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Sensitivity Analysis of Gap Conductance for Heat Split in an Annular Fuel Rod

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1. Introduction

To increase of the core power density in the current PWR cores, an annular fuel rod was proposed by MIT [1]. As shown in Fig.1, this annular fuel rod has two coolant channels and two cladding-pellet gaps unlike the current solid fuel rod. It's important to predict the heat split reasonably because it affects coolant enthalpy rise in each channel and Departure from Nuclear Boiling Ratio (DNBR) in each channel. Conversely, coolant conditions affect fuel temperature and heat split. In particular if the heat rate leans to either inner or outer channel, it is out of a thermal equilibrium. To control a thermal imbalance, placing another gap in the pellet is introduced. The heat flow distribution between internal and external channels as well as fuel and cladding temperature profiles is calculated with and without the fuel gap between the inner and outer pellets.

2. Steady State Heat Transfer

Energy equation is coupled by the steady state condition that the heat lost by the fuel must equal the heat gained by the cladding, which in turn is gained by the internal and external coolants. Assumptions and approximations are almost invariably made to simplify these equations in steady state fuel rod performance computer codes. Some of the most important assumptions are: (a) Temperature and velocity at the steady state are fully developed. (b) There is a heat source within the pellet only. (c) There is no azimuthal and axial variation of fuel heat generation so that heat generation is a radial function. (d) There is an azimuthal and axial uniform cladding to coolant heat transfer and fuel to cladding conductance.

Given these approximations, the heat is allowed to flow only in the radial directions so that the fuel and cladding temperatures at a given axial location are therefore a function of the radius alone and the heat transfer equation is reduced to:

$$\frac{1}{r}\frac{\partial}{\partial r}\left(r\alpha\frac{\partial T}{\partial r}\right)+Q(r)=0 \tag{1}$$

This equation requires inner and outer cladding wall boundary conditions:

$$T_{Wo}=T_{Bo}+\frac{k_o}{h_o}\frac{dT_o}{dr} \tag{2}$$

$$T_{Wi}=T_{Bi}+\frac{k_i}{h_i}\frac{dT_i}{dr} \tag{3}$$

The equation is non-linear because the gap conductance depends on both the fuel and cladding temperatures as well as the boundary conditions. An iterative solution procedure must, therefore, be followed to find a temperature distribution that simultaneously satisfies the heat transfer equation and the gap conditions.

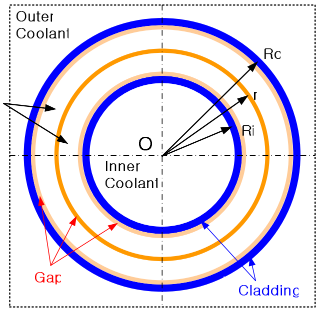

Figure 1. Cross section view of the annular fuel rod with the inner and outer coolant channels.

3. Gap Conductance and Conductivity

Gap conductance (h) may be considered as the sum of three terms: heat transfer across the gap by a conduction through the helium; solid conductance across points or areas of a contact between the fuel and cladding; convective heat transfer within the gap and finally a radiative heat transfer.

The present gap thickness (δ) is small, about 2 to 3% of the fuel radius. After a correction for the differential thermal expansion, the hot gaps during an operation are even smaller. Gap thickness is generally the sum of the open gap width and the effective one that is related to the roughness and temperature jump distances. Therefore the gap conductance in the present code must be replaced by $k_{gap}=h\delta$.

Thermal conductivity of UO2 is:

$$k_p(K)=\frac{1}{0.1148+0.004B+2.475\times10^{-4}(1-(1-0.0035B))T} \tag{4}$$
$$+0.0132EXP(-0.00188T)$$

Here B is a model coefficient for the burn-up effect.

Thermal conductivity of Zircaloy used for a cladding is:

$$k_c(K)=7.51+2.09\times10^{-2}T-1.45\times10^{-5}T^2 \tag{5}$$
$$+7.67\times10^{-9}T^3$$

The standard deviation of the data points with respect to this equation is 1.01 W/m-K. The data extend from 300 to 1800K.

4. Results of the computation

This section will investigate the sensitivity of the middle gap and side gap conductance for the heat flux split. The heat split effects for the thermal resistance, burn-up and radial power are also investigated.

4.1 Thermal Resistance

The overall heat transfer is calculated as the ratio of the overall temperature difference to the sum of the thermal resistance. The border between the inner and outer heat resistances is determined by the location of the fuel peak temperature.

$$q_i = \frac{T_{peak}(r) - T_{Ri}}{\sum R_{th}^{i}}, q_o = \frac{T_{peak}(r) - T_{Ro}}{\sum R_{th}^{o}} \qquad (6)$$

where

$$\sum R_{th}^{i} = \frac{1}{h_i A_i} + \frac{\delta_{ci}}{k_{ci} A_{ci}} + \frac{\delta_{gi}}{k_{gi} A_{gi}} + \frac{\delta_{pi}}{k_{pi} A_{pi}} + \frac{\delta_{gm}}{k_{gm} A_{gm}} \qquad (7)$$

$$\sum R_{th}^{o} = \frac{1}{h_o A_o} + \frac{\delta_{co}}{k_{co} A_{co}} + \frac{\delta_{go}}{k_{go} A_{go}} + \frac{\delta_{po}}{k_{po} A_{po}} + \frac{\delta_{gm}}{k_{gm} A_{gm}} \qquad (8)$$

4.2 Middle Gap Effects

The sensitivity of the middle gap conductance is performed by increasing it from $10^{-4} h^R$ to $10^{2} h^R$ (here, h^R is reference gap conductance, 4000 W/m2-K), while the inner and outer gap conductance ratio is constantly varying for each case. The heat splits are plotted in Figure 2. In the event of the middle gap semi-isolated, heat splits of all test cases are closed to 0.67 ± 0.01. This is because the border point of the peak temperature moves toward the middle gap from the inner pellet region. However an active middle gap conductance region may be limited between $0.5 h^R$ and $5 h^R$ at the normal operating condition.

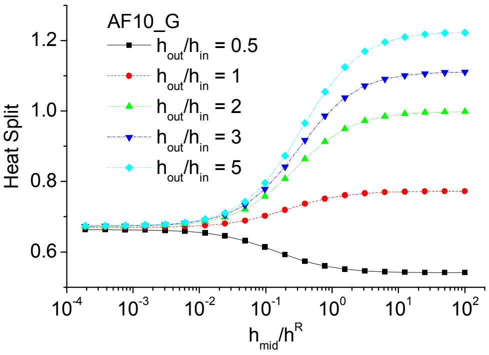

Figure 2. Heat split distribution for the variation of the middle gap conductance.

4.3 Side Gap Effects

On the other hand, the side gap conductance sensitivities are investigated in Figure 3. The seven cases have the same middle gap conductance and the constant ratio of the inner and outer gap conductance for each case. Only the gap conductance of both sides is increased from 0.1 to $20 h^R$. For all the test cases, the heat split of AF11_G (with the middle gap) is more moderate than that of AF11_NG (without the middle gap) in comparison with the reference case. These results mean that the safety margins of DNBR are improved. It is the important role of the middle gap to shift the peak temperature point to the center of the pellet by intercepting it doing an overheat transfer between the inner and outer pellet.

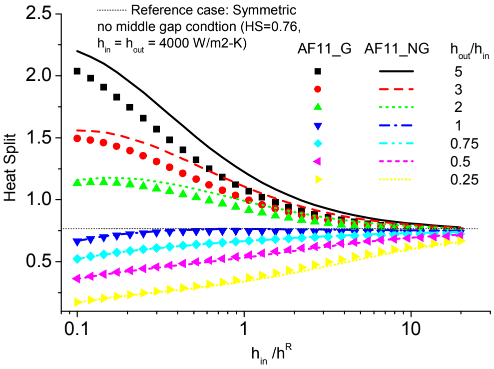

Figure 3. Heat split distribution for the variation of the inner and outer gap conductance.

5. Conclusions

The heat split effects were investigated in accordance with a variation of the gap conductance. According to the results above, the gap resistance ratio is nearly equal to the pellet one. Although the pellet conductivity is much smaller than the gap conductivity, because the order of the pellet thicknesses is opposed to that of the gap conductivity therefore the gap and pellet resistance ratio of the total resistance is equal to 46% and 47%, respectively, in the case of AF01_NG (without the middle gap) at normal conditions. For AF01_G (with the middle gap) the total gap resistance is increased to 51%, and the resistance of both pellets is decreased to 39%. It is still as much a part of the thermal resistance of the pellet as that of the gap. In spite of the larger difference between the inner and outer gap conductance, the reason that the ratio of the inner and outer heat fluxes is smaller than that of the gap conductance is due to the pellet resistance.

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