THE THERMAL-HYDRAULICS ANALYSIS ON RADIAL AND AXIAL POWER FLUCTUATION FOR AP1000 REACTOR

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ABSTRACT

THE THERMAL-HYDRAULICS ANALYSIS ON RADIAL AND AXIAL POWER FLUCTUATION FOR AP1000 REACTOR. The reduction of fissile material during reactor operation affects reactivity reduction. Therefore, in order to keep the reactor operating at fixed power, it must be compensated by slowly withdrawing the control-rod up. However, it will change the shape of the horizontal/axial power distribution and safety margin as well. The research carries out the calculations of the core thermal-hydraulics to determine the effect of the fluctuations of the power distribution on the thermal-hydraulic AP1000's parameters and study their impacts on the safety margin. The calculation is done using the COBRA-EN code and the result shows that the maximum heat flux at the Beginning of Cycle (BOC) is 1624.02 kW/m^2. This heat flux will then decrease by 22.75% at the Middle of Cycle (MOC) and by 0.29% at the End of Cycle (EOC). The peak fuel centerline temperature at the BOC, MOC and EOC, are 1608.15°C, 1232.15°C, and 1301.75°C, respectively. These temperature differences are caused by the heat flux effects on sub-cooled boiling regions in the cladding surface. Moreover, the value of MDNBRs at the MOC and EOC are 3.23 and 3.00, which are higher than the MDNBR at the BOC of 2.49. It could be concluded that the operating cycle of the AP1000 reactor should be operated in the MOC and the EOC, which will be more safely than be operated in the BOC.

Keywords: Core thermal-hydraulics, AP1000, fluctuation of power distribution, COBRA-EN.

ABSTRAK

ANALISIS TERMOHIDRAULIKA PADA FLUKTUASI DAYA AXIAL DAN RADIAL UNTUK REAKTOR AP1000. *Berkurangnya material fisil selama operasi reaktor, mengakibatkan reaktivitas berkurang. Oleh karena itu, agar reaktor tetap beroperasi pada daya yang tetap, maka harus dikompensasi dengan menarik batang kendali ke atas sedikit demi sedikit. Akan tetapi, hal ini akan berakibat pada berubahnya bentuk distribusi daya ke arah horisontal/aksial dan berdampak ke perubahan marjin keselamatan. Penelitian ini melakukan perhitungan termohidrolika teras untuk mengetahui pengaruh fluktuasi distribusi daya pada parameter termohidrolika AP1000 dan mempelajari dampaknya terhadap marjin keselamatan. Hasil perhitungan dilakukan dengan menggunakan kode COBRA-EN dan hasilnya menunjukkan bahwa fluks kalor maksimum pada awal siklus (BOC) sebesar 1624,02 kW/m^2 berkurang 22,75% di tengah siklus (MOC) dan berkurang lagi 0,29% di akhir siklus (EOC). Temperatur puncak tengah bahan-bakar di awal, tengah dan akhir siklus adalah sebesar 1608,15°C; 1232,15°C; dan 1301,75°C akibat dari fluks kalor pada daerah kelongsong yang mengalami pendidihan tak jenuh. Sedangkan nilai MDNBR pada tengah dan akhir siklus adalah 3,23 dan 3,00; meningkat dibanding MDNBR pada awal siklus 2,49. Dari hasil tersebut dapat disimpulkan bahwa pada kondisi tengah dan akhir siklus operasi reaktor AP1000 memiliki marjin keselamatan yang lebih baik dibanding kondisi awal siklus.*

Kata kunci : Termohidrolika teras, AP1000, fluktuasi distribusi daya, COBRA-EN

INTRODUCTION

To study the technical design characteristics of Pressured Water Reactor (PWR), many design parameters must be verified during reactor operation and one of them is the condition during the reactivity dynamic occurred. The reactivity dynamic is occurred due to the control rod withdrawals to compensate the reactivity reduction caused by the fuel burnup during reactor

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operation. The control rod compensation will change the axial and horizontal power distribution at the Beginning of Cycle (BOC), the Middle of Cycle (MOC) and the End of Cycle (EOC).

The similar scheme of the power distribution due to control rod compensation has been studied for RSG-GAS research reactor as well due to the limitation data for PWR case [1]. At BOC, the excess reactivity would be higher due to the loading of fresh fuel. Therefore, the control rods must be inserted to compensate the excess reactivity. In this initial condition, the axial power factor will be formed at the bottom of the active core. Due to the power generation process, the fissile material in the fuel is reduced and hence it is necessary to compensate the reactivity decrease by withdrawing the control rod. Furthermore, the axial power factor during control rod withdrawal will be shifted upward. For stabilizing the power at reactor full power operation, the control rods are withdrawn slowly until they reach the highest positions at EOC.

The control rod compensation at AP1000 reactor as one of PWR typed will change the safety margin as well. Therefore, the reactivity dynamics should be studied in more detail by varying the reactor operation cycle. This research aims to determine the fluctuations effect of the power distribution against the thermal-hydraulic AP1000's parameters and study their impact on the safety margin. The analysis includes the power fluctuation effects on the temperature distribution change in the coolant, cladding and meat, as well as the heat flux and the Departure from Nucleate Boiling Ratio (DNBR). This study focuses on the fluctuation effect of the reactivity dynamics of the AP1000 reactor [2] by using the COBRA-EN code that has been utilized for standard VVER-1000 thermalhydraulics calculations [3-7]. The AP1000 core [2] consists of 157 fuel assemblies, with power generation of 3400 MWt and core coolant flow-rate of 48.44×10^6 kg/h. This study results is important to complete a technical justifications for the AP1000 such as DNBR and temperature mapping [8], thermal-hydraulics evaluation for subchannel design [9] as well as the influence of nozzle and spacer grid [10].

METHODOLOGY

The main problem in the thermal-hydraulics analysis during reactor operation is the change of the control rod position. At the initial reactor criticality at nominal power, control rods are withdrawn about 45% of the core height. Due to fuel burnup, the control rods must be withdrawn continuously. Consequently, the change of control rod position will change the distribution of the axial neutron flux shape.

In the thermal-hydraulics calculation on the axial power fluctuation, the modeling and calculation were done using the COBRA-EN code based on the axial power distribution at BOC, MOC, and EOC. The axial power distributions at BOC, MOC and EOC as shown in Figure 1 are calculated by SIMULATE-3 code for the one of PWR type, which is the OPR1000 reactor. Consequently, the active core height of the OPR1000 reactor [11] is modified to meet the active core height of the AP1000 reactor.

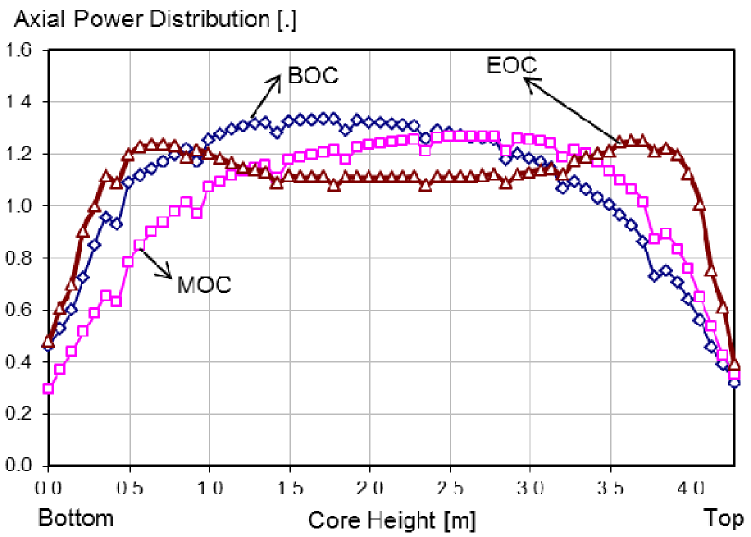

Figure 1. Axial power distribution at BOC, MOC, and EOC.

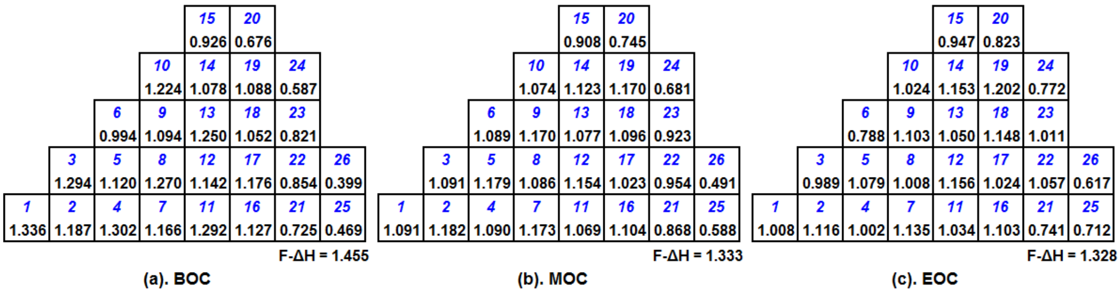

Figure 2. Horizontal power distribution at BOC, MOC, and EOC [4].

From the Figure 1, the axial power density factors (F_Z) at the BOC, MOC and EOC are 1.34, 1.27 and 1.27, respectively. The analysis is done for the maximum temperature of the channel indicated by the value of the horizontal power factor (F_{XY}) of 1.336 (position of H-8), 1.182 (position of H-9) and 1.202 (position of E-13) as well as the hot channel factor ($F_{\Delta H}$) for enthalpy rise are of 1.455, 1.333 and 1.328 for BOC, MOC and EOC, respectively, as shown in Figure 2. However, the position of cold channel is never changed at G-15 position, and the horizontal power factors in this channel are 0.399, 0.491 and 0.617 for BOC, MOC and EOC, respectively.

There are two models of conducted thermal-hydraulics calculations, i.e. the core (channel) model and sub-channel model. Each fuel assembly is modeled as one channel for model simplification. The sub-channel based calculation will result in thermal-hydraulics values of average core and each channel such as the distribution of pressure drop, coolant, cladding and fuel meat temperatures, heat conductivity, heat flux and the safety margin of DNBR. In channel model, the heat-flux hot channel factor, F_Q [·], is defined in equation (1).

$$F_Q = F_{XY} \times F_Z \tag{1}$$

In the sub-channel model, the calculation is to determine the maximum temperature of the fuel rod taken from the maximum temperature of fuel assembly (channel) using the boundary conditions of pressure drop and mass flow rate obtained from the previous channel analysis. The results will provide more conservative values on the distribution of the coolant, cladding and fuel temperatures, heat flux and DNBR. The heat flux hot channel factor, F_Q, is defined by equation (2).

$$F_Q = F_{XY} \times F_Z \times F_{\Delta H} \tag{2}$$

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Whereas, for the other channels, the heat flux hot channel factor only analyzed using the axial power factor F_Z [·] and horizontal power factor F_{XY} [·]. Table 1 showed the value of the total heat channel factors that are used in the calculation of each maximum temperature of channel conditions at BOC, MOC, and EOC. After calculation are done, the thermalhydraulic analysis is carried out for completing the characteristics of the coolant, cladding, fuel-meat temperature distributions, heat flux, and DNBR of AP1000 reactor.

Table 1. The total heat channel factor for the BOC, MOC and EOC.

Parameter	BOC	MOC	EOC
Channel position in the core	H-8	H-9	E-13
Axial power peaking factor (F_Z)	1.34	1.27	1.27
Horizontal peaking power factor (F_{XY})	1.336	1.182	1.202
Nuclear enthalpy rise hot channel factor ($F_{\Delta H}$)	1.455	1.333	1.328
Total peaking factor or heat flux hot channel factor, F_Q	2.60	2.001	1.995

RESULTS AND DISCUSSIONS

Comparisons of core calculation results, which are based on channel and sub-channel model in the hot fuel assembly position of H-8 at BOC, are shown in Table 2. Table 2 showed that the outlet coolant, cladding and fuel rod temperatures and the maximum heat flux in subchannel model are higher than ones in channel model, as well as the MDNBR in sub-channel model is lower than the MDNBR in channel model. These mean that the thermal hydraulis calculation results based on subchannel model are more conservative than the ones based on channel model. Furthermore, the results of thermal hydraulic calculations due to the influence of fluctuations in the power distribution are focused on sub-channel calculation.

Table 2. Comparison of calculation results based on channel and subchannel model position of H-8 at BOC.

Parameter	Calculation Model		
	Channel	Subchannel	Deviation
Channel position in the core	H-8	H-8	
Axial power peaking factor (F_Z)	1.340	1.340	-
Horizontal peaking power factor (F_{XY})	1.336	1.336	
Nuclear enthalpy rise hot channel factor ($F_{\Delta H}$)	-	1.455	
Total peaking factor (F_Q)	1.79	2.60	45.25%
Pressure drop, ΔP [kPa]	275.44	275.50	0.02%
Maximum temperature [ºC]			
outer cladding -	347.75	348.85	0.32%
inner cladding -	397.05	422.75	6.47%
fuel rod -	521.85	606.25	16.17%
peak fuel centerline -	1208.65	1608.15	33.05%
Maximum heat flux (q") [kW/m^2]	1118.79	1624.02	45.16%
MDNBR	3.38	2.49	-26.46%

Based on the evaluation, the maximum temperature of channel positions are shifted from the middle core at BOC (position of H-8) to outer middle core at MOC (position of H-9) and EOC (position of E-13). However, the minimum temperature of channel at BOC, MOC, and EOC are in the position of G-15 in the edge core.

The calculation results of AP1000 sub-channel thermal-hydraulics using COBRA-EN code due to the influence of fluctuations in the power distribution (radial and axial) during reactor operation conditions at nominal power are shown in Figure 3-7.

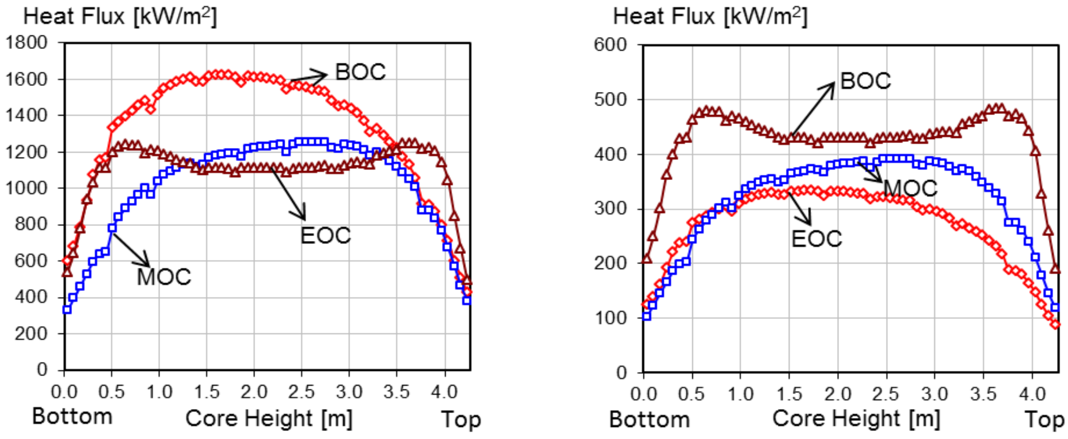

Figure 3. The axial heat flux distribution for (a) hot subchannel and (b) cold subchannel, at BOC, MOC and EOC.

Figure 3 showed the axial heat flux distribution for (a) hot sub-channel and (b) cold sub-channel at BOC, MOC and EOC. The heat flux at MOC is lower than the heat fluxe at BOC and EOC in Figure 3(a), whereas the heat flux at MOC and EOC are higher than the one at BOC in Figure 3(b). The maximum temperature of channel is shifted from middle core to outer core, which means that the heat generation in the middle core tends to decrease at the MOC and EOC, otherwise the heat generation at the edge core tends to increase, as well as the horizontal power factor at MOC and EOC are higher than the one at BOC. The results of the calculations on the maximum temperature of sub-channel showed that the maximum heat flux is reduced from 1624.02 kW/m^2 at BOC to 1254.54 kW/m^2 at MOC (decrease by 22.75%) and reduced again to 1250.96 kW/m^2 at the end of the cycle (decreased 0.29%). In the cold channel, the heat flux increased from operation time of BOC to MOC, which is started from 333.72 kW/m^2 to 390.95 kW/m^2 or increase by 17.15%. Furthermore, the heat flux will increase by 23.68% or become 483.54 kW/m^2 at EOC. Comparing the maximum heat flux in the hot channel and cold channels, it is found that the ratio of the heat flux at BOC, MOC and EOC are 4.87, 3.21 and 2.59, respectively. The ratio at the EOC is the lowest, which means that the horizontal power distribution at EOC is more flattened than the ones at BOC and MOC.

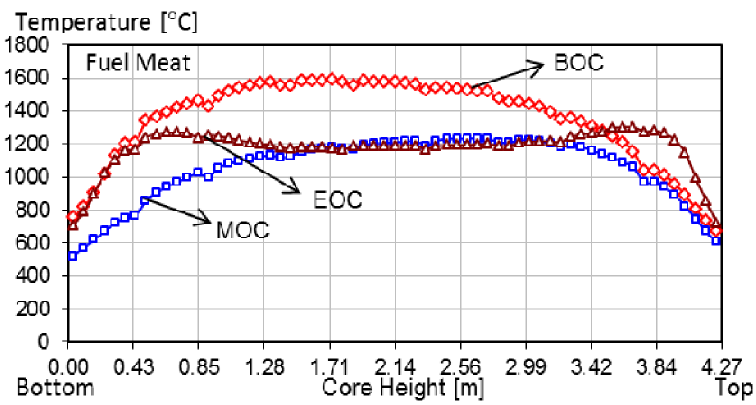

Figure 4. The axial temperature distribution of peak fuel center line for hot subchannel at BOC, MOC and EOC.

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Figure 4 showed the temperature distribution of fuel meat centerline for hot sub-channel at BOC, MOC and EOC. The peak fuel center liner temperature in Figure 4 at the MOC and EOC are 1232.15°C and 1301.75°C, lower than the temperature at the BOC, which is 1608.15°C. The peak fuel centerline temperature decreased due to the decrease of the heat generation in the middle core and shifted towards the edge of the core.

Figure 5 showed the axial temperature distribution of the outer cladding for hot sub-channel at BOC, MOC and EOC. The maximum temperatures of the outer cladding at BOC, MOC and EOC are 348.85°C, 347.45°C and 348.35°C, respectively. It is shown that the maximum outer cladding temperatures are almost the same. Likewise, the outlet coolant temperatures are almost the same. Figure 6 showed that the outlet coolant temperature at BOC, MOC and EOC are 332.18°C, 327.52°C and 332.69°C, respectively.

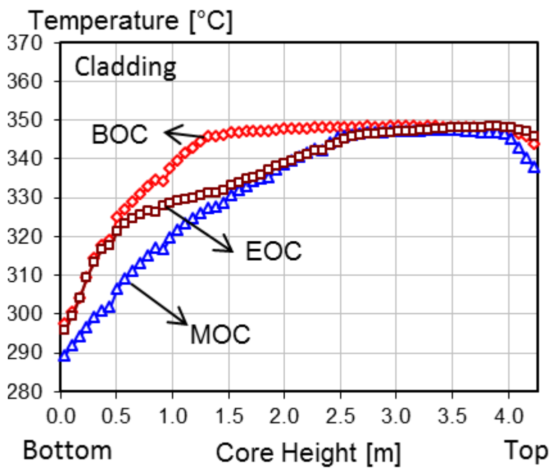

Figure5. The axial temperature distribution of outer cladding for hot subchannel at BOC, MOC and EOC.

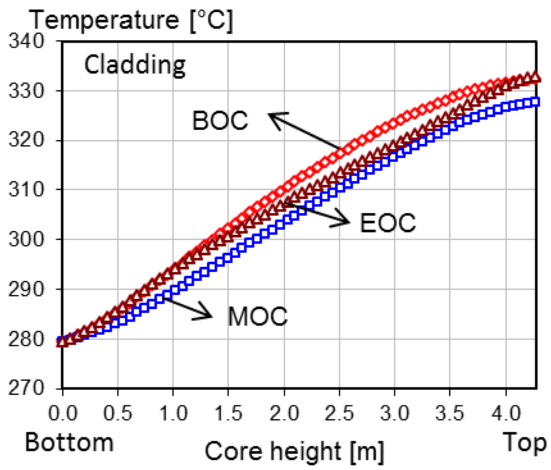

Figure 6. The axial temperature distribution of coolant for hot subchannel as at BOC, MOC and EOC.

From Figures 5 and 6, it describes that the outer cladding temperature at upper fuel length tends to be flat, however the flatten temperature of channel length at BOC, MOC and MOC are different by 66.65%, 36.51% and 38.10% of the active fuel length. In the operating pressure of the primary coolant of 15.513 MPa, it is known that the temperature of saturation is at 345.63°C. Because the cladding surface temperature is higher than the saturation temperature and the primary coolant temperature is under the saturation temperature, the heat removal by the coolant flow is in the condition of sub-cooled boiling. The sub-cooled regime is only happening in the surface boiling occurred when the reactor has reached hot zero power, which is different from Boiling Water Reactor that could be boiled in cold or hot zero power. This sub-cooled regime is typical for PWR's under normal operating condition. The mechanism in this regime is called nucleate boiling that is characterized by a very high heat transfer rate for only a small temperature difference.

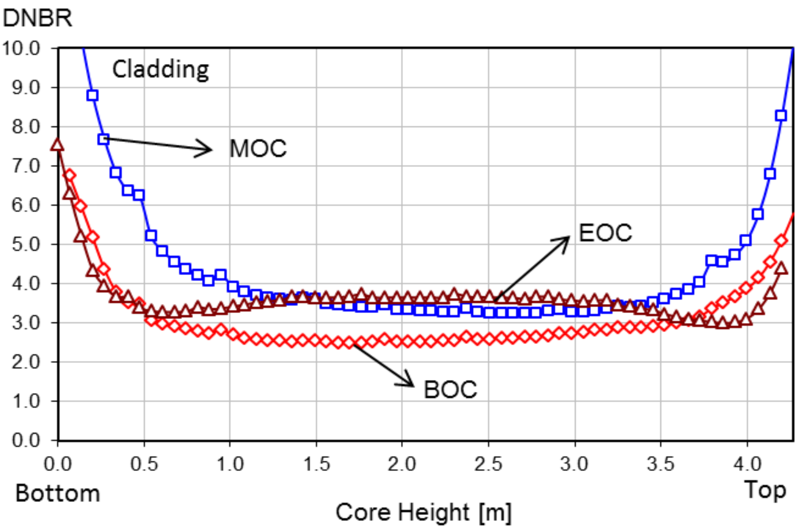

Figure 7. The axial DNBR distribution for hot subchannel at BOC, MOC and EOC.

To justify the safety of this reactor condition, DNBR parameters at BOC, MOC and EOC are calculated and the safety margin of DNBR is measured as well. Figure 7 showed the axial DNBR distribution for hot sub-channel at BOC, MOC and EOC. The minimum DNBRs (MDNBR) are 2.49, 3.23 and 3.00 for BOC, MOC and EOC, respectively. The MDNBR at MOC and EOC are different by 29.67% and 20.18%, respectively, from the MDNBR at BOC.

AP1000 thermal hydraulic analysis of the effect of fluctuations in the power distribution can be summarized that (1) the maximum heat flux at MOC and EOC are lower than the heat flux at BOC; (2) the peak fuel centerline temperature at MOC and EOC are lower than the peak fuel centerline temperature at BOC; (3) the sub-cooled boiling region at MOC and EOC are shorter than the one at BOC; and (4) the MDNBR at EOC is higher than the MDNBR at BOC and MOC.

CONCLUSION

The comparison of thermal-hydraulics calculation of AP1000 reactor at nominal power and steady state conditions due to the influence of power distribution fluctuations at BOC, MOC and EOC using COBRA-EN code indicates that the horizontal heat generation tends to be flattened at MOC and EOC. Especially, the heat flux of the hot channel at MOC is reduced by 22.75% compared to the heat flux at BOC and will decreased again by 0.29% at EOC. Decreasing the heat flux on the hot channel gave effect on the decrease of the peak fuel centerline temperature, the decrease of the sub cooled boiling region and the increase of the MDNBR. These results indicate that safety margin at MOC and EOC is better than the one at BOC.

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