculations were validated against the hand calculations carried out using fundamental laws of radiative heat transfer. Calculations were also performed for view factors for 19- pin bundle with ballooned PT geometry. The effect of ballooning of Pressure Tube (PT) under accident conditions on view factors was also calculated and represented using linear curve fits. View Factor change is not so significant (0.145%) for VF within pins, but significant for PT (2.535%).

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