A Comparative Study on Control Element Assembly Thermal Characteristics

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1. Introduction

Control Element Assembly (CEA) contains the nuclear absorbing material and positions it such that its location with respect to the fuel assembly is controlled by a direct connection to the extension shaft which in turn is axially positioned by control element drive mechanism (CEDM). The CEA shall provide sufficient negative reactivity insertion and insertion rate for adequate control and shutdown of the reactor for specified conditions. For the thermal integrity of B_4C pellet the centerline temperature of the B_4C pellet should not exceed 4000°F. The paper describes the methods and results related to this design criterion. The design code is used to evaluate this design criterion. ANSYS analyses are performed to verify this code.

2. Methods [1,2]

To check the thermal design criterion of B_4C pellet, the maximum gap conditions are to be considered. As a worst case data set, the maximum gap consists of the maximum inner diameter of clad, the minimum thickness of felt metal, and the minimum diameter of B_4C pellet.

The key material properties for the B_4C thermal design analysis are thermal conductivity, heat transfer coefficient, thermal expansion coefficient, surface roughness. These material properties are selected from the well-known data-base of the materials.

The thermal design analysis models take into account the geometric data as well as the reactor operating data. The geometric data are pellet diameter, clad outer diameter, clad inner diameter, and surface roughness, etc, while operating data are heat generation rate, and coolant mass temperature, etc.

For the control rod tip region, the clad and feltmetal geometric changes due to external overpressure are neglected for the thermal design evaluation. For the thermal design analysis, therefore the geometric changes occur only due to thermal expansion. On the other hand, the clad tube can be represented as a free standing right circular tube of a uniform wall thickness. Then, the temperature of the components can be calculated sequentially by the models for six regions, which can be seen in the equations (1) through (10).

(a) Coolant-Cladding Interface

The clad outer surface temperature is derived with the bulk coolant temperature, film heat transfer coefficient and local surface heat flux. Then, the temperature increase through the boundary layer surrounding the cladding is defined as follows :

$$T_{co} - T_b = \frac{q'_{co}}{2\pi r_{co}} \cdot \frac{1}{h_{film}} \quad (1)$$

(b) Cladding Region

In the cladding reion, the steady state heat conduction equation is given as

$$\frac{1}{r}\frac{d}{dr}\left(k_c r \frac{dT}{dr}\right) = -q'''_c \quad (2)$$

By integrating the above equation once with the constant value of q'''_c and using the boundary conditions at the inner cladding, we can readily see that the integration of the equation gives

$$T_{ci} - T_{co} = \frac{q'''_c}{4k_c}(r_{co}^2 - r_{ci}^2) + \frac{r_{ci}^2}{2k_c} q'''_c \ln\frac{r_{ci}}{r_{co}} + \frac{q'_{ci}}{2\pi k_c}\ln\frac{r_{co}}{r_{ci}} \quad (3)$$

(c) Cladding-Feltmetal Interface

The temperature drop across the cladding-feltmetal interface is defined as

$$T_{FO} - T_{ci} = q''_{ci}\frac{1}{h_1} \quad (4)$$

Considering thermal conductivity of gap and surface roughness(R_C,R_F) we have

$$T_{FO} - T_{ci} = \frac{q'_{ci}}{\pi(r_{ci} + r_{FO})}\left(\frac{\bar{k}_g}{(r_{ci} - r_{FO}) + (R_C + R_F)}\right)^{-1} \quad (5)$$

(d) Feltmetal Region

The temperature drop across the feltmetal thickness can be derived in the same way as the cladding temperature drop with no volumetric heat generation rate (q'''_c). It gives

$$T_{FI} - T_{FO} = \frac{q'_{ci}}{2\pi k_f}\ln\left(\frac{r_{FO}}{r_{FI}}\right) \quad (6)$$

(e) Feltmetal and B_4C Pellet Interface

The temperature drop across the feltmetal-Pellet interface can be derived in the same way as the temperature drop across the cladding-feltmetal interface . Then, we have

$$T_{BS} - T_{FI} = \frac{q'_{ci}}{\pi(r_{FI} + r_B)} \cdot \left(\frac{\bar{k}_g}{(r_{FI} - r_B) + (R_F + R_B)}\right)^{-1} \quad (7)$$

(f) B_4C Pellet Region

The steady state radial temperature distribution through a solid cylindrical pellet with internal heat generation and temperature dependent thermal conductivity is given by

$$\frac{1}{r}\left[\frac{d}{dr}\left(k_B r \frac{dT}{dr}\right)\right] = -q'''(r) \quad (8)$$

The thermal conductivity integral can be readily solved by the known thermal conductivity of the B_4C and polynomial constants from curve fitting.

By substituting thermal conductivity of the B_4C,k_B into double integration of the above equation, we obtain

$$\beta T_{BC}^2 - \alpha T_{BC} - \beta T_{BS}^2 + \alpha T_{BS} + \gamma = 0 \quad (9)$$

Where, α,β,γ are constants

Now, the root of the equadratic equation is

$$T_{BC} = \frac{\alpha - \left[\alpha^2 - 4\beta(\alpha T_{BS} - \beta T_{BS}^2 + \gamma\right]^{1/2}}{2\beta} \qquad (10)$$

So, centerline temperatre, T_{BC} can be readily obtained if outer diameter temperature T_{BS} is known.

3. Results and Discussion

To verify control rod components temperature calculated by the code, two dimensional axis-symmetric ANSYS model was created. Using plane 75 element type, the model was meshed to have 882 nodes which can be shown in the Figure 1.

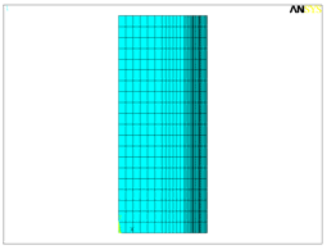

Figure 1. ANSYS model for thermal analysis

Using the design parameters, such as the heating rate, heat generation rate radial profile of the B_4C pellet, axial power peaking factor, and overpower factor, heating rate of unit element volume are calculated and the inputted for B_4C pellet, felt metal, and clad tube.

Fine element meshing was done for Helium region between feltmetal and B_4C and heat transfer coefficient using surface roughness as a parameter was inputted with other property coefficients for the element modeling Helium. [3]

For the case which has biggest gap, the ANSYS analysis was performed to compare the temperature calculated using the code. The model is described in Figure 2. The model has biggest gap between pellet and felt metal which contacts clad tube. The outer and inner diameter of clad tube is modeled to be maximum whereas the thickness of felt metal and diameter of B_4C Pellet is minimum in the model to get worst condition.

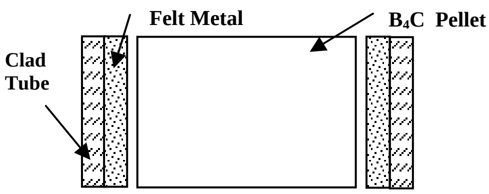

Figure 2. Modelling Case for CEA Thermal Analysis

Figure 3 shows the temperature profile calculated in the ANSYS. It shows that the maximum temperature in the B_4C pellet is 2489°F.

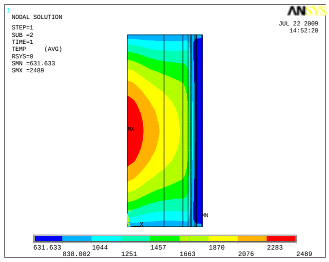

Figure 3. ANSYS calculation result

The temperature profile for the centerline path is plotted in Figure 4 to show radial temperature change. It shows the temperatures of components as to radial position and it compares the temperature calculated in the ANSYS with that of code. The innermost temperature of B_4C pellet of ANSYS model is 2489°F whereas the code calculates it as 2560°F. The difference between them is below 3%, which is nearly the same result.

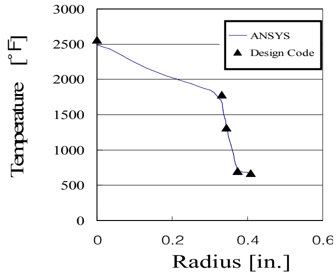

Figure 4. Comparison of temperature (ANSYS vs. Design Code)

4. Conclusion

(1) The FEM model has been developed using ANSYS to verify thermal design criteria of CEA.

(2) For the maximum gap condition, the centerline temperature of the B_4C pellet is evaluated to be 2560°F whereas the ANSYS calculates it as 2489°F. From this comparative study result, it can be concluded that ANSYS analysis result is consistent with the design code.

Acknowledgement

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