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A Numerical Analysis on the Correlation between the Core Exit Temperature Distribution and Hot Leg RTD Temperature

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1. Introduction

The RCS(Reactor Coolant System) flow rate is one of the important plant operating parameters, which is periodically inspected and should be maintained within a pre-designated range to assure a safe plant operation. The heat balance flow rate measurement method, officially used for OPR1000s, needs the hot leg average temperature as an input. If the measured average hot leg RTD(Resistance Temperature Detector) temperature is higher than the actual average hot leg temperature, then the calculated RCS flow rate will be smaller than the actual RCS flow rate as can be seen in the following equation, and vice versa. If measured RCS flow rate goes smaller, then the operation margin and safety margin will also be reduced.

$$\dot{m} = \frac{Q}{C_P(T_H - T_C)}$$

where, $\dot{m}$: RCS mass flow rate, Q: core thermal power, C_P: coolant specific heat, T_H: measured average hot leg RTD temperature, T_C: measured average cold leg RTD temperature.

The RCS flow rates measured by heat balance method for OPR1000s in the past have shown a considerable change depending on the operation cycle or even within the same operation cycles. Specifically, in recent years, the measurements for YGN 3&4 and UCN 3&4 by heat balance method unexpectedly showed very low RCS flow rates. However, the flow rates measured by pump DP(Differential Pressure) method, which well represents the trend of flow rate change, showed that relatively constant RCS flow rates were maintained during the operation cycles. As an example, the measured RCS flow rates for UCN 4 calculated by heat balance and pump DP methods are plotted in Fig.1 from beginning of operation up to recent time. This suggests that there was actually no significant change in RCS flow rate.

To investigate the reason for the seemingly changing flow rate measured by heat balance method, various operation parameters, such as core thermal power, hot/cold leg temperatures, core exit temperatures, turbine power, etc., were observed. One thing noticed is that there might be a strong relationship between core exit temperature distribution and the hot leg RTD temperature measurements. This suggests that, even though the average core exit temperature is the same, the different patterns of local core exit temperature distribution may cause the different thermal stratification patterns in the hot leg. In this case, the average of hot leg RTD temperatures may not represent the real or actual hot leg average temperature. One notable observation is that as the core exit temperature at core center region goes higher, then the average temperature of hot leg RTDs goes higher. In recent years, low leakage core loading pattern is prevailing to improve the neutron economy. Then the core power distribution is more concentrated in the core center region, and in turn the temperature of core center region may go even higher. This causes the heat balance method to calculate the smaller RCS flow rate than the actual. In this paper, a CFD analysis for the flow field from core exit to inlet of steam generator was performed to quantify the relationship between core exit temperature distribution and hot leg RTD temperatures.

2. Observed Relationship

Fig.2 represents the core exit plane divided into 3 regions according to the distances from the core center. They are core center, middle, and peripheral regions. Generally, the local temperature at core exit plane is higher when it goes closer to the center. Fig.3 shows the schematic diagram for coolant flow path from core exit plane to hot leg RTD location and RTD circumferential locations. As shown in Fig.3, the coolant exiting core center region mainly passes through the upper part of hot leg, while the coolant from core peripheral region mainly passes through the lower part of hot leg. Fig.4 represents the difference in the measured average CET temperature between center region and peripheral region classified in Fig.2 (hereafter called as core exit DT(Differential Temperature)) for UCN 4. Also shown in Fig.4 is the difference in the measured average temperature between hot leg and cold leg (hereafter called as hot leg - cold leg DT) for UCN 4. The trend of changing shapes suggests that there is a strong correlation between core exit DT and hot leg - cold leg DT. The similar trend can also be observed for YGN 3&4 and UCN 4. This phenomenon means that though the total core power is maintained constant, the hot leg

RTD temperature measurement can change due to the thermal stratification if the local core exit temperature changes. Especially, under current RTDs location of OPR1000s, the average RTD temperature tends to go higher if the core power distribution concentrates in center region. Thus, the calculated RCS flow rate goes smaller than the actual flow rate.

3. CFD Analysis

Fig.5 shows the flow model for CFD analysis, which models the flow region from core exit plane to inlet of steam generator. All the important reactor internals which can affect the flow pattern such as fuel alignment plate flow holes and control rod guide tubes were modeled as their original shapes and dimensions. The flow conditions were set similar to those of normal reactor operations. The analysis was performed by two turbulence modeling methods: $k-\varepsilon$ and Reynolds Stress models. Fig.6 shows the temperature profile of the flow field for one run case with $k-\varepsilon$ model as an example.

The temperature difference between the average of hot leg RTD locations and the cross-sectional bulk at the location are plotted in Fig.7 for several run cases of core exit DTs. This difference increases as the core exit DT increases. This difference means the amount of adjustment which is needed to obtain the actual average of hot leg temperature.

4. Conclusion

The result of CFD analysis supports the evidence of correlation between the core exit DT and the hot leg RTD temperature observed in the OPR1000s. If a correction is applied to the RTD temperature measurement by the amount of adjustment through the CFD analysis, the heat balance method will give a better result. But to determine a quantitatively well tuned adjustment factor, it is thought that a further study is needed.

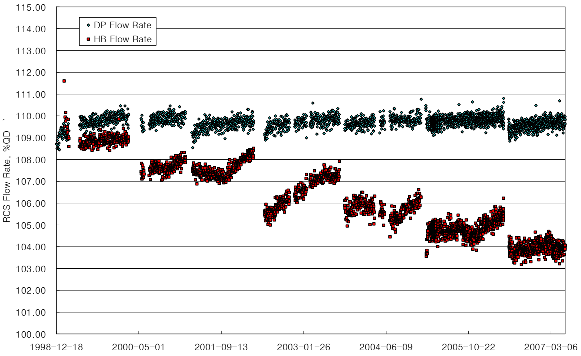

Fig.1 RCS Flow Rates Measured by RCP DP and Heat Balance Methods (UCN 4)

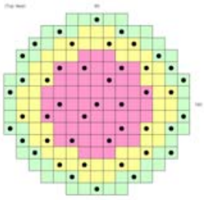

Fig.2 Core Exit Regions Divided (3 Regions)

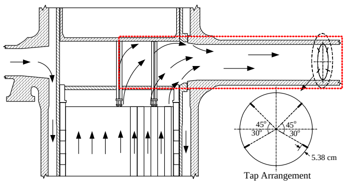

Fig.3 Coolant Flow Path from Core Exit Plane to Hot Leg RTD Location

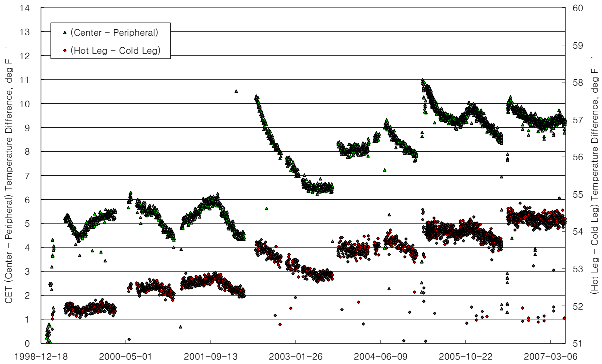

Fig.4 Core Exit DT and Hot Leg - Cold Leg DT (UCN 4)

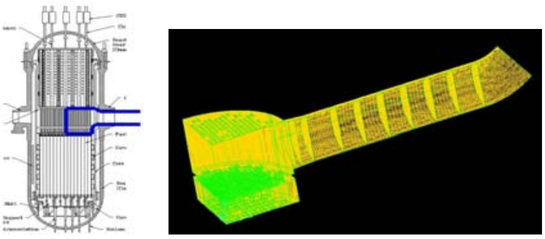

Fig.5 CFD Flow Model from Core Exit to SG Inlet

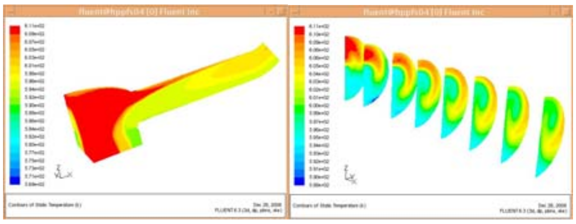

Fig.6 Temperature Profile of the Flow Field

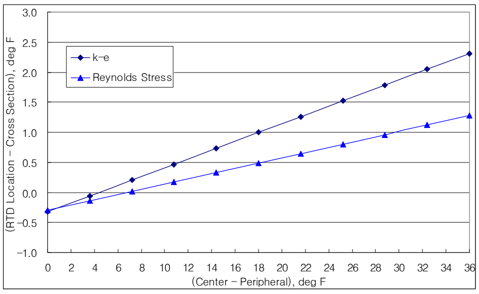

Fig.7 Core Exit DT vs. (RTD – Cross Section) Average