CHAPTER 4

TRANSIENT HEAT CONDUCTION IN NUCLEAR FUEL PIN

In chapter 3, stability map was obtained by considering the constant wall heat flux to be independent of flow conditions and specified to be constant. In this chapter, we try to integrate the fuel pin conduction to the coolant flow model by considering the volumetric heat generation in fuel pin to find the influence of fuel pin conduction on the stability boundary for NCBWR.

4.1 Radial Heat conduction in nuclear fuel elements

Reactor fuel pin is a cylindrical fuel element that contain fuel pellet, gap and cladding as shown in Figure 4.1. Coolant can be in single phase or two phase. Fuel and clad properties are available as a function of temperature. The state of the coolant is obtained from convection equations. Thus, the information is provided by these to transient conduction solver. As the equation is non-linear due to complex property and boundary conditions, numerical solutions are called for. In section 4.2, finite volume approach is presented which is used for present code. Heat transfer coffecient (h_f) is obtained from appropriate correlation. Gap conductance (h_{gap}) obtained from conservative values.

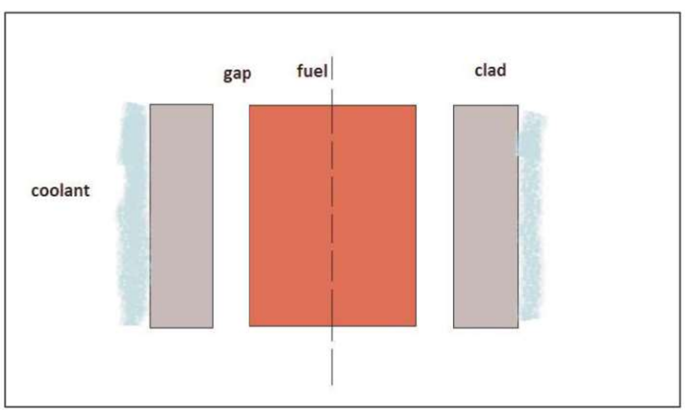

Figure 4.1 Illustrative representation of fuel pin geometry

Basic governing equation is

$$\frac{\partial}{\partial t}\left(\rho c_p T\right) = \nabla.(K\ \nabla \mathrm{T}) + q''' \tag{4.1}$$

Over assumption of azimuthal symmetry and neglecting axial conduction affects as the temperature gradients in radial direction are usually very high when compared to those in axial direction, the governing Eq. (4.1) becomes

$$\frac{\partial}{\partial t}\left(\rho c_p T\right) = \frac{1}{r}\frac{\partial}{\partial r}\left(rk\frac{\partial T}{\partial r}\right) + q''' \qquad [4.2]$$

4.2 Discretized equations for fuel pin geometry using finite volume approach

In this section, governing Eq. 4.2 is integrated over volume and time at i[th] node to obtain the discretized equations.

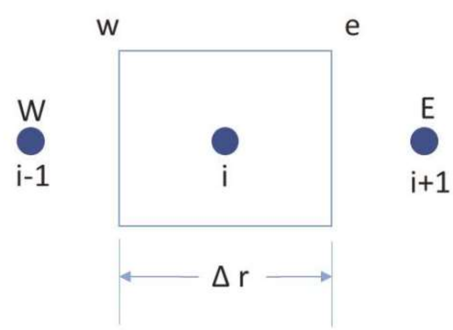

Figure 4.2 Unit cell representation

I. Transient term

$$\int_{r-(\Delta r/2)}^{r+(\Delta r/2)} \int_{t}^{t+\Delta t} \frac{\partial}{\partial t}(\rho CT) r dr dt \;=\; \rho C_{Ti}(T_i^{n+1} - T_i^{n}) r_i \Delta r_i \qquad [4.3]$$

Where, T_i^{n+1}, T_i^{n} represents average values in the control volume at n+1$^{\text{th}}$ and n$^{\text{th}}$ timesteps at i$^{\text{th}}$ node location.

II. Conduction term

$$\int_t^{t+\Delta t}\int_w^e \frac{1}{r}\frac{\partial}{\partial r}\left(rk\frac{\partial T}{\partial r}\right)rdrdt = \frac{r_e k_e}{\left(\frac{\Delta r_i + \Delta r_{i+1}}{2}\right)}T_e^{n+1} + \frac{r_w k_w}{\left(\frac{\Delta r_{i-1} + \Delta r_i}{2}\right)}T_w^{n+1} - \left[\frac{r_e k_e}{\left(\frac{\Delta r_i + \Delta r_{i+1}}{2}\right)} + \frac{r_w k_w}{\left(\frac{\Delta r_{i-1} + \Delta r_i}{2}\right)}\right]T_p^{n+1}$$

.....[4.4]

III. Heat generation term

$$\int_t^{t+\Delta t}\int_w^e q''' rdrdt = q_i''' \Delta t\left(\frac{r_e^2 - r_w^2}{2}\right) = q_i''' \Delta t\, r_i \Delta r_i \qquad [4.5]$$

Over substitution of equations 4.3,4.4 and 4.5 in Eq. 4.2, we get

$$A_i T_{i+1}^{n+1} + D_i T_i^{n+1} + B_i T_{i-1}^{n+1} = C_i \qquad [4.6]$$

Where,

$$A_i = \frac{r_e k_e}{\left(\frac{\Delta r_i + \Delta r_{i+1}}{2}\right)} \quad \text{where} \quad r_e = \left(\frac{r_i + r_{i+1}}{2}\right)$$

$$B_i = \frac{r_w k_w}{\left(\frac{\Delta r_{i-1} + \Delta r_i}{2}\right)} \quad \text{where} \quad r_w = \left(\frac{r_i + r_{i-1}}{2}\right)$$

$$D_i = -A_i - B_i - \frac{\rho_i C_i}{\Delta t} r_i \Delta r_i$$

$$C_i = -\frac{\rho_i C_i}{\Delta t} r_i \Delta r\, T_i^n + q_i''' r_i \Delta r_i$$

The above Eq. (4.6) represents the internal nodes of fuel pellet and cladding.

IV. Boundary condition at centerline

The boundary treatment in general is

$$A_1 \frac{dT}{dr} + B_1 T = C_1$$

At centerline, $\left.\frac{dT}{dr}\right|_0 = \frac{T_2 - T_1}{\Delta r_1}; \; T = \frac{T_1 + T_2}{2}$

$$T_1\left[\frac{-A_1}{\Delta r_1}+\frac{B_1}{2}\right]+T_2\left[\frac{A_1}{\Delta r_1}+\frac{B_1}{2}\right]=C_1 \qquad [4.7]$$

As $\left.\frac{dT}{dr}\right|_0=0$, $A_1=1, B_1=0, C_1=0$

V. Gap treatment

At fuel-gap interface, heat conducted from fuel is equal to heat convected through gas which gives

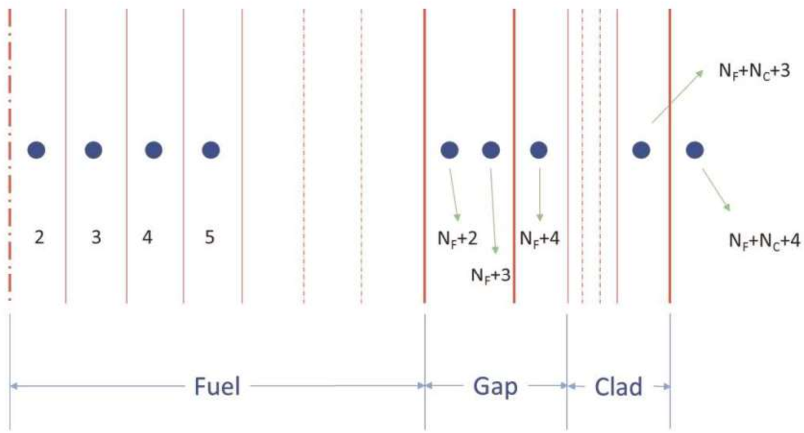

Figure 4.3 Node distribution in fuel pin

$$T_{NF+1}\left(\frac{k_{fi}r_{fi}}{\Delta r_{NF+1}}-\frac{r_{fi}h_g}{2}\right)+T_{NF+2}\left(-\frac{k_{fi}r_{fi}}{\Delta r_{NF+1}}-\frac{r_{fi}h_g}{2}\right)+T_{NF+3}\left(\frac{r_{fi}h_g}{2}\right)+T_{NF+4}\left(\frac{r_{fi}h_g}{2}\right)=0 \qquad [4.8]$$

Similarly for gap-cladding interface, heat convected through gap at clad surface is equal to heat conducted into clad which gives

$$T_{NF+1}\left(\frac{r_{fi}h_g}{2}\right)+T_{NF+2}\left(\frac{r_{fi}h_g}{2}\right)+T_{NF+3}\left(-\frac{k_{ci}r_{ci}}{\Delta r_{NF+4}}-\frac{r_{fi}h_g}{2}\right)+T_{NF+4}\left(\frac{k_{ci}r_{ci}}{\Delta r_{NF+4}}-\frac{r_{fi}h_g}{2}\right)=0 \qquad [4.9]$$

VI. Boundary condition at clad outer diameter

At clad outer diameter, boundary conditions are bulk fluid temperature (T_∞) and coolant fluid heat transfer coeffecient (h_f).

$$-k\frac{\partial T}{\partial r}=h_f(T-T_\infty)$$

$$-k_c\left(\frac{T_{NF+NC+4}-T_{NF+NC+3}}{\Delta r_{NF+NC+3}}\right)=h_f\left(\frac{T_{NF+NC+3}+T_{NF+NC+4}}{2}-T_\infty\right)$$

$$T_{NF+NC+3}\left(\frac{k_c}{\Delta r_{NF+NC+3}}-\frac{h_f}{2}\right)+T_{NF+NC+4}\left(-\frac{k_c}{\Delta r_{NF+NC+3}}-\frac{h_f}{2}\right)=-h_fT_\infty \qquad [4.10]$$

Where, NF and NC represents number of nodes in fuel pellet and clad respectively. Subscripts f,g,c represents fuel,gap and clad respectively.

Equations 4.6 to 4.10 forms tridiagonal matrix system of order NF+NC+4 which can be solved to get the temperatures of the fuel pin at each time step.

4.3 Benchmarking of code

Code is developed to solve for transient heat conduction using finite volme method. To benchmark the code, a simple transient radial heat conduction problem is considered. Code is benchmarked by comparing the analytical results with code results.

The problem considered has the conditions

Volumetric heat generation, $q''' = e^t[r^2-4]$

At centerline $\frac{dT}{dr}=0$; At outer radius $T(r=R)=e^tR^2$

The analytical solution for above conditions is $T(r,t)=e^tr^2$

Figure 4.2 shows the comparison of analytical and code results with cylinder outer radius R has the value of 0.1. Code results are found to agree with analytical results, hence the code is benchmarked.

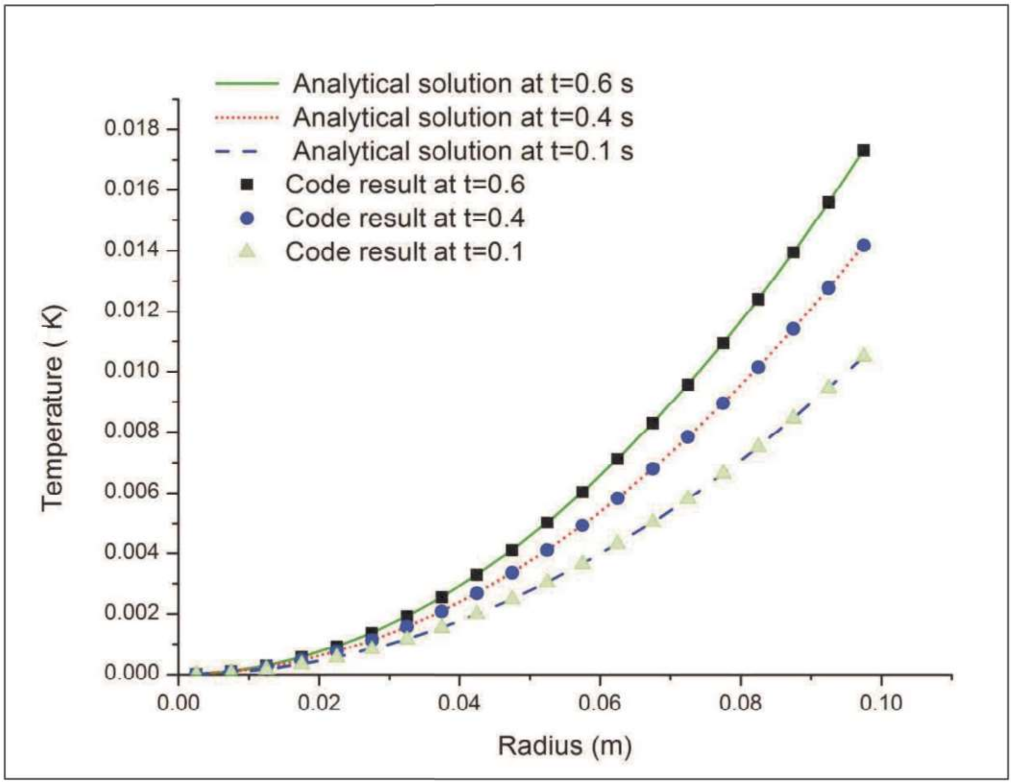

Figure 4.4 Temperature distribution along the radius for benchmark problem

4.4 Fuel pin heat conduction for NCBWR

Code is extended for NCBWR fuel pin data taken from BARC [30].

Fuel pin data considered is as follows.
Fuel pin length- 3.5m
Fuel pin radius- 0.1120m
Clad thickness- 0.0006m
Gap conductance-7000 W/m^2 K

Fuel (UO2) and clad (Zircalloy-2) thermo-physical properties are taken as functions of temperature from INSC [28]. Chen's correlation [29] is used to find the two phase heat transfer coeffecient.

I. For steady state temperature distribution of fuel pin rod

To obtain steady state results, following procedure is followed

1) Coolant channel flow is solved for steady state without fuel pin conduction from which bulk fluid temperatures are obtained.

2) Clad wall temperatures are solved iteratively using bulk fluid temperature and chen's correlation.

3) Now, steady state fuel temperatures are obtained by solving fuel pin heat conduction with wall temperature as boundary condition.

Figure 4.5 shows the steady state temperature profiles at various sections along the length of the fuel pin.

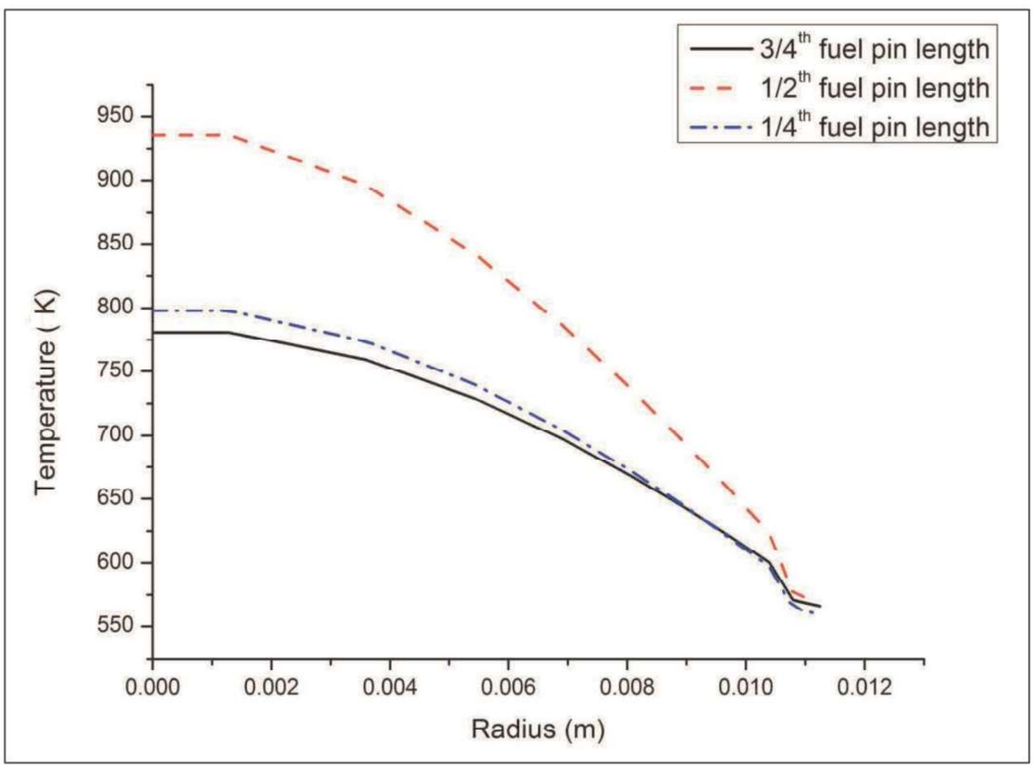

Figure 4.5 Temperature distribution along the radius of NCBWR fuel pin