

PREDICTION OF FUEL TEMPERATURE OF AP1000 DUE TO THE FORMATION OF CRUD AND OXIDE LAYER

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ABSTRACT

PREDICTION OF FUEL TEMPERATURE OF AP1000 DUE TO THE FORMATION OF CRUD AND OXIDE LAYER. An analysis to predict the fuel temperature due to crud and oxide layer formed on the hot sub-channel cladding surface of AP1000 reactor has been performed. During reactor operation, the heat transfer and cooling process occur on the fuel cladding surface. During the heat exposure process, an oxide layer and crud are formed on the cladding surface. The decrease of heat transfer performance will increase the fuel and cladding temperatures. Therefore, the effect of fuel temperature increase during the heat exposure process has to be analyzed. The analysis was conducted for nominal power of 3400 MWt using COBRA-EN code, by varying the modular oxide thickness of 0, 20, 40, 60, 80, 100 and 120 μm , crud thickness of 0, 10 and 20 μm and black oxide thickness of 0, 10, 20, 30 and 40 μm . For full cycle hot sub-channel condition, the combination of crud thickness of 20 μm and modular oxide thickness of 115 μm give prediction of the peak fuel center line temperature and the peak cladding surface temperature of 1870.73°C and 609.40°C, respectively. However, the oxide layer is predicted only formed on hot sub-channel during BOC (about 40% of full cycle). The results show that the prediction of the peak fuel center line temperature and the peak cladding surface temperature are 1713.18°C and 451.87°C, respectively. Compared to the normal and fresh fuel conditions, the peak fuel center line temperature and the peak cladding surface temperature increase by 6.53% and 29.86%, respectively.

Keywords: Fuel temperature, Crud, Oxide layer, COBRA-EN, AP1000

ABSTRAK

PREDIKSI TEMPERATUR BAHAN BAKAR AP1000 AKIBAT ADANYA BENTUKAN ENDAPAN DAN LAPISAN OKSIDA. Telah dilakukan penelitian untuk memprediksi temperatur bahan bakar akibat terbentuknya endapan dan lapisan oksida pada permukaan kelongsong sub kanal panas dari reaktor AP1000. Selama operasi reaktor, proses pemindahan kalor and pendinginan terjadi pada permukaan kelongsong. Selama proses pemaparan kalor, endapan dan lapisan oksida terbentuk pada permukaan kelongsong. Berkurangnya pemindahan kalor akan berakibat pada kenaikan temperatur bahan bakar dan kelongsong. Oleh karena itu, dampak kenaikan temperatur bahan bakar selama proses pemaparan kalor perlu dianalisis. Analisis dilakukan pada kondisi daya nominal sebesar 3400 MWt dengan menggunakan kode COBRA-EN, untuk variasi tebal lapisan oksida modular 0, 20, 40, 60, 80, 100 dan 120 μm , variasi tebal endapan 0, 10 dan 20 μm , dan variasi tebal lapisan oksida hitam 0, 10, 20, 30 dan 40 μm . Untuk kondisi sub kanal panas selama siklus penuh, kombinasi tebal 20 μm dan tebal lapisan oksida modular 115 μm memberikan prediksi temperatur puncak sumbu bahan bakar dan temperatur puncak permukaan kelongsong masing-masing sebesar 1870,73°C dan 609,40°C. Akan tetapi, lapisan oksida diprediksi hanya terjadi pada sub kanal panas selama awal siklus (sekitar 40% waktu satu siklus penuh). Hasil perhitungan menunjukkan bahwa prediksi temperatur puncak sumbu bahan bakar dan temperatur puncak permukaan kelongsong masing-masing sebesar 1713,18°C dan 451,87°C. Dibandingkan dengan temperatur bahan bakar pada kondisi segar dan normal, maka temperatur puncak sumbu bahan bakar dan temperatur puncak permukaan kelongsong mengalami kenaikan masing-masing sebesar 6,53% dan 29,86%.

Kata kunci: Temperatur bahan bakar, endapan, lapisan oksida, COBRA-EN, AP1000.

INTRODUCTION

When Light Water Reactor (LWR) is operated, the heat is generated by nuclear fission in the solid cylindrical pellets. Then, the heat is removed from the fuel by the coolant water through the outer cladding. The cladding is made of a zirconium alloy (i.e. Zircaloy-2 and Zircaloy-4). Zirconium alloy has been used as fuel cladding owing to its low neutron absorption cross section area, proper mechanical properties at high temperature, and high corrosion resistance [1]. The cladding surface is smooth and clean. However, a very thin oxide layer ZrO_2 (about 2-5 nm of thickness) always presents due to oxidation of air [2]. At the same time, there are heat transfer and cooling process on the fuel cladding surface. During exposure to coolant at low temperature for long periods, or high temperature for short periods, an oxide layer and crud are formed on the cladding surface of the fuel rod. At nominal power, the fuel cladding temperature is about 300°C , however higher temperatures could be reached during transient [3]. For transient condition, retention of maximum ductility for about 17% of oxidized cladding sets the fuel cladding peak temperature of 1204°C in the loss of coolant accident (LOCA). This acceptance criteria is related to cladding embrittlement [4]. As a comparison, in Supercritical Water Cooled Reactor (SCWR), the temperature of hot spot on the fuel cladding were designed exceeds 600°C at normal operations [5]. For zircaloy-4, the growth strain significantly increases after transient stage at a fluence of around $1.0 \times 10^{25} \text{ n/m}^2$, at temperature of 280°C [6].

Zirconium oxide (oxide layer) and crud will be formed on zircaloy-4 cladding surface throughout reactor operation which is about 12-18 months. The oxidation reaction is described as:



This oxide layer product has a poor thermal conductivity, therefore fuel temperature increases during operation. There are two types of oxide layer employed i.e., modular oxide and black oxide. The characteristics of these two layers were reported in high temperature. The modular oxide thermal conductivity was higher than black oxide. At temperature less than 1200°C , it was found that the maximum modular oxide thickness was around $113 \mu\text{m}$, whereas black oxide thickness was around $20 \mu\text{m}$. The values of thermal conductivity of modular oxide varied from $1.0 \text{ W/m}^\circ\text{C}$ at 400°C to $1.6 \text{ W/m}^\circ\text{C}$ at 1200°C . However, the values of thermal conductivity of black oxide are in the range $0.13 \text{ W/m}^\circ\text{C}$ to $0.86 \text{ W/m}^\circ\text{C}$ for the same temperature [3]. The other fuel rod performance evaluation is to analyze the corrosion characteristic which was conducted by using thermal conductivity of the crud that vary from 0.8648 to $0.4324 \text{ W/m}^\circ\text{C}$ [7].

Since crud and oxide layer have low thermal conductivity, thus heat transfer process from fuel rod through the cladding by primary coolant will be hindered. Consequently, due to the crud and oxide layer, the decreasing of heat transfer will effect on the increasing of fuel and cladding temperatures, especially the cladding surface and the peak center line temperature. Therefore, it is important to predict the fuel and cladding temperature that are influenced by crud and oxide layer formed on cladding surface of AP1000 fuel rod. The prediction was conducted using COBRA-EN code [8]. Some researchers have used COBRA-EN code for thermal-hydraulics analysis on radial and axial power fluctuation [9], comparison analysis using fixed and temperature function of thermal conductivity [10], validation of SIMBAT-PWR [11], optimizing gap conductance [12], capability test for VVER [13,14] as well as core and sub-channel analysis of VVER [15,16].

In case of the analysis using fuel heating model, COBRA-EN code could only be used for fixed value of thermal conductivity. The oxidation occurs only on the cladding of the hot rod. It can cause the increasing of flow resistance in the sub-channel around it. Fuel model of AP1000 was taken. In AP1000, the hot sub-channel has total peaking factor of 2.60 or equal to 48.88 kW/m of peak linear power.

This research aims to determine the influence of crud and oxide layer against the sub-channel thermal-hydraulic parameters of AP1000. The analysis includes the effect on peak fuel center line temperature as well as peak cladding surface temperature. This study focuses on the variation of crud and oxide layer thickness on fuel cladding surface of AP1000, which is conducted using COBRA-EN code. The AP1000 core consists of 157 fuel assemblies, and each fuel assembly consists of 264 fuel rods. The reactor has output power of 3400 MWt and effective flow rate for

heat transfer of 48,443.7 ton/hr [9,11]. This research accomplishes the previous research about thermal-hydraulics analysis on radial and axial power fluctuation [9] as well as analysis using fixed and temperature function thermal conductivity [10].

THEORY

The prime objective of any safety action in a nuclear power plant is maintaining the nuclear fuel cladding's structural integrity which protects radioactive fuel from undergoing nuclear fission [17]. Zirconium alloys are main structural material of fuel cladding, due to the combination of excellent corrosion resistance, good neutron penetration and suitable mechanical properties [18]. It is required to keep the integrity of fuel rod and assembly until the designed burn up (life limit). If the fuel and cladding temperature are higher than normal temperature, such as in LOCA conditions, hence some phenomenon can be occurred such as degradation of fuel pellet thermal properties, cracking, swelling, strain, pellet-cladding mechanical interaction, etc, as shown in Figure 1 [19, 20].

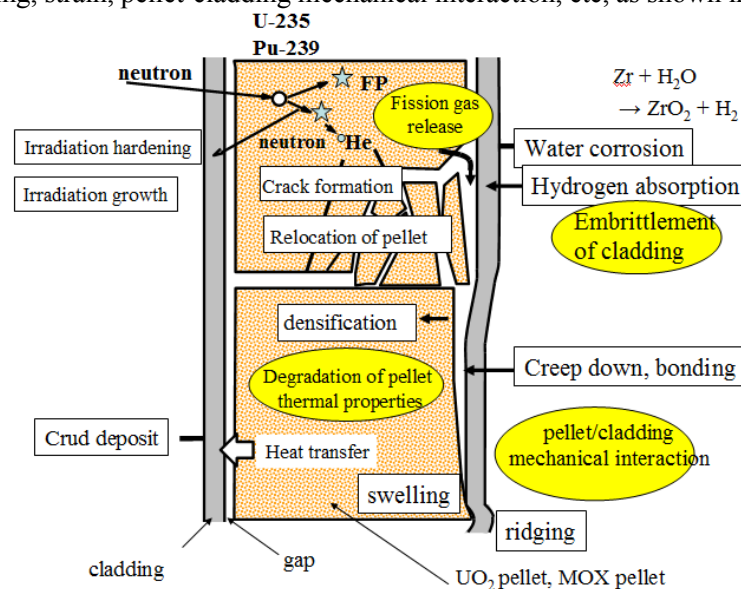


Figure 1. Phenomenon occurred when fuel temperature is higher than normal condition during reactor operation [20].

In COBRA-EN code [8], the calculation of the fuel rod temperature distribution is performed by using the CRTN fuel heating model. The model is based on the assumption of no axial and no circumferential heat conduction, and involves correlations for the film, crud, oxide, gap and cladding temperature drops and for the fuel pellet temperature profile. The fuel pellet surface temperature can be written as:

$$T_{sp} = T_w + \Delta T_f + \Delta T_{ZrO_2} + \Delta T_{clad} + \Delta T_{gap} \quad (2)$$

For forced convection, the temperature drop across the coolant film layer at the surface of the rod is based on the expression:

$$\Delta T_f = q/h_f \quad (3)$$

where q is the heat flux, given by $Q/(\pi D_g)$, Q is the linear power density, D_g is the cladding outer diameter and h_f is the film heat transfer coefficient. The film heat transfer coefficient is expressed by Dittus-Boelter as [8]:

$$h_f = (0.023k_w/D_e)Re^{0.8}Pr^{0.4} \quad (4)$$

where:

k_w = thermal conductivity of coolant (in liquid phase),

D_e = equivalent diameter of the coolant channel,

Re = Reynolds number ($D_e G / \mu$),
 Pr = Prandtl number ($C_p \mu / k_w$),
 G = flow rate per unit flow area,
 C_p = specific heat of coolant,
 μ = viscosity of coolant.

For fuel rod cladding of zircaloy (such as in PWR type), the temperature drop across the crud and the zirconium oxide (oxide layer) is determined by the expression [8]:

$$\Delta T_{ZrO_2} = q \left(\frac{\delta_{crud}}{k_{crud}} + \frac{\delta_{ox}}{k_{ox}} \right) \quad (5)$$

where:

δ_{crud} = crud thickness,
 k_{crud} = crud thermal conductivity,
 δ_{ox} = oxide thickness,
 k_{ox} = oxide thermal conductivity.

The cladding temperature drop (the difference temperature between outer and inner cladding) is calculated according to the expression [8]:

$$\Delta T_{clad} = q \frac{D_g}{2k_g} \log \frac{D_o}{D_i} \quad (6)$$

where D_i is cladding inner diameter, and k_g is cladding thermal conductivity.

The temperature drop in the gap (between inner cladding and fuel pellet surface) is determined by the expression [8]:

$$\Delta T_{gap} = q / h_{gap} \quad (7)$$

where h_{gap} is gap heat transfer coefficient. The equation for radial heat conduction in a solid cylindrical pellet can be written as [8]:

$$\int_0^r P(r) r dr + r k_f (dt / dr) = 0 \quad (8)$$

where:

$P(r)$ = volumetric heat generation rate at the radius r ,
 r = radial coordinate,
 T = temperature,
 k_f = pellet thermal conductivity.

METHODOLOGY

Modeling and calculation to predict fuel temperature due to oxide layer were performed using COBRA-EN code. This analysis used fixed thermal properties of fuel and cladding. The calculation was based on the hot sub-channel. It has peak linear power of 48.88 kW/m and the axial power factor (F_z) of 1.34, respectively, at the Beginning of Cycle (BOC) [9].

In modeling the impact of corrosion and crud, a uniform layer of crud and zirconium oxide was added on the inner and outer cladding surface of the hottest rod, as shown in Figure 2. The assumptions that were used in this model as follows:

- Oxide layer is assumed to be developed first and then a crud layer to be developed on the top of it.
- The oxide layer and crud occur along the entire height of the hot rod which is unlikely due to the non-uniform axial power profile.
- The oxide layer and crud occur only on the hot rod

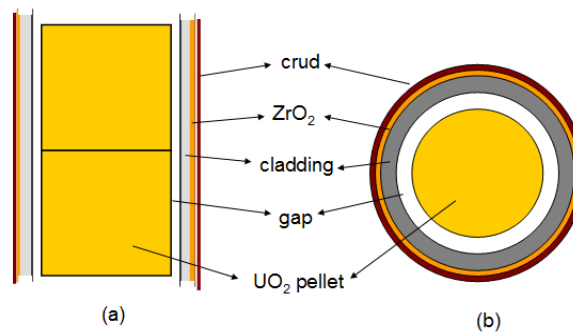


Figure 2. Scheme of crud and oxide layer formed on fuel rod (no scale), (a) front view and (b) top view [8].

At the first step, the sub-channel thermal-hydraulics calculation at nominal power and steady state condition were conducted, especially for hot sub-channel which has peak linear power of 48.88 kW/m. The separate calculations were done for varying thickness of oxide layer (modular oxide) of 0, 20, 40, 60, 80, 100 and 120 μm and for varying thickness of crud of 0, 10 and 20 μm . The calculations for varying thickness of oxide layer and crud were performed to show that temperature increases from the condition of cladding without oxide layer and crud to the condition of cladding with maximum oxide layer and crud. The calculations were conducted using conservative modular oxide's thermal conductivity of 1.0 W/m $^{\circ}\text{C}$ [3] and conservative crud's thermal conductivity of 0.4324 W/m $^{\circ}\text{C}$ [7].

At the second step, the calculations for predicting the fuel temperature due to combination of modular oxide layer and crud were compared with the calculation for black oxide layer. The calculations for black oxide layer were done by varying thickness of black oxide layer of 0, 10, 20, 30 and 40 μm using conservative thermal conductivity of 0.13 W/m $^{\circ}\text{C}$ [3]. The varying thickness of black oxide layer was done to show that temperature increases from the condition of cladding without black oxide layer to the condition of cladding with maximum black oxide layer.

RESULTS AND DISCUSSION

The distribution of center line temperature, radial average fuel temperature and cladding surface temperature of hot sub-channel along the fuel rod length based on the calculation results [9], were shown in Figure 3. Figure 3 shows that the peak fuel center line temperature, the peak radial average fuel temperature and the peak cladding surface temperature are 1608.15 $^{\circ}\text{C}$, 1126.35 $^{\circ}\text{C}$, and 348.85 $^{\circ}\text{C}$, respectively. Moreover, the Minimum Departure from Nucleate Boiling Ratio (MDNBR) is 2.49. These calculations were conducted by using COBRA-EN, for hot sub-channel without crud and oxide layer on nominal power and steady state condition.

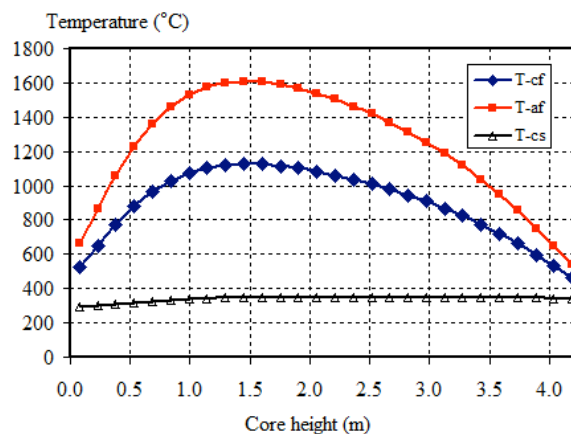


Figure 3. Distribution of center line fuel temperature, radial average fuel temperature and cladding surface temperature of hot sub-channel along the fuel rod length.

Due to crud and oxide layer were formed on the cladding surface, thus the fuel and cladding temperatures increase, as shown in Figure 4. Figure 4 (a) shows the increasing of peak fuel center line temperature and peak cladding surface temperature as a function of crud thickness. The calculations on the influence of crud thickness variations of 5, 10, 15 and 20 μm give results for the peak fuel center line temperatures of 1626.98 $^{\circ}\text{C}$, 1645.81 $^{\circ}\text{C}$, 1664.63 $^{\circ}\text{C}$ and 1683.46 $^{\circ}\text{C}$, respectively. It means that the peak fuel center line temperatures increase by 1.17%, 2.34%, 3.51% and 4.68%, respectively, as compared to without crud peak fuel center line temperature of 1608.15 $^{\circ}\text{C}$. Moreover, the calculations result in the peak cladding surface temperature of 366.03 $^{\circ}\text{C}$, 384.73 $^{\circ}\text{C}$, 403.50 $^{\circ}\text{C}$ and 422.26 $^{\circ}\text{C}$. It means that the peak cladding surface temperatures increase by 5.19%, 10.57%, 15.96% and 21.35%, respectively, as compared to without crud peak cladding surface temperature of 347.96 $^{\circ}\text{C}$.

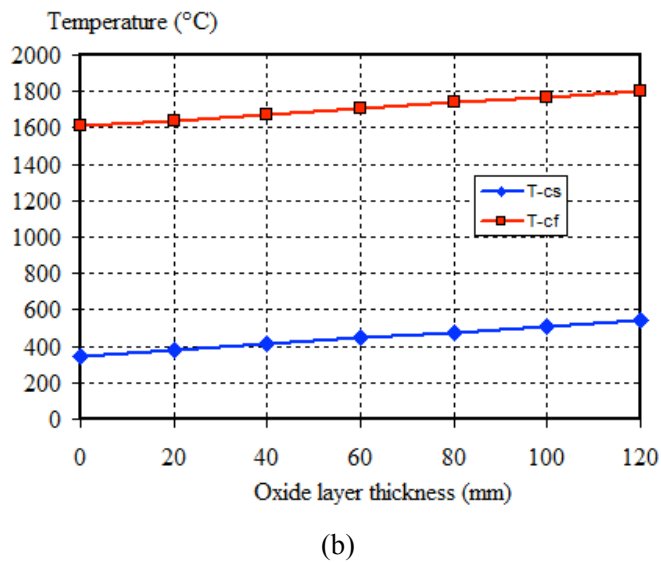
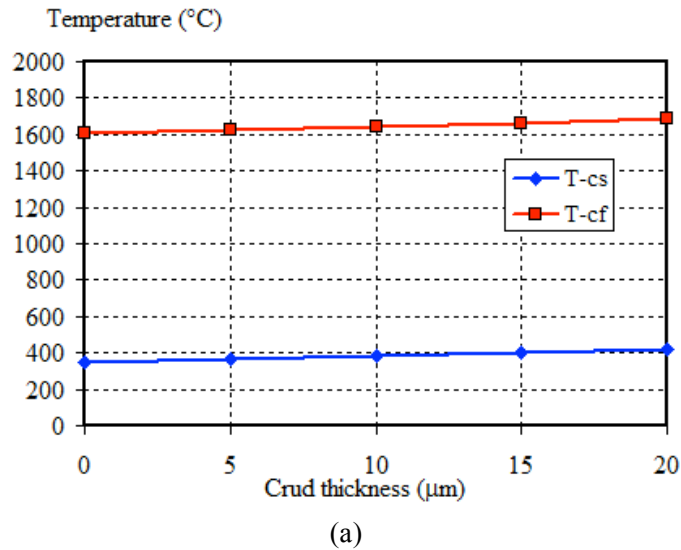
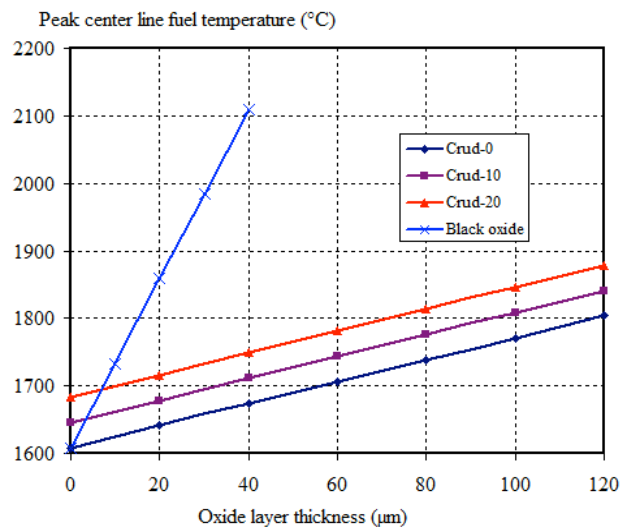


Figure 4. Graph of peak fuel center line temperature and peak cladding surface temperature as a function of the thickness of (a) crud, and (b) oxide layer

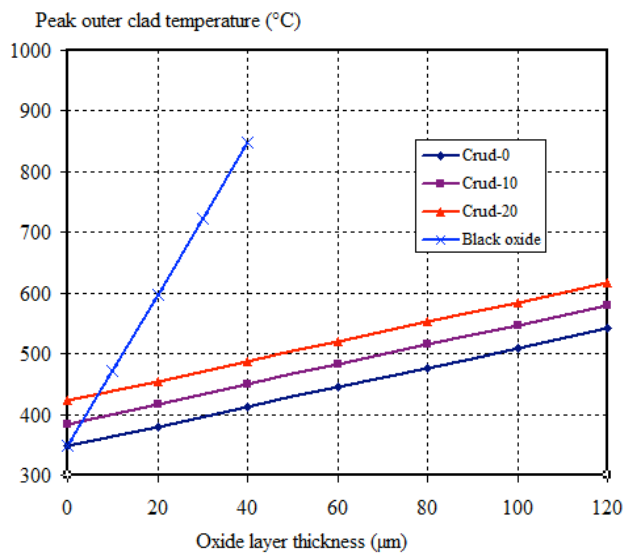
Figure 4 (b) shows the increasing of peak fuel center line temperature and peak cladding surface temperature as a function of oxide layer thickness. The calculations on the influence of oxide layer thickness variations of 20, 40, 60, 80, 100 and 120 μm give result for the peak fuel center line temperature of 1640.71 $^{\circ}\text{C}$, 1673.28 $^{\circ}\text{C}$, 1705.85 $^{\circ}\text{C}$, 1738.42 $^{\circ}\text{C}$, 1770.98 $^{\circ}\text{C}$ and 1803.55 $^{\circ}\text{C}$, respectively. It means that the peak fuel center line temperatures increase of 2.03%, 4.05%, 6.08%, 8.10%, 10.13% and 12.15%, respectively, as compared to without crud peak fuel

center line temperature of 1608.15°C. Moreover, the calculations result in the peak cladding surface temperature of 379.66°C, 412.11°C, 444.57°C, 477.09°C, 509.65°C and 542.22°C, respectively. It means that the peak cladding surface temperature increase by 9.11%, 18.44%, 27.76%, 37.11%, 46.47% and 55.83%, respectively, as compared to without crud peak cladding surface temperature of 347.96°C. Based on Figure 4(b), the maximum of peak fuel center line temperature is 1803.55°C and the maximum of peak cladding surface temperature is 542.22°C, which occur upon 120 µm oxide layer on cladding surface.

Figure 5 describes the influence of crud and modular oxide layer combination on cladding surface. The results are also compared with the influence of black oxide layer. The calculations were conducted using combination of crud thickness of 0, 10 and 20 µm and oxide layer of 0, 20, 40, 60, 80, 100, and 120 µm. Whereas the calculations for black oxide layer thickness vary of 0, 10, 20, 30 and 40 µm.



(a)



(b)

Figure 5. Comparison between calculation for combination of crud and modular oxide layer and calculation for black oxide layer; (a) peak fuel center line temperature, and (b) peak cladding surface temperature

Figure 5(a) shows that the peak fuel center line temperature for combination of crud thickness of 0, 10 and 20 µm and without oxide layer are 1608.15°C, 1645.81°C and 1683.46°C,

respectively. Moreover, the peak fuel center line temperature for combination of crud thickness of 0, 10 and 20 μm and oxide layer of 120 μm are 1803.55 $^{\circ}\text{C}$, 1841.21 $^{\circ}\text{C}$ and 1878.87 $^{\circ}\text{C}$, respectively. Whereas, the peak fuel center line temperature for condition without black oxide layer is 1608.15 $^{\circ}\text{C}$, and the temperature for oxide layer condition of 40 μm was 2109.19 $^{\circ}\text{C}$, respectively. The black oxide layer has 12.25% of fuel temperature higher than the highest fuel temperature of combination model. It is caused by the black oxide layer's thermal conductivity of 0.13 W/m $^{\circ}\text{C}$ less than thermal conductivity of combination model of crud and oxide layer.

Figure 5(b) shows that the peak cladding surface temperature for combination of crud thickness of 0, 10 and 20 μm and without oxide layer are 347.96 $^{\circ}\text{C}$, 384.73 $^{\circ}\text{C}$ and 422.26 $^{\circ}\text{C}$, respectively. Moreover, that the peak cladding surface temperature for combination of crud thickness of 0, 10 and 20 μm and oxide layer of 120 μm are 542.22 $^{\circ}\text{C}$, 579.88 $^{\circ}\text{C}$ and 617.54 $^{\circ}\text{C}$, respectively. Whereas, the peak cladding surface temperature for condition of without black oxide layer is 347.96 $^{\circ}\text{C}$, and the temperature for condition of oxide layer of 40 μm is 847.86 $^{\circ}\text{C}$, respectively. The black oxide layer has 37.30% of cladding surface temperature higher than the highest cladding surface temperature of combination model.

For full cycle hot sub-channel condition, the combination of crud thickness of 20 μm and modular oxide thickness of 115 μm give prediction for the peak fuel center line temperature and the peak cladding surface temperature of 1870.73 $^{\circ}\text{C}$ and 609.40 $^{\circ}\text{C}$, respectively. Whereas, for black oxide thickness of 20 μm gives prediction for the peak fuel center line temperature and the peak cladding surface temperature of 1858.57 $^{\circ}\text{C}$ and 597.34 $^{\circ}\text{C}$, respectively. The results show that peak fuel center line temperature and the peak cladding surface temperature deviation are -1.98% and -0.64%, respectively.

The power peaking factor in AP1000 operation cycle divided into 3 sub cycles, i.e., beginning of cycle (BOC), middle of cycle (MOC) and end of cycle (EOC) [9]. By using conservative assumption, the BOC takes place at 40% of full cycle. Therefore, the realistic of crud thickness is 8 μm , the modular oxide is 46 μm and the black oxide thickness is 8 μm , respectively. For the combination of crud thickness of 8 μm and modular oxide thickness of 46 μm , the conservative prediction of the peak fuel center line temperature and the peak cladding surface temperature were 1713.18 $^{\circ}\text{C}$ and 451.87 $^{\circ}\text{C}$, respectively. Whereas, for 8 μm of black oxide thickness, the prediction of the peak fuel center line temperature and the peak cladding surface temperature are 1708.35 $^{\circ}\text{C}$ and 447.06 $^{\circ}\text{C}$, respectively. The results show that deviation of peak fuel center line temperature and the peak cladding surface temperature are -1.06% and -0.28%, respectively. By using conservative prediction, the peak fuel center line temperature and the peak cladding surface temperature increase of 6.53% and 29.86% as compared with the temperature of normal and fresh condition, respectively.

CONCLUSION

An analysis to predict fuel and cladding temperature due to crud and oxide layer has been carried out. The effect of an oxide layer and crud formed on the cladding surface, decreases the total heat transfer from the cladding to the coolant. Consequently, the fuel and cladding temperatures increase. The analysis was conducted for nominal power using COBRA-EN code, by varying modular oxide layer thickness of 0 – 120 μm and crud thickness of 0 – 20 μm , and compared with black oxide thickness variations of 0 – 20 μm . The oxide layer is predicted only formed on hot sub-channel during BOC (40% of full cycle). The results show that the prediction of the peak fuel center line temperature and the peak cladding surface temperature are 1713.18 $^{\circ}\text{C}$ and 451.87 $^{\circ}\text{C}$, respectively. Compared to the normal and fresh fuel conditions, the peak fuel center line temperature and the peak cladding surface temperature increase by 6.53% and 29.86%, respectively.

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