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Influence of Asymmetric Gap Conductances in Annular Fuel on Thermal Hydraulics

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1. Introduction

A dual side cooling annular fuel having internal and external coolant channels has many advantages basically due to low fuel temperature and high DNBR margin, which can make a significant increase of core power density possible [1]. So recently a 12x12 square annular fuel array was proposed for the fuel assembly to be reloaded without interference with operating reactors of the OPR-1000s [2]. However, even through the inherent potential of the annular fuel on the high power density, it may be seriously eroded in the case of a severe asymmetric heat split to the internal and external channels since it degrades DNBR performance of the annular fuel.

The asymmetric heat split comes mainly from the difference of gap conductance between inside and outside clearances as the fuel burn-up increases in the core. The variation of the gap conductance results from the swelling, expanding, cracking, and so on. Since the gap conductance plays a major role of the thermal resistance in the heat flow from the fuel to coolant, its impact on the heat flux split was estimated.

Furthermore, a remedy is suggested to mitigate the severe heat split unbalance. It is a concept of dual annular pellets, which places a clearance to give a thermal barrier in between concentric pellets. The effect was also evaluated in stand point of thermal hydraulics.

2. Thermal Resistance in Annular Fuel Rod

2.1 Overall Thermal Resistance in Annular Fuel

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

$$q_i = \frac{T_{peak}(r) - T_{Ri}}{\sum R_{th}^i}, \quad q_o = \frac{T_{peak}(r) - T_{Ro}}{\sum R_{th}^o} \tag{1}$$

Where,

$$\sum R_{th}^i = \frac{1}{h_i A_i} + \frac{\delta_{ci}}{k_{ci} A_{ci}} + \frac{\delta_{gi}}{k_{gi} A_{gi}} + \frac{\delta_{pi}}{k_{pi} A_{pi}} + \frac{\delta_{gm}}{k_{gm} A_{gm}} \tag{2}$$

$$\sum R_{th}^o = \frac{1}{h_o A_o} + \frac{\delta_{co}}{k_{co} A_{co}} + \frac{\delta_{go}}{k_{go} A_{go}} + \frac{\delta_{po}}{k_{po} A_{po}} + \frac{\delta_{gm}}{k_{gm} A_{gm}} \tag{3}$$

Total thermal resistance in annular fuel rod (KAERI-AF1) arises from pellet, claddings, gaps and coolants of both channels. While thermal resistances of pellet, claddings, gaps depend on their conductivity, heat transfer area and thickness, those of coolants in inner and outer channels are decided by heat transfer coefficients. Figure 1 shows the occupation ratio of thermal resistance in each component to the total thermal resistance at the reference condition: pellet (52.3%), gap (35.8%), cladding (7.5%) and coolant (4.4%). So the gap conductance is a major factor in overall thermal resistance. When both gap conductances increase as high as double or decrease as low as half of the reference case, the thermal resistance ratio of the gap conductance changed to 22.3% and 51.1%, respectively. This means that an asymmetry of gap conductances in inner and outer clearances may affect greatly the heat split to inner and outer channels.

2.2 Gap Conductance Variation

In order to obtain effective gap conductivities from inner and outer gaps, gap conductance and gap thickness model is required. Sensitivity analysis of the gap conductance was performed by increasing the inner gap conductance up to 80% and at the same time reducing the outer gap conductance down to 20%, or vice versa. This is a conservative assessment since the eccentricity of the pellets is not likely to be so uniform. Therefore, the gap conductance in the present code must be replaced by

$$k_{gap} = h_{gap} R_{gap} \ln\left(R_{gap}^o / R_{gap}^i\right). \tag{4}$$

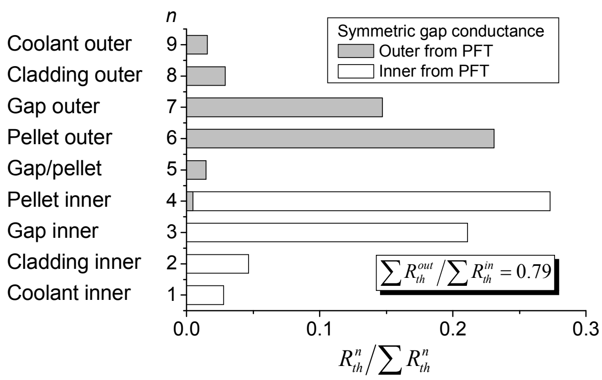

Figure 1 Thermal resistance at each component of KAERI-AF1 based on the peak fuel temperature (PFT).

3. Results

A simplified thermal hydraulic model of the annular fuel rod was developed using the conservative isolated hot channel approach, which does not include external flow mixing. Heat transfer from an annular fuel to cladding surface in contact with coolant is computed by a numerical solution of the one-dimensional heat conduction equation, which is coupled by the steady state condition. The boundary conditions involve the heat transfer coefficients, heat conductance coefficients and bulk temperatures in the inner and outer channels.

A mass flow split between the inner and outer channels is calculated under the same pressure drops in both channels. There are 11 spacer grids in the outer channel of which the form loss coefficient was assumed 0.4. The pressure drop in each channel is determined by applying coupled mass and momentum conservation equations accounting for friction, form, gravitation, and acceleration pressure losses. Analysis is made at 100% normal power and 100% coolant flow rate based on the operating reactors of the OPR-1000s.

On the other hand, to reduce the severe asymmetry of the annular fuel a concentric annular pellet concept was examined (KAERI-AF2). It was introduced for the middle gap to play a thermal barrier. The gap conductance of the middle clearance is assumed also as h_c =6000W/m2-K.

3.1 Heat Flux Split Ratio

Heat flux split for the same pressure drops and the conservative reference gap conductance at both sides was estimated and plotted in Figure 2. In case of the same reference gap conductances, the split ratios of mass flow rate and mass flux of the outer to inner channels are 0.97 and 0.69, respectively. At this time, heat flux split ratio is 0.72, especially, at the state of the same enthalpy that is 0.58. As applicable region of gap conductances, if the outer gap conductance is larger 3 times than that of the inner gap, heat split ratio is increased by about 1 and, in case of vice versa, decreased by about 0.5.

3.2 Enthalpy Rise Ratio

Compared with KAERI-AF1 without thermal barrier gap, KAERI-AF2 seems to more appropriately adjust enthalpy rise ratio toward the same enthalpy rise. At the same reference gap conductance, assuming that gap conductance ratio is 3.0 (hi=3000, ho=9000W/m2-K), the enthalpy rise ratio is improved by 4.8% from 1.82 to 1.73. In case of vice versa, that is improved by 3.2% a little lower. The effects of thermal barrier gap for the other sums of gap conductances are investigated in Table 1(a). When the gap conductance of the thermal barrier gap reduces as low as half, that effects are investigated in Table 1(b).

3.3 Discussions

The results for the variations of gap conductances show that if the value of h_c is relatively decreased, the performance capability of thermal barrier gap increases. When outer gap conductance is larger than inner gap conductance, the performance capability for heat split balance of thermal barrier gap is more effective. Also, when the sum of gap conductances of both sides is increased, enthalpy rise ratios are more close to 1.0. At this time, the applicable region of heat split is η =0.5~1.0. Therefore, since heat flux to the inner channel is higher, minimum DNBR occurs in the inner channel.

4. Conclusions

An influence of the asymmetric gap conductance on heat split and enthalpy rise in the annular fuel was investigated here. Heat split of annular fuel rod depends on the gap conductances and pressure drops in both inner and outer channels. Also, thermal barrier gap is effective to adjust enthalpy rise ratio toward 1. Given lower thermal barrier gap conductance and higher side gap conductances, the heat balance of thermal barrier gap is improved.

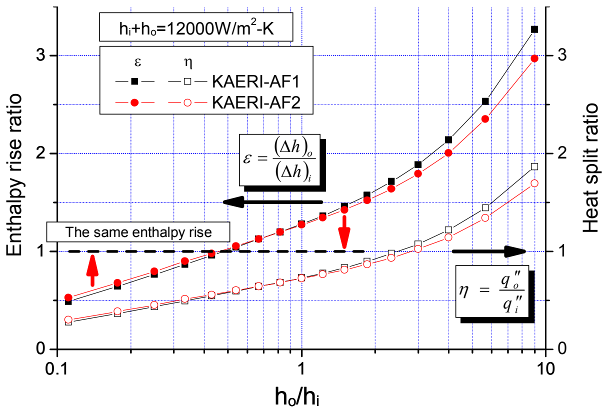

Figure 2 Enthalpy rise rate and heat split of outer channel to inner channel for KAERI-AF 12x12 fuel assembly with thermal barrier gap or not.

Table 1 Comparison of thermal barrier gap effects on enthalpy rise along the variation of both gap conductances

(a) Thermal barrier gap conductance, $h_c = 6000\,W/m^2K$.

$h_o + h_i$ / h_o/h_i	6000 (W/m2-K)	12000 (W/m2-K)	24000 (W/m2-K)
3.0	6.0%	4.8%	4.2%
0.333	4.3%	3.2%	1.5%

(b) Thermal barrier gap conductance, $h_c = 3000\ W/m^2K$.

$h_o + h_i$ / h_o/h_i	6000 (W/m2-K)	12000 (W/m2-K)	24000 (W/m2-K)
3.0	9.8%	8.6%	7.0%
0.333	7.9%	6.3%	3.9%

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