RERTR 2011 — 33rd INTERNATIONAL MEETING ON
REDUCED ENRICHMENT FOR RESEARCH AND TEST REACTORS

October 23-27, 2011
Marriott Santiago Hotel
Santiago, Chile

APPLICABILITY OF A HOT CHANNEL FACTOR-BASED HOT STRIPE APPROACH TO MODEL THE AZIMUTHAL POWER PEAKING IN A BR2 FUEL ASSEMBLY

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ABSTRACT

In a BR2 fuel assembly, a power peak can occur at any azimuthal angle along the arc length of a fuel plate. In steady-state thermal-hydraulic analyses, this type of behavior is generally analyzed using a hot stripe approach, i.e., modeling the azimuthal region near the power peak as an isolated vertical stripe (neglecting the lateral heat conduction and coolant mixing). To verify the applicability of that approach for a BR2 fuel assembly, CFD simulation results were compared to analytical results obtained by neglecting the lateral heat conduction and coolant thermal mixing. This comparison showed that for a power peak occurring near the azimuthal center of a fuel plate, the lateral heat conduction does not significantly change the heat flux in that region. Therefore, under these conditions, the increased heat flux near the peak can be properly modeled using the azimuthal power peak-to-average ratio as a hot channel factor on both the heat flux and film coefficient. This comparison also showed that the azimuthal thermal coolant mixing is small within the coolant channel, and that consequently, the additional heat produced near the power peak remains essentially within that region. Therefore, the effect of the power peak on the coolant temperature can also be properly modeled by using the azimuthal power peak-to-average ratio as a hot channel factor on the bulk temperature rise.

1. Introduction

To support the conversion of the BR2 research reactor from highly-enriched uranium (HEU) to low-enriched uranium (LEU) fuel, thermal-hydraulics analyses must be performed to evaluate the safety margins. In a BR2 fuel assembly (FA), the limiting location with respect to Onset of

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Nucleate Boiling (ONB) occurs on the inner side of "tube[1]" 6, i.e., in coolant channel 6 (see Fig. 1). However, the power peak (and consequently the peak cladding temperature) can occur at any azimuthal angle along the arc length of any of the 3 fuel plates (see Section 2).

For FAs exhibiting a strong lateral power peaking (i.e., the azimuthal power peaking in the case of the BR2 FA), a hot stripe approach is generally used. This paper studies the applicability of such an approach for a BR2 FA.

Since the PLTEMP/ANL code [1] is used to evaluate the margins to ONB, this paper also presents a study of the applicability of using the engineering hot channel factors (HCFs) in PLTEMP/ANL to model the hot stripe.

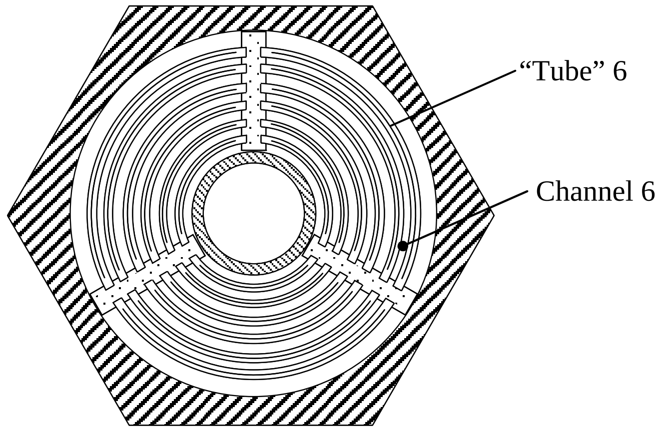


Figure 1. Cross-section of a BR2 fuel assembly

The paper is organized as follows. Section 2 presents an overview of the BR2 reactor core and a description of azimuthal power peaking in a BR2 FA. Section 3 describes the computational methodology used to verify the applicability of the hot stripe approach. Section 4 describes the various computational models used in this work. Sections 5 and 6 present the computational results and conclusions, respectively.

2. BR2 Fuel Assembly Power Peaking

BR2 is a water-cooled thermal reactor moderated by water and beryllium. The core is located inside an aluminum pressure vessel. The coolant flows from the top of the core to the bottom. The beryllium moderator consist of a matrix of hexagonal prisms each having a central bore that contains either a FA, a control or regulating rod, an experimental device, or a aluminum/beryllium plug. As shown in Fig. 1, each FA is composed of six concentric "tubes" divided by aluminum stiffeners into three sectors.

Figure 2 shows a schematic of the BR2 reactor core.

In a BR2 FA, an azimuthal power peak can occur at any given angle along the arc length of any of the 3 fuel plates based on the orientation of the FA. In the BR2 core "configuration 4" used as a reference configuration in this work, the power peak azimuthal location depends on the orientation of a fuel plate with respect to the thermal

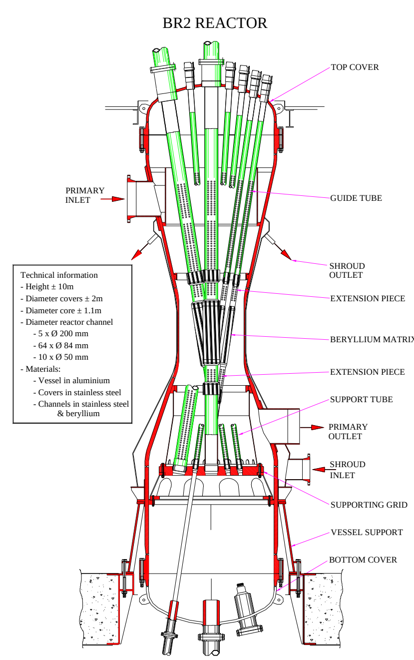


Figure 2. BR2 reactor schematic

[1] A "tube" refers to the 3 fuel plates located at the same radius and separated by the stiffeners

neutron flux peak occurring between the rows of control rods.

Using MCNP5 [2], the power distribution in the hot plate (fuel plate colored in red in Fig. 3) is obtained. Figure 3 shows the local-to-average (averaged of the whole core) power peaking in the hot plate for two different FA orientations.

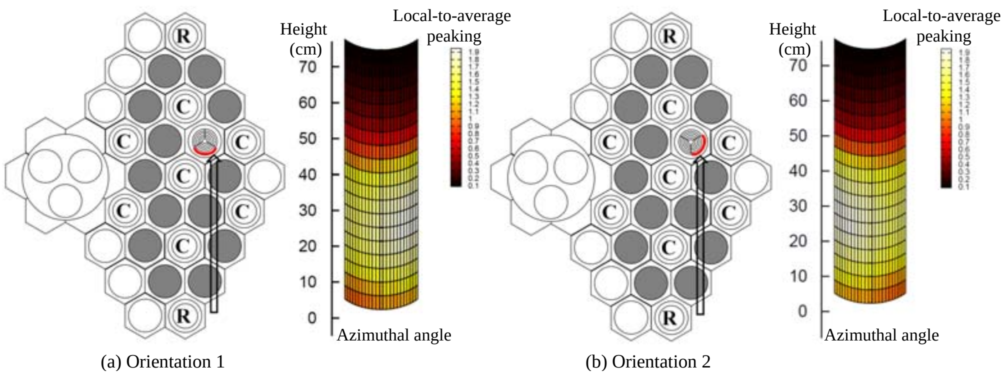


Figure 3. Impact of a FA orientation on power peaking in the BR2 core "configuration 4"

Figure 3 clearly illustrates that, based on the orientation of the FA, the power peak occur at different azimuthal angles within a fuel plate. It can be concluded that if the FA is further rotated, the power peak will occur in a different fuel plate. The same type of azimuthal power peaking occurs in the current BR2 core configuration. For the current configuration, the power peak azimuthal location depends on the FA orientation relative to core center [3]. Therefore, the conclusions of this work also apply to current BR2 core configuration.

For both configurations mentioned above, the limiting FA's orientation produces a power peak near the azimuthal center of a fuel plate. This orientation is expected to be limiting since the lateral heat conduction to the plate's unfueled edges and the stiffeners should be minimal near the azimuthal center.

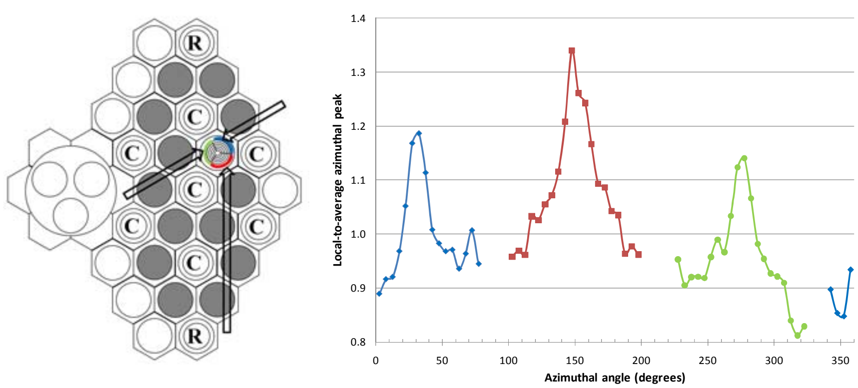


Figure 4. Local-to-average power azimuthal peaking for a third FA orientation

Figure 4 shows the local-to-average (averaged of the 3 fuel plates in "tube" 6) azimuthal power peaking, at the hot plane[2], for the limiting FA orientation.

[2] The hot plane is the height at which the axial power peak occurs.

3. Applicability of a Hot Stripe Approach

In the hot stripe approach, the lateral region near the power peak is modeled as an isolated vertical stripe (see Fig. 5) by

1. neglecting the lateral heat conduction in the fuel plate, i.e., assuming that the azimuthal heat flux peaking is identical to the azimuthal power peaking for the stripe,

2. neglecting the azimuthal thermal coolant mixing, i.e., assuming that bulk coolant temperature rise in each coolant stripe depends only on the heat transferred from that stripe.

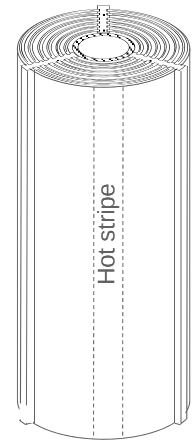


Figure 5. Hot stripe in a BR2 FA

Therefore, the applicability of the hot stripe can be verified by, 1) studying the impact of the lateral heat conduction on the peak heat flux, 2) studying the impact of the azimuthal power distribution on the coolant temperature profile, and 3) studying the impact of neglecting the azimuthal coolant thermal mixing.

To perform those studies, a 3D computational fluid dynamics (CFD) analysis of the hot channel is performed and the results are compared to analytical models for the heat flux and the bulk coolant temperature rise [4].

4. Computational Models

This section describes the various computational models used to verify the applicability of the hot stripe approach for a BR2 FA and the applicability of using PLTEMP/ANL HCFs to model a hot stripe.

4.1. STAR-CD Computational Fluid Dynamics Model

Section 4.1.1 describes the geometry and boundary conditions of STAR-CD [5] model used to perform the CFD analyses. Section 4.1.2 describes methodology used to generate the power density distribution used in that model.

4.1.1. Geometry and boundary conditions

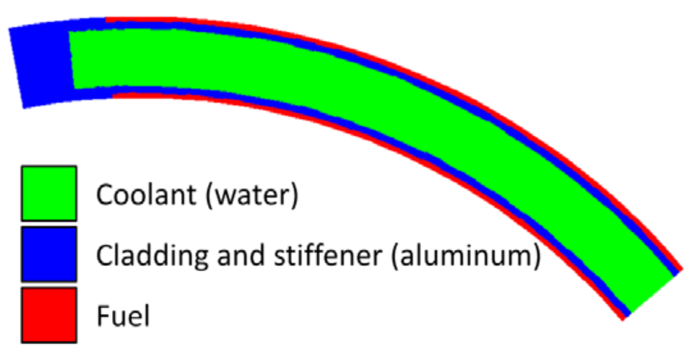


Figure 6. STAR-CD model geometry

Figure 6 shows the STAR-CD geometry modeling half of the hot channel assuming symmetry at the azimuthal center of the channel. This geometry includes two half-fuel plates and one half of the stiffener section. In the axial direction, the full height (970 mm) of the plate is modeled. Note that the inlet and outlet plenums were not modeled.

With the exemptions of the coolant inlet and outlet, all other boundaries are treated as adiabatic. A uniform flow velocity (11.8 m/s) and uniform temperature (35°C) are used as boundary conditions at the inlet and an outflow boundary condition is used at the outlet.

For the simulation of turbulence, the widely used standard high Reynolds (high-Re) number model was used.

4.1.2. Power density distribution in STAR-CD model

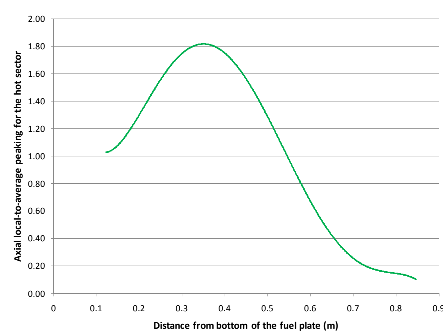
The STAR-CD power density distribution is based on the MCNP5 power distribution in the hot plate (colored red in Fig. 4) for the limiting FA orientation (see Section 2). More specifically, the power distribution is calculated for 24 axial locations using 5 degrees azimuthal meshes.

Since the power density (W/m^3) must be specified for each fuel meat mesh, the detailed distribution is approximated using polynomial functions representing the axial and azimuthal power peaking independently. An axial local-to-average power peaking function (azimuthally-averaged), $p(z)$, is evaluated from the power distribution. Two azimuthal local-to-average power peaking functions, $p_i(\theta)$, are evaluated to approximate the axial dependency of the azimuthal power shape (i=1 below 0.5612 m, i=2 above 0.5612 m). These functions are combined in a STAR-CD user's subroutine to generated the power density according to

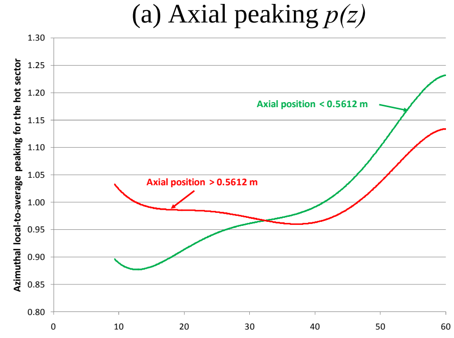
$$Q_j(\theta, z) = q_j \, p_i(\theta) \, p(z) \tag{1}$$

where $Q_j(\theta, z)$ is the power density in plate 5 (j=5) and plate 6 (j=6), and q_j is the plate j average power density. For simplicity, the same polynomial functions are used to define the power density shape in each half-fuel plate.

Figure 7 shows the polynomial functions used in conjunction with Eq. 1 to input the power density into the STAR-CD model.



(a) Axial peaking *p(z)*



(b) Azimuthal peaking $p_i(\theta)$

Figure 7. Power peaking polynomial functions

4.2. Stripe Bulk Coolant Temperature Rise Model

To study the importance of the azimuthal coolant thermal mixing, the half coolant channel is divided into 6 azimuthal stripes.

The analytical results without azimuthal thermal coolant mixing are obtained by integrating the heat transferred to the coolant over the height of each stripe using the heat flux generated from the CFD calculation. The mass flow rate obtained from the CFD calculation is then used in conjunction with Eq. 2 to obtain the bulk coolant temperature rise for each stripe.

$$\Delta T(\theta_i) = q(\theta_i) / \dot{m}(\theta_i) C_p \tag{2}$$

where $\Delta T(\theta i)$ is the temperature rise from inlet to outlet for the stripe i of size $\Delta\theta_i$ around angle θ_i, $q(\theta_i)$ is the heat transferred to the coolant stripe, $m(\theta_i)$ is the flow rate in the stripe, and C_p is the specific heat.

4.3. Hot Stripe Modeling Using PLTEMP/ANL Hot Channel Factor

The evaluation of safety margins necessitates the use hot channel factors (HCFs). In PLTEMP/ANL, the HCF model uses six factors. The first three factors represent global systematic uncertainties that affect the total power measurement (F_{POWER}), total flow measurement (F_{FLOW}) and single-phase heat transfer coefficient (F_{NUSLT}). The last three HCFs are used to model the impact of the manufacturing tolerances and uncertainties on bulk coolant temperature rise (F_{BULK}), film temperature rise (F_{FILM}), and local heat flux (F_{FLUX}). These last three HCFs are applied analytically (after the PLTEMP/ANL numerical solution is obtained) according to the following equations:

$$Q''_{i,HCF} = Q''_i \times F_{FLUX} \tag{3}$$

$$T_{WALL,i,HCF} = T_{i,HCF} + (T_{WALL,i} - T_i) \times F_{FILM} \tag{4}$$

$$T_{i,HCF} = T_0 + (T_i - T_0) \times F_{BULK} \tag{5}$$

Since the hot stripe approach assumes that heat flux peaking is the same as the power peaking, Q''_i can be multiplied by the azimuthal peak-to-average power peaking of the hot stripe ($P_{azim\ peak\text{-}to\text{-}average}$) to obtain the heat flux in the hot stripe. F_{FLUX} in Eq. 3 can be expressed as

$$F_{FLUX} = F'_{FLUX} \times P_{azim\ peak-to-average}, \tag{6}$$

where F'_{FLUX} is the engineering HCF reflecting the uncertainties.

Assuming that the film coefficient is not significantly affected by the local increase in heat flux, the temperature drop $(T_{WALL,i} - T_i)$ can also be multiplied by $P_{azim\ peak\text{-}to\text{-}average}$. Therefore, F_{FILM} in Eq. 4 can be expressed as

$$F_{FILM} = F'_{FILM} \times P_{azim\ peak-to-average}, \tag{7}$$

where F'_{FILM} is the engineering HCF reflecting the uncertainties.

Finally, since the hot stripe approach assumes that only the heat transferred from the stripe contributes to the bulk coolant temperature rise, the term $(T_i - T_0)$ in Eq. 5 can also be multiplied by $P_{azim\ peak\text{-}to\text{-}average}$. Therefore, F_{BULK} in Eq. 4 can be expressed as

$$F_{BULK} = F'_{BULK} \times P_{azim\ peak-to-average}, \tag{8}$$

where F'_{BULK} is the engineering HCF reflecting the uncertainties.

5. Results

This section presents the analyses performed to study: 1) the impact of the lateral heat conduction of the peak heat flux, 2) the impact of the azimuthal power distribution on the coolant temperature profile, and 3) the impact of coolant thermal mixing. The results of the analysis verifying the applicability of the use of HCFs to model the hot stripe are also presented.

5.1. Impact of the Lateral Heat Conduction on the Peak Heat Flux

In order to evaluate the impact of the lateral heat conduction, the heat flux azimuthal profile predicted by the CFD model is compared to the heat flux profile calculated directly from the power azimuthal profile (i.e., not taking into account the axial and azimuthal heat conduction). Figure 8 shows the heat flux azimuthal profile, at the hot plane, obtained with STAR-CD and analytically.

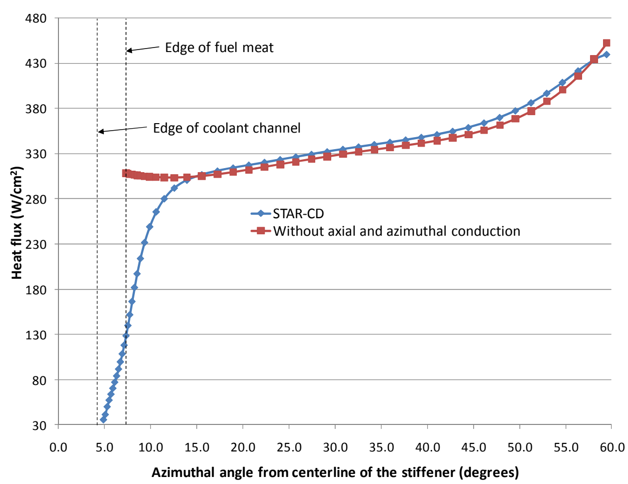


Figure 8. Heat flux azimuthal profiles obtained with and without lateral conduction

It can be observed in Fig. 8 that the lateral heat conduction has only a small impact on the peak heat flux when it occurs near the azimuthal center of the fuel plate. However, as expected, a more significant reduction in heat flux is observed near edge of the fuel meat. This reduction can be attributed to the lateral heat conduction in the unfueled edge as well as the stiffener. Note that 2.9% of the total heat is azimuthally conducted of the fuel plate while only 0.2% is axially conducted out of the fuel plate.

These results confirm that in the BR2 FA hot stripe region, the assumption that the heat flux has the same azimuthal peaking as the power is adequate.

5.2. Impact of the Azimuthal Power Distribution on the Coolant Temperature Profile

The use of a hot stripe approach implies that an azimuthal power distribution produces a coolant temperature profile that can be approximated by “stripes”. Figure 9 shows the coolant temperature profile at the outlet of the coolant channel. The presence of “stripes” in the coolant temperature profile indicates that the coolant is far from being completely mixed.

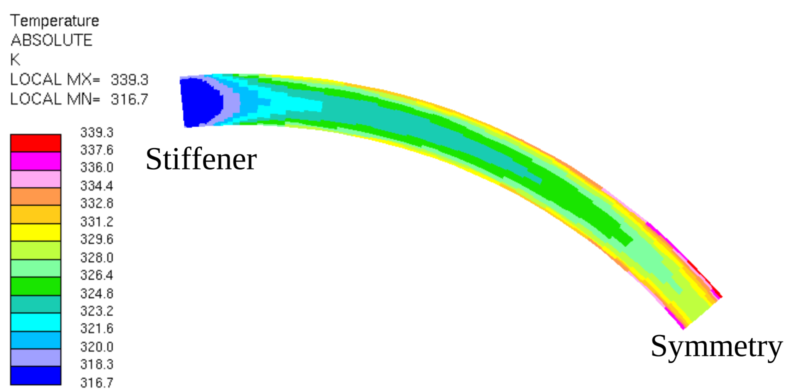


Figure 9. Azimuthal coolant temperature profile at the channel’s outlet

However, in order to be able to verify the level of conservatism introduced by the hot stripe approach, the bulk coolant temperature rise in each of the “stripes” illustrated in Fig. 9 needs to be compared to the analytical results without azimuthal coolant thermal mixing.

5.3. Impact of Coolant Thermal Mixing on Bulk Coolant Temperature Rise

To evaluate the impact of the thermal coolant mixing, a bulk coolant temperature rise is calculated for each of the 6 stripes using the CFD coolant temperatures. Figure 10 compares the coolant bulk temperature rise (from the inlet to the outlet) in each stripe obtained from CFD and the analytical model.

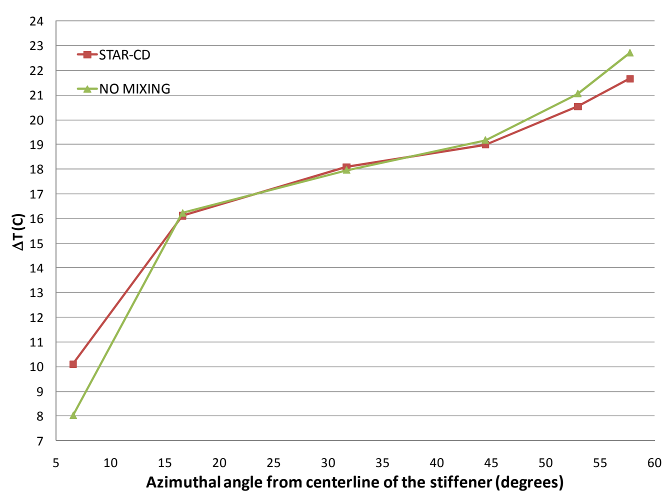


Figure 10. STAR-CD and analytical bulk coolant temperature rise in each stripe

From Fig. 10, it can be seen that the azimuthal coolant thermal mixing is minimal since the bulk coolant temperature rise taking into account the azimuthal coolant thermal mixing (STAR-CD) is reduced only by 1°C near the power peak. It can also be observed that the coolant temperature rise at the edge is increased only by 2°C when taking into account the azimuthal coolant thermal mixing. This confirms that striping is a good approximation at steady-state.

5.4. Applicability of Hot Channel Factors to Model a Hot Stripe

It is necessary to show that Eqs 6 to 8 are applicable for modeling the hot stripe. Since the heat flux azimuthal peaking can be approximated by the power azimuthal peaking, analytically multiplying the heat flux by $P_{azim\,peak-to-average}$ as in Eq. 6 is adequate to represent the hot stripe.

To show that the bulk coolant temperature rise and film temperature drop in the hot stripe can be obtained analytically by scaling them by $P_{azim\,peak-to-average}$, it is useful to obtain an expression that predicts the cladding temperature in the hot stripe in term of the inlet coolant temperature and the cladding temperature obtained without azimuthal peaking. Such an expression can be obtained using the PLTEMP/ANL HCF model by replacing Eq. 4 in Eq. 5 in order to obtain the following equation.

$$T_{WALL,i,HCF} = T_0 + (T_i - T_0) \times F_{BULK} + (T_{WALL,i} - T_i) \times F_{FILM} \tag{9}$$

By replacing Eqs 7 and 8 into Eq. 9 ($F'_{FILM} = F'_{BULK} = 1$, no manufacturing tolerances and uncertainties are taken into account in order to compare to azimuthally-average CFD results), the peak cladding temperature in the hot stripe can be obtained analytically by

$$T_{WALL,i,hot\ stripe} = T_0 \times (1 - P_{azim\ peak-to-average}) + T_{WALL,i} \times P_{azim\ peak-to-average} \tag{10}$$

Using Eq. 10 it is now possible to compare the hot stripe peak cladding temperatures obtained using CFD and the analytical approach. $T_{WALL,i}$ can be obtained from any calculation using an azimuthally-averaged power distribution (c.g. PLTEMP/ANL). For this comparison, a STAR-CD calculation is performed with p(θ$_i$) set to 1.0 in Eq. 1, (i.e., average azimuthal power distribution) in order to obtain $T_{WALL,i}$. Figure 11 shows the peak cladding temperature in the hot stripe ($T_{WALL,peak,CFD}$) as well as the peak cladding temperature with an azimuthally-averaged power distribution ($T_{WALL,peak}$) obtained from CFD.

Using the azimuthally-averaged peak cladding temperature ($T_{WALL,peak}$ = 80.6°C) from Fig. 11, the inlet coolant temperature (T_0 = 35 °C) and an azimuthal power peak-to-average ratio of 1.26, Eq. 10 predicts a peak cladding temperature in the hot stripe of 92.5 °C. This value is in good agreement with the peak cladding temperature in the hot stripe (91.8°C) predicted by CFD. Therefore, in practice, it is applicable to model analytically the hot stripe by scaling the HCF in PLTEMP/ANL model by $P_{azim\,peak-to-average}$.

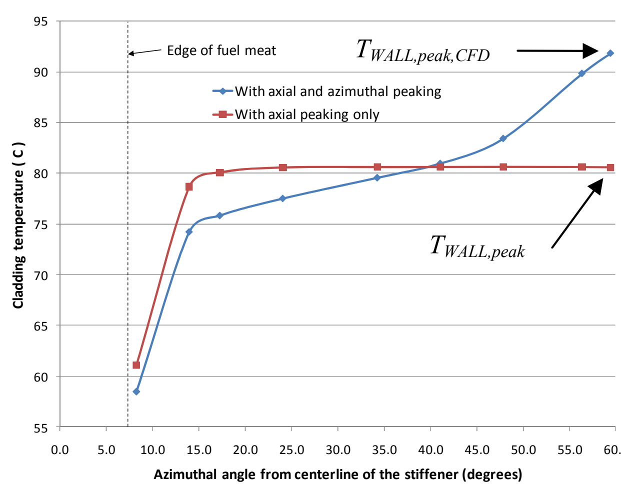


Figure 11. STAR-CD cladding temperatures with and without azimuthal peaking

6. Summary and Conclusions

This paper presented work studying the applicability of a hot stripe approach to model the azimuthal power peaking in a BR2 fuel assembly (FA).

It was first shown that the FAs can be oriented such that the power peak occurs near the azimuthal center of a fuel plate and that this orientation produces a limiting power distribution.

Using this power distribution, STAR-CD calculations (CFD) were performed and compared to analytical solutions for the heat flux and bulk coolant temperature rise. It was shown that the lateral heat conduction has no significant impact on the peak heat flux when the power peak occurs near the azimuthal center of a BR2 fuel plate. It can therefore be concluded that the power azimuthal peaking is an adequate approximation to the heat flux peaking at that location. It was then shown that the azimuthal power distribution produces “stripes” in the coolant temperature profiles and that the coolant thermal mixing in the azimuthal direction was minimal in a BR2 channel. This confirmed that the use of a hot stripe approach to model the azimuthal power peaking in BR2 FA is not overly conservative.

Finally, it was shown that the hot stripe can be modeled analytically through the use of the PLTEMP/ANL HCF model by scaling F_{BULK}, F_{FILM} and F_{FLUX} by the azimuthal peak-to-average power ratio of the hot tripe.

7. References

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