## 1-Steady State Thermal Hydraulic Analysis In Single Channel

Thermal hydraulic analysis aims to ensure that certain safety criteria are met. The fuel's temperature must not exceed the maximum limit established by materials engineers, which usually corresponds to the temperature at which the metal begins to soften. Similarly, the cladding's temperature needs to stay within a safe range, defined by the temperature at which a reaction between metal and water might occur. Additionally, the heat flux must be kept below the Critical Heat Flux (CHF) limit to avoid potential hazards.

The reactor core is essentially defined as the assembly that includes the fuel material, along with the moderator and coolant materials. It can be envisioned as a uniform array of rods. Each of these rods consists of an outer cladding and inner fuel pellets.

Power density (Q''') is defined as the thermal power generated per unit core volume.Linear heat rate (q') is defined as the thermal power generated per unit length of the fuel rod. Heat flux (q'') is defined as the thermal power generated per unit external surface area of the fuel rod. Volumetric heat generation (q''') rate is defined as the thermal power generated in the core per unit fuel volume. Consider an infinitesimal volume (d V) of unit cell and let the thermal power generated be (d Q). The power density can be written as per equation 1.1.

$$Q''' = \frac{d\,Q}{p^2\,d\,l} \quad [1.1]$$

Similarly, the linear heat rate can be written for the control volume of length dl as per equation 1.2.

$$q' = \frac{d\,Q}{d\,l} \quad [1.2]$$

Similarly, the heat flux for the control volume can be written as per equation 1.3 and finally, the volumetric heat generation rate can be written as per equation 1.4.

$$q'' = \frac{d\,Q}{\pi\, d_{rod}\, d\,l} \quad [1.3] \quad \text{and} \quad q''' = \frac{d\,Q}{\frac{\pi}{4}\, d_{pellet}^2\, d\,l} \quad [1.4]$$

Since dQ is same in all the above equations,above equations can be merged and concluded as per equation 1.5.

$$Q'''\,p^2 = q' = q''\pi d_{rod} = q'''\frac{\pi}{4} d_{pellet}^2 \quad [1.5]$$

Single channel hot channel analysis is typically conducted to evaluate the overall safety of a nuclear reactor. The steps involved are as follows:

i. Identify the Hot Channel: This is usually the central fuel channel within the reactor.
ii. Calculate Maximum Linear Heat Rate: Determine the maximum linear heat rate in the central channel by dividing the global average linear heat rate by the product of the radial and axial power factors.
iii. Determine Mass Flow Rate: Compute the mass flow rate for the channel by dividing the average mass flow rate per channel by any radial factor introduced by orifices.
*iv.* Initial Analysis: Begin the analysis with a single-phase, constant-property flow to simplify the process.

The linear heat rate variation can be written in terms of sinusoidal variation of axial positions as per equation [1.6]

$$q' = q'_{max} sin\left(\frac{\pi\, z}{H}\right) \quad [1.6]$$

Energy Balance:

$$\dot{m} C_p dT_B = q'\,dz = q'_{max} sin\left(\frac{\pi\, z}{H}\right) dz \quad [1.7]$$

Upon integrating equation 1.7, Bulk temperature is obtained which is mentioned below in per equation 1.8.

$$T_B = T_{B-in} + \frac{q'_{max}\, H}{\dot{m}\, C_p \pi}\left(1 - cos\left(\frac{\pi\, z}{H}\right)\right) \quad [1.8]$$

After determining the temperature distribution for the fluid, the next step is to focus on calculating the outer cladding temperature. Using the definition of the convective heat transfer coefficient, the relationship can be expressed as per equation 1.9.

$$T_{CO}(z) = \frac{q''(z)}{h} + T_B(z) \quad [1.9]$$

To determine the cladding temperature distribution, a conduction analysis must be performed within the cladding material. This involves solving the heat conduction equation, taking into account the thermal properties of the cladding and the boundary conditions imposed by the surrounding fluid and fuel. Therefore after applying the governing equation for axis-symmetric conduction equation 1.10 is obtained.

$$-\int_{T_c}^{T_{CO}} k_c \, dT_c = \int_{r}^{R_{co}} q''R_{CO}\frac{dr}{r} \quad [1.10]$$

Assuming clad conductivity to be constant and taking the other limit to the clad inner radius equation 1.11 be obtained that is used to calculate inner clad temperature.

$$T_{CI} = T_{CO} + \frac{q''}{k_c}R_{CO}ln\left(\frac{R_{CO}}{R_{CI}}\right) \quad [1.11]$$

Before performing conduction analysis in fuel pellet, it is important to calculate pellet outer temperature due to gap between clad and the fuel. The thermal resistance of the gap between fuel and cladding can be reduced by filling it with helium. For conservative estimates, the gap conductance is often assumed to be 5500 W/m²-K. The temperature drop across the gap can be estimated using equation 1.12.

$$\Delta T_{gap} = \frac{q''}{h} \quad [1.12]$$

Thus, the fuel surface temperature can be computed as per equation 1.13.

$$T_f(R_f) = T_{CI} + \Delta T_{gap} \quad [1.13]$$

Now on perform conduction analysis in fuel pellet and using the boundary condition that $\frac{dT_f}{dr} = 0$ at centre equation 1.14 is obtained as follow.

$$\int_{0}^{T_f(0)} k_f dT_f - \int_{0}^{T_f(R_f)} k_f dT_f = \frac{q'}{4\pi}R_f^2 \quad [1.14]$$

The integral $\int kdT$, derived from Westinghouse Composite K, is closely aligned with Lyon's equation when considering 95% theoretical density. This approach is detailed in the works of Kazimi and Todreas. Equation 1.15 shown below is used to calculate $\int kdT$.

$$\frac{\ln\left(\frac{11.8 + 0.0238 \, X \, T}{11.8}\right)}{0.0238} + (8.78 \, X \, 10^{-13} X \, T^4)/4 \quad [1.15]$$

Following steps to be taken while calculating fuel centre-line temperature, $T_f(0)$.

a) Axially divide the entire fuel rod into certain number of elemental sections.
b) Evaluate bulk temperature, outer clad temperature, inner clad temperature and pellet surface temperature.
c) Assume certain fuel centre-line temperature and calculate $\int_0^{T_f(0)} k_f dT_f$ using equation 1.15. Similarly calculate $\int_0^{T_f(R_f)} k_f dT_f$ using same equation.
d) Calculate difference of both the integrals calculated in part 'c' and then find $\frac{q'}{4\pi}$.
e) Take absolute error of both and goal seek to zero.
f) This will find the fuel center-line temperature.Note that it is important to design the material of clad and fuel pins within the maximum temperature limits.

The general data provided to complete the analysis is tabulated in table 1 for SMR 220. The results obtained have been plotted below in Figure 1.