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An Analysis of the Hot Leg Thermal Stratification Effect on the Hot Leg Temperature Measurement for KSNP

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Abstract

For Korea Standard Nuclear Power Plant (KSNP), four Resistance Temperature Detectors (RTDs) are installed at each hot leg - two in the upper region and two in the lower around the pipe wall. It has been recognized that the degree of so-called thermal stratification in the hot leg grows as the non-uniformity of power distribution grows in the reactor core, usually having a peak in the center area. Since the arithmetic mean of RTDs may not correctly represent the coolant bulk temperature, some correction offset has been made to it to obtain the bulk temperature. Since it has been hard to quantify the stratification effect, an unrealistically large uncertainty has been assumed for conservatism, which has been the largest contributor to the hot leg temperature measurement uncertainty.

The present work is aimed at quantifying the correction offset and associated uncertainty based on the coolant velocity profiles and local temperatures in the hot leg pipe which, respectively, have been measured in CENP's System 80 reactor flow model test and the KSNPs in operation. The results show that the correction offset is minimal and 0.3°F is enough for the uncertainty to the extent of hot leg thermal stratification observed in the KSNPs. Considering the current uncertainty of 0.5°F, it is expected to contribute to reducing the excessive conservatism involved in the measurement uncertainty of the hot leg temperature.

1. Introduction

The uncertainty parameters related with the secondary calorimetric heat balance flow rate measurement method are the instrumentation uncertainties of the coolant temperatures of cold and hot legs and system pressure, core power uncertainty, and the uncertainty of the hot leg temperature correction offset for the thermal stratification in the hot leg. Among these uncertainty parameters, the uncertainties of the hot leg temperature correction and the core power are the major contributors on the overall uncertainty. In this paper, among these two important parameters, an analytical approach to quantify the magnitude of uncertainty for the hot leg temperature correction was made to improve the confidence of the measurement method. Because the different configurations of RTD locations and numbers may produce different results, the contents in this paper apply only to KSNP type of reactors.

Hot leg temperature stratification phenomenon means that the coolant temperatures in the upper region of cross sectional area of hot leg are higher than in the lower region, which has been observed in the plant operations. There are four RTDs in each hot leg as shown in Figure 1, i.e., total eight RTDs in two hot legs, to obtain the average hot leg temperature. But the arithmetic mean value may not represent the bulk temperature of the coolant passing through the hot leg pipe. Therefore some correction offset is introduced to compensate for the difference between the mean of RTDs and the bulk temperature. However the correction inevitably has uncertainty because it is impossible to get the exact value of the correction offset based on the existing information. Thus, while assuming "zero" for the correction offset, a large value has been used for the uncertainty of correction offset in the existing design, which has been believed to be definitely conservative. In this paper, an analytic and realistic estimation is done to obtain both the best estimate and the limiting values for the correction offset using the measured velocity profile of the System 80 reactor flow model test[1] and the hot leg temperature measurement data taken during the startup tests and commercial operations of YGN 3&4[2,3,4], UCN 3&4[2,5,6], and PVNGS 1&2[7,8]. The "limiting" correction offsets cover all the conservative combinations of velocity and temperature distributions. Then, the probability of the limiting value being exceeded in the actual situation is so low that the limiting value itself can be conservatively used as the uncertainty of the correction offset. From the analytic and realistic calculations, the conservatism which has been imposed upon the existing uncertainty is expected to be quantified. As a result, excessive conservatism can be reduced or eliminated.

2. Mathematical Analysis

2.1 RCS Flow Measurement and Hot Leg Temperature Correction

The basic equation for the determination of RCS flow rate by the heat balance method is expressed as follows :

$$Q = \frac{v_c P}{h_H - h_C} \tag{1}$$

where, Q, v_c, P, h_H, and h_C represent RCS volume flow rate, cold leg coolant specific volume, core power, hot leg coolant enthalpy, and cold leg coolant enthalpy, respectively. The uncertainty of the measured flow rate is calculated by combining the uncertainties of the individual parameters. Among these, h_H is determined by measuring hot leg temperature and system pressure. However, it may be affected by the hot leg temperature stratification phenomenon. As mentioned before, the average of RTDs may not represent the bulk temperature T^{bulk} so that some correction is made as follows :

$$T^{bulk} = \frac{1}{8}\sum_{i=1}^{8} T_i + \Delta T_{HS} = T^{avg} + \Delta T_{HS} \quad (2)$$

where ΔT_{HS} is the hot leg temperature correction offset. The uncertainty of T^{bulk} can be obtained by the following equation[9] :

$$\sigma^2_{T^{bulk}} = \sum_{i=1}^{8}\left(\frac{\partial T^{bulk}}{\partial T_i}\right)^2 \sigma^2_{T_i} + \left(\frac{\partial T^{bulk}}{\partial \Delta T_{HS}}\right)^2 \sigma^2_{\Delta T_{HS}} \quad (3)$$

where $\sigma_{\Delta T_{HS}}$ represents the uncertainty of ΔT_{HS}.

For YGN 3&4 and UCN 3&4 design, $\Delta T_{HS} = 0$ and $\sigma_{\Delta T_{HS}} = 0.5$°F were used. ΔT_{HS} has a direct effect on the measured flow rate, and $\sigma_{\Delta T_{HS}}$ has an effect on the uncertainty of the measured flow rate. The physical definition of the T^{bulk} is as follows[10] :

$$T^{bulk} = \frac{\int \rho C_P T v \, dA}{\int \rho C_P v \, dA} \quad (4)$$

where $\rho, C_P, T, v,$ and A represent the density, specific heat, temperature, velocity, and cross-sectional area of the hot leg pipe, respectively. From Equation (2), ΔT_{HS} is expressed as follows :

$$\Delta T_{HS} = T^{bulk} - T^{avg} \quad (5)$$

In this paper, ΔT_{HS} is estimated by Equation (5) using T^{avg} measured during the start-up test and commercial operations and T^{bulk} calculated per Equation (4). For the limiting ΔT_{HS}, a combination which is expected to maximize ΔT_{HS} is chosen among the local v and T profiles. For the best estimate ΔT_{HS}, actual local profiles of v and T are used.

2.2 Velocity Profiles in the Hot Leg Pipe

Generally, the coolant velocity in the hot leg pipe is known to be greater in the upper half region than in the lower half region. It is believed this phenomenon is attributed to the unique geometric arrangement of the reactor and pipings. But the coolant velocity distribution in the hot leg pipe of KSNP was not measured in the YGN 3&4 flow model test. Instead, the velocity distribution of the System 80 flow model test[1] is used since there is a geometric similitude between KSNP and System 80. Figure 2 shows the schematic of traverse port locations for velocity measurement. The velocity distributions for 6 traverse angles were measured in the model test. Figure 4 shows the measured velocity profiles for traverse angles of 15^o-195^o, 45^o-225^o, 75^o-255^o and 165^o-345^o, 135^o-315^o, 105^o-285^o. In comparison with the velocity profiles of 15^o-195^o, 45^o-225^o, 75^o-255^o, those of 165^o-345^o, 135^o-315^o, 105^o-285^o have similar trends due to the geometric symmetry, but slightly flatter slopes. In calculating T^{bulk} as defined in Equation (4), the steeper velocity profile makes the difference of $T^{bulk} - T^{avg}$ larger. Thus, for simple and conservative calculation, the velocity profiles of 15^o-195^o, 45^o-225^o, 75^o-255^o are used as representative ones. By means of the least square method, the measured profiles of 15^o-195^o, 45^o-225^o, 75^o-255^o are curve-fitted and provided in Figure 5. All these profiles show that the velocities are greater in the upper region than in the lower region. The 15^o-195^o curve slope is steeper than that of 45^o-225^o, and the 45^o-225^o curve slope is steeper than that of 75°-255°. The curve fitted equations as a function of the distance from the center of hot leg pipe are as follows :

$$15^o\text{-}195^o : \; v_{15-195} = -16.1639(r/r_o)^3 - 9.8985(r/r_o)^2 + 26.7919(r/r_o) + 36.7079 \quad (6)$$

$$45^o\text{-}225^o : \; v_{45-225} = -14.5971(r/r_o)^3 - 6.6856(r/r_o)^2 + 20.9971(r/r_o) + 37.5765 \quad (7)$$

$$75^o\text{-}255^o : \; v_{75-255} = -27.4180(r/r_o)^4 - 4.2414(r/r_o)^3 + 18.8326(r/r_o)^2 + 7.4115(r/r_o) + 36.8523 \quad (8)$$

where, r and r_o are the radial distance and the radius of the hot leg pipe, respectively. In the above velocity equations, r/r_o should be negative if $90^o < \theta \leq 270^o$, i.e., downward direction from the pipe horizontal center line and positive if $270^o < \theta < 360^o$ or $0^o \leq \theta \leq 90^o$, i.e., upward direction. For the limiting ΔT_{HS} estimation, the 15°-195° curve is used for all angles because it makes ΔT_{HS} largest. For the best estimate ΔT_{HS}, the pipe cross-sectional area is divided into 3-regions as shown in Figure 3 and the velocity profiles are applied to relevant regions. The 15°-195° curve is used for region 1; the 45°-225° curve for region 2; and the 75°-255° curve for region 3. 68% of total flow passes through the upper half of the pipe for the limiting ΔT_{HS} case, while 61% passes for the best estimate ΔT_{HS} case.

2.3 Temperature Distribution in the Hot Leg Pipe

Local coolant temperatures at core exit region are not uniformly distributed because the heating rates are different depending on the coolant paths in the core region. Exiting the core and progressing into hot leg pipes, the coolant undergoes rapid mixing because it is in high turbulent flow regime. At a position in the hot leg pipe where the measurement is taken, the coolant temperatures at any point of the pipe cross-section are very close to each other, but not exactly the same. Figure 6 shows the locations of Core Exit Thermocouples(CETs). Figure 7 shows the temperature difference between the average of inner region CETs and that of outer region as function of core power level, which increases with core power. Also shown in the Figure is the temperature difference between the average of upper region RTDs and lower region RTDs located in the hot leg. It is found that the temperature differences at the core exit are much greater than at the hot leg RTD location. This supports the fact that coolant flowed out core region gets mixed as it further goes to downstream. Generally the temperature of the upper region is known to be slightly higher than that of lower region due to the geometric characteristics of the reactor and piping arrangement. The measured temperatures of RTD channels C and D (see Figure 1 for channel locations) were substantially higher than those of channels A and B for start-up and commercial operation period of YGN 3&4 and UCN 3&4.

To calculate T^{bulk} as defined in Equation (4), the temperature, density, specific heat and velocity should be expressed as a function of location in the cross-section of the hot leg pipe. The assumed temperature distribution for this calculation is that temperature varies linearly depending on the vertical height only. This assumption may not be exact but consistent in the overall trend with those stated above. And also from the fact that the temperature distribution shows large deviation at the core exit but very small in the hot leg; i.e., the coolant is sufficiently mixed flowing from the core exit to the hot leg RTD location, it is believed that the temperatures at any locations of the cross-section are not so different from the RTD measurement data. Thus the assumed linear temperature function is believed to comply well with the actual hot leg temperature characteristics.

As mentioned before, ΔT_{HS} is estimated for two cases. For the best estimate ΔT_{HS}, all four RTD temperatures for one hot leg are used in generating the linear temperature function. For the limiting ΔT_{HS}, the maximum and minimum temperatures are used in calculating the slope of the linear temperature function because it makes the difference of T^{bulk} and T^{avg} larger. The fitted temperatures as a function of vertical height for the best estimate and limiting cases are as follows :

Best Estimate Case :
$$T_{avg\ slope} = \frac{T^{lower} h_U - T^{upper} h_L}{h_U - h_L} + \frac{T^{upper} - T^{lower}}{h_U - h_L} h \quad (9)$$

where, $T^{upper} = \frac{1}{2}(T^C + T^D)$, $T^{lower} = \frac{1}{2}(T^A + T^B)$, $h = r/r_0 \cos\theta$, $h_U = \cos 45^o$, $h_L = \cos 120^o$

Limiting Case :
$$T_{max\ slope} = T^{avg} - \frac{T^{upper} - T^{lower}}{h_U - h_L} \frac{h_U + h_L}{2} + \frac{T^{upper} - T^{lower}}{h_U - h_L} h \quad (10)$$

where, $T^{avg} = \frac{1}{4}(T^A + T^B + T^C + T^D)$, $T^{upper} = MAX(T^A, T^B, T^C, T^D)$, $T^{lower} = MIN(T^A, T^B, T^C, T^D)$

h is positive for the upward from the horizontal center line and negative for the downward, which is automatically determined by the sign of $\cos\theta$. In the calculation of limiting ΔT_{HS}, the mean value of T^{upper} and T^{lower} should be retained as the original mean value of 4 RTDs despite that the maximum and the minimum temperatures are used because we are estimating $T^{bulk} - T^{avg}$. So Equation (10) is a curve which has been moved in parallel with the slope made by the maximum and minimum temperatures to have the same mean value of 4 RTDs.

2.4 Density and Specific Heat in the Hot Leg Pipe

The density and specific heat are expressed as functions of temperature. In the hot leg pipe cross-section, the temperature variation is so small. So the density and specific heat can be assumed to change linearly with temperature. The fitted equations for density and specific heat as a function of temperature are as follows :

$$\rho[lb/ft^3] = 101.4126 - 0.184058\,T[℃], \quad C_P[Btu/lb/°F] = -3.57099 + 0.0157151\,T[℃]$$
$$\rho[lb/ft^3] = 104.6848 - 0.102255\,T[°F], \quad C_P[Btu/lb/°F] = -3.85037 + 0.0087306\,T[°F] \quad (11)$$

2.5 Calculation of T^{bulk}

The velocity and temperature distributions have been obtained as functions of radial distance r/r_o and azimuthal angle θ in Sections 2.2 and 2.3. T^{bulk} is calculated using Equation (4). Due to the symmetry with the vertical center line of pipe, it is sufficient to integrate right or left half side of the cross-sectional area.

$$T^{bulk} = \frac{\int_A \rho C_P T v\, dA}{\int_A \rho C_P v\, dA} = \frac{\int_0^{\pi}\int_0^1 \rho C_P T v y dy d\theta}{\int_0^{\pi}\int_0^1 \rho C_P v y dy d\theta} \tag{12}$$

where, y means r/r_o . For the calculation of the limiting ΔT_{HS}, Equations (6) and (10) are inserted into Equation (12). For $90^o < \theta < 180^o$, r/r_o should be negative in velocity equation. Therefore,

$$T^{bulk} = \frac{\int_0^{\pi/2}\int_0^1 \rho C_P T_{max\ slope} v_{15-195}\, y dy d\theta + \int_{\pi/2}^{\pi}\int_{-1}^0 \rho C_P T_{max\ slope} v_{15-195} |y| dy d\theta}{\int_0^{\pi/2}\int_0^1 \rho C_P v_{15-195}\, y dy d\theta + \int_{\pi/2}^{\pi}\int_{-1}^0 \rho C_P v_{15-195} |y| dy d\theta} \tag{13}$$

For the best estimate ΔT_{HS}, Equations (6), (7) and (8) are used for the velocity distribution and Equation (9) is used for the temperature distribution. As shown in Figure 3, the different velocity profiles are applied depending on the azimuthal angles so the integral should be divided into several regions as below :

$$\begin{aligned} T^{bulk} = & \Big[\int_0^{\pi/6}\int_0^1 \rho C_P T_{avg\ slope} v_{15-195}\, y dy d\theta + \int_{\pi/6}^{\pi/3}\int_0^1 \rho C_P T_{avg\ slope} v_{45-225}\, y dy d\theta \\ & + \int_{\pi/3}^{\pi/2}\int_0^1 \rho C_P T_{avg\ slope} v_{75-255}\, y dy d\theta + \int_{\pi/2}^{2\pi/3}\int_{-1}^0 \rho C_P T_{avg\ slope} v_{75-255} |y| dy d\theta \\ & + \int_{2\pi/3}^{5\pi/6}\int_{-1}^0 \rho C_P T_{avg\ slope} v_{45-225} |y| dy d\theta + \int_{5\pi/6}^{\pi}\int_{-1}^0 \rho C_P T_{avg\ slope} v_{15-195} |y| dy d\theta \Big] \\ & \Big/ \Big[\int_0^{\pi/6}\int_0^1 \rho C_P v_{15-195}\, y dy d\theta + \int_{\pi/6}^{\pi/3}\int_0^1 \rho C_P v_{45-225}\, y dy d\theta + \int_{\pi/3}^{\pi/2}\int_0^1 \rho C_P v_{75-255}\, y dy d\theta \\ & + \int_{\pi/2}^{2\pi/3}\int_{-1}^0 \rho C_P v_{75-255} |y| dy d\theta + \int_{2\pi/3}^{5\pi/6}\int_{-1}^0 \rho C_P v_{45-225} |y| dy d\theta + \int_{5\pi/6}^{\pi}\int_{-1}^0 \rho C_P v_{15-195} |y| dy d\theta \Big] \end{aligned} \tag{14}$$

3. Results and Discussion

The present work has quantified the correction offset and associated uncertainty. The coolant velocity profiles in the hot leg pipe were measured in CENP's System 80 reactor flow model test, and the local coolant temperature data have been accumulated from the start-up tests of PVNGS 1&2 through the start-up tests and commercial operations of YGN 3&4, and UCN 3&4. The results are summarized in Table 1.

The best estimate correction offsets for all cases range from -0.01°F to 0.05°F for the average of accumulated data for each hot leg, and from -0.02°F to 0.07°F for the maximum one. Those for the limiting cases spread from 0.02°F to 0.22°F for the average of accumulated data for each hot leg, and from 0.03°F to 0.28°F for the maximum one. The limiting cases have larger offsets than the best estimate cases due to the conservatism imposed on the velocity and temperature profiles. From the present work, it is known that the best estimate correction offsets for all cases are nearly "zero", which supports the appropriateness of existing design assumption for the RTD arrangement in the KSNP hot leg pipe to measure the coolant bulk temperature.

It is also found that the correction offsets for all cases are far less than the existing uncertainty of 0.5°F. Considering the fact that the velocity and temperature profiles for the limiting cases are extremely conservative, it is thought that even the 0.3°F has a sufficient margin for the uncertainty. Table 2 is an example showing the contributions of individual parameters to the overall uncertainty of heat balance flow rate measurement method, where the case of 0.5°F uncertainty is compared with that of 0.3°F uncertainty. The 0.2°F reduction of correction offset uncertainty contributes to effectively reducing the uncertainty of the hot leg coolant temperature measurement, eventually improving the overall flow rate measurement uncertainty by about 0.4%.

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References

1. Test Report TR-ESE-401, "System 80 Open Core Flow Model Outlet Traverse Test", L.M. Russel, Dec. 23, 1980.
2. Startup RCS flow measurement test data of YGN 3&4 and UCN 3&4, Courtesy of KEPCO
3. Snapshot data of Cycles 2 through 5 for YGN 3, Courtesy of KEPCO
4. Snapshot data of Cycles 1 through 4 for YGN 4, Courtesy of KEPCO
5. Snapshot data of Cycles 1 and 2 for UCN 3, Courtesy of KEPCO
6. Snapshot data of Cycle 1 for UCN 4, Courtesy of KEPCO
7. Test Report 72PA-1RX59, "RCS Flow Measurement 100%", - PVNGS Integrated Test Results Package for Palo Verde Unit 1.
8. Test Report 72PA-2RX59, "RCS Flow Measurement 100%", - PVNGS Integrated Test Results Package for Palo Verde Unit 2.
9. "Describing Uncertainties in Single-Sample Experiments", S.J. Kline and F.A. Mcclintock, J. of Mechanical Engineering, Jan., 1953.
10. "Heat Transfer", 5th. ed., J.P. Holman, McGRAW-HILL International Book Company, 1981.

Table 1. Summary of the Estimated Hot Leg Temperature Correction

Unit	Operation	Hot Leg	Best Estimate Case, °F		Limiting Case, °F		No. of Data*
			max	avg	max	avg	
YGN 3	Start-Up	1	0.02	-	0.11	-	-
		2	0.01	-	0.08	-	
	Cycle 2	1	0.02	0.01	0.10	0.06	92
		2	0.01	0.01	0.12	0.09	
	Cycle 3	1	0.02	0.01	0.12	0.06	304
		2	0.02	0.01	0.13	0.07	
	Cycle 4	1	0.02	0.01	0.14	0.07	327
		2	0.03	0.02	0.21	0.15	
	Cycle 5	1	0.03	0.02	0.16	0.10	249
		2	0.02	0.01	0.16	0.09	
YGN 4	Start-Up	1	0.03	-	0.12	-	-
		2	0.02	-	0.09	-	
	Cycle 1	1	0.03	0.01	0.25	0.22	211
		2	0.03	0.02	0.17	0.10	
	Cycle 2	1	0.04	0.02	0.18	0.09	220
		2	0.02	0.01	0.14	0.07	
	Cycle 3	1	0.04	0.02	0.17	0.11	386
		2	0.03	0.02	0.24	0.18	
	Cycle 4	1	0.07	0.05	0.28	0.18	337
		2	0.03	0.01	0.24	0.13	
UCN 3	Start-Up	1	0.01	-	0.09	-	-
		2	0.00	-	0.03	-	
	Cycle 1	1	0.01	0.00	0.09	0.04	305
		2	0.01	0.00	0.08	0.02	
	Cycle 2	1	0.01	0.00	0.11	0.06	343
		2	0.00	-0.01	0.11	0.07	
UCN 4	Start-Up	1	0.00	-	0.04	-	-
		2	0.00	-	0.04	-	
	Cycle 1	1	0.01	0.00	0.11	0.04	304
		2	0.02	0.01	0.11	0.05	
PVNGS 1	Start-Up	1	0.02	-	0.18	-	-
		2	-0.02	-	0.26	-	
PVNGS 2	Start-Up	1	0.01	-	0.07	-	-
		2	0.00	-	0.10	-	

note * No. of data represents the number of snapshots which were taken approximately daily basis during the commercial operations.

Table 2. Contributions of Parameters on the Overall Uncertainty (YGN 3&4)

Parameter	Contribution, $\%Q_D$
Specific Volume	0.09
Cold Leg Enthalpy	1.09
Hot Leg Enthalpy	2.33 (1.75)*
Core Power	1.81
Total	3.1 (2.7)*

note * The values in parenthesis are the reduced uncertainty if 0.3°F is applied instead of 0.5°F as the uncertainty of hot leg temperature correction.

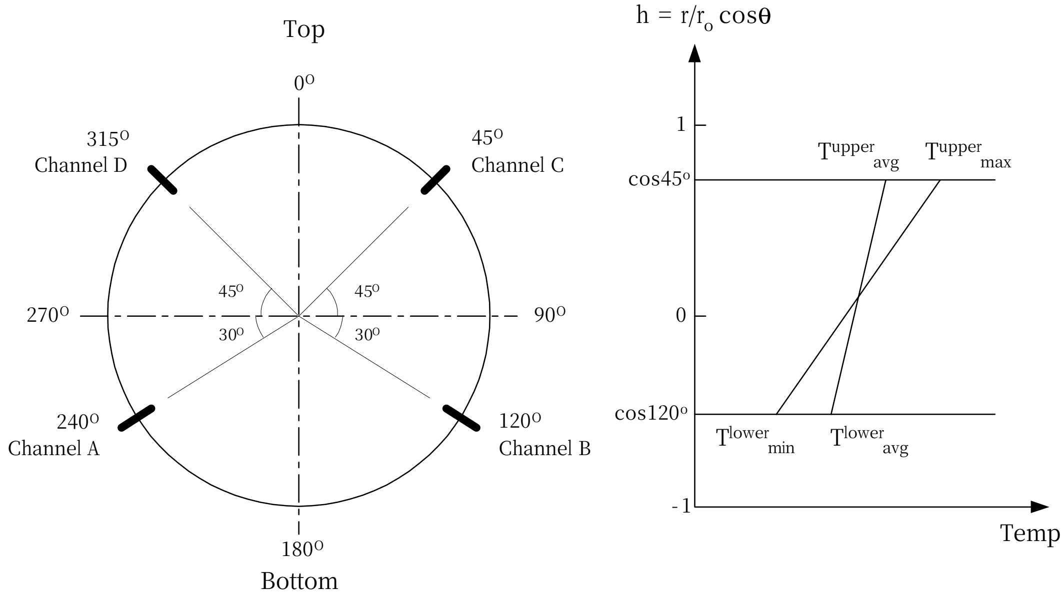

Figure 1. RTD Channel Locations in the Hot Leg for KSNP and Assumed Temperature Distribution

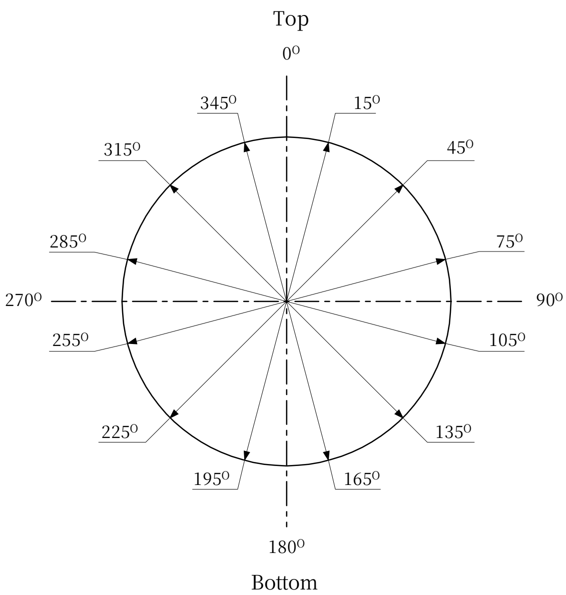

Figure 2. Schematic of Traverse Port Locations for Velocity Measurement

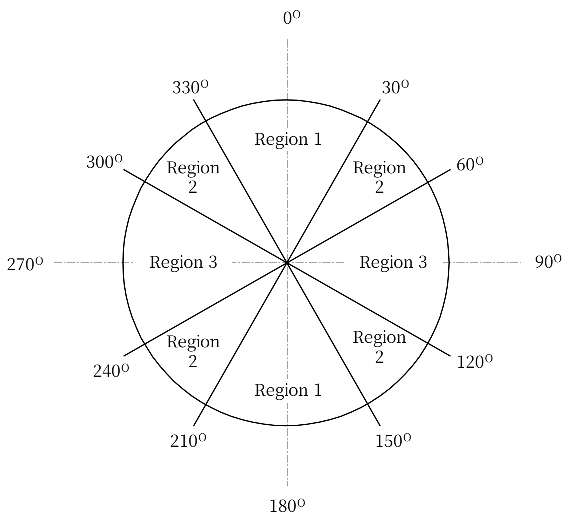

Figure 3. Divided Regions by the Patterns of the Velocity Profile

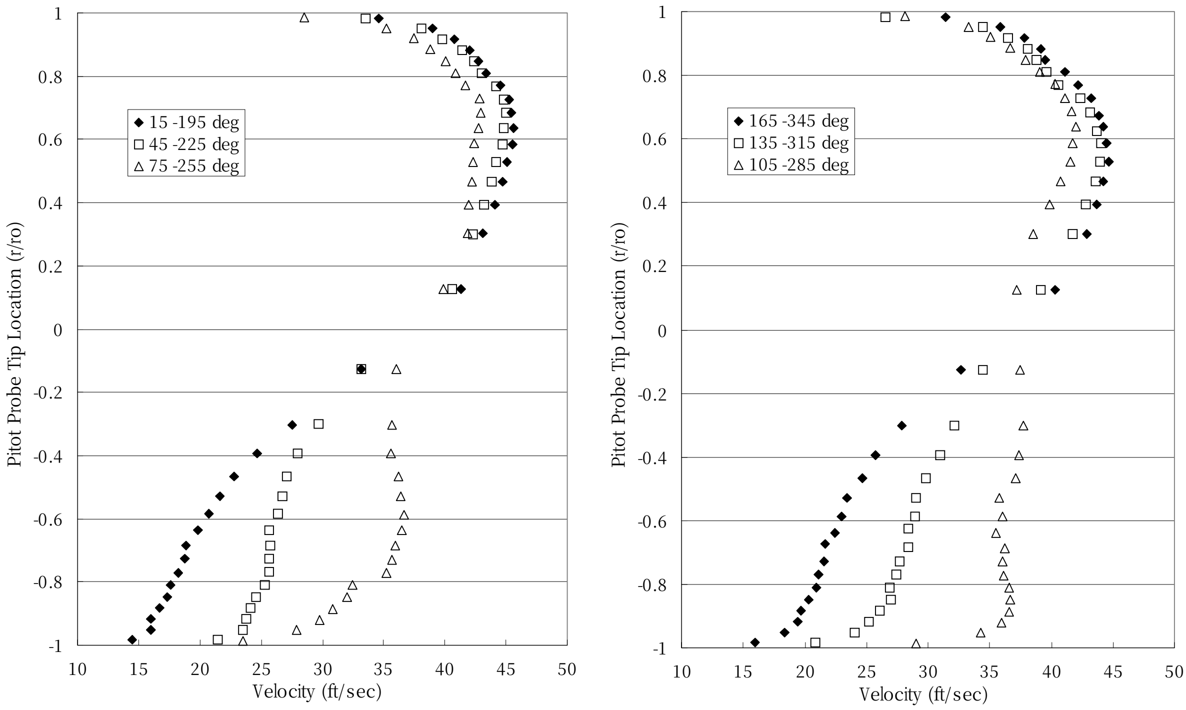

Figure 4. Measured Hot Leg Velocity Profiles of System 80 Reactor Flow Model Test[1]

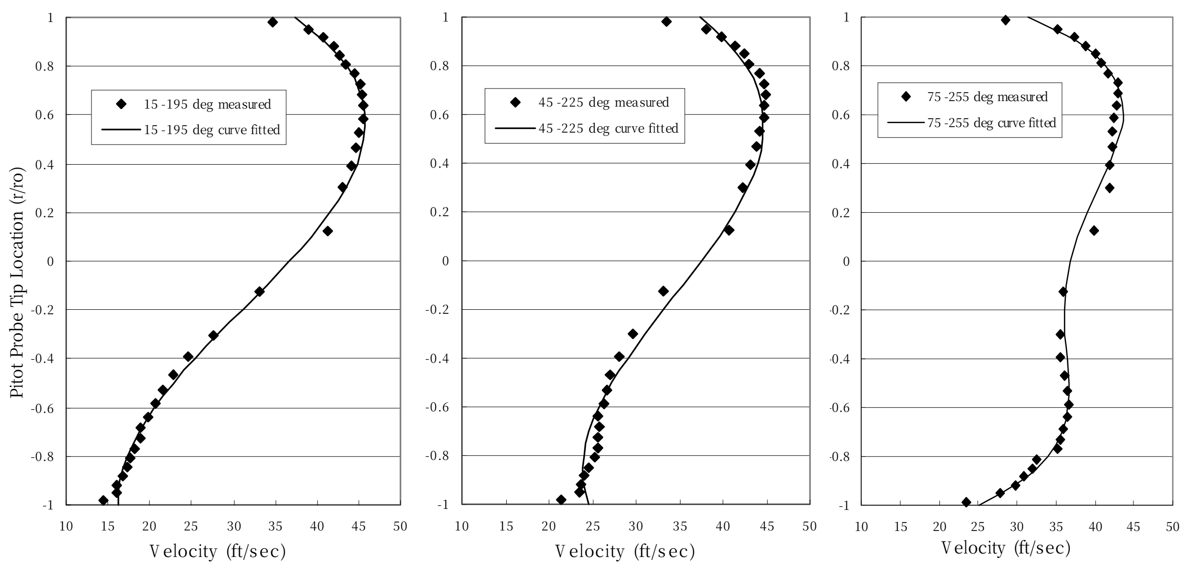

Figure 5. Comparison of Measured and Curve Fitted Velocity Profiles of System 80 Reactor Flow Model Test

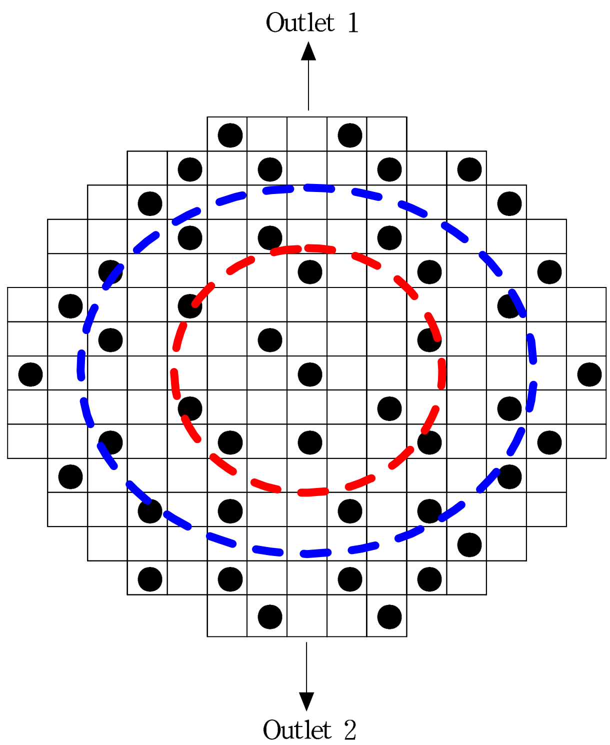

Figure 6. Schematic of CET Locations of KSNP

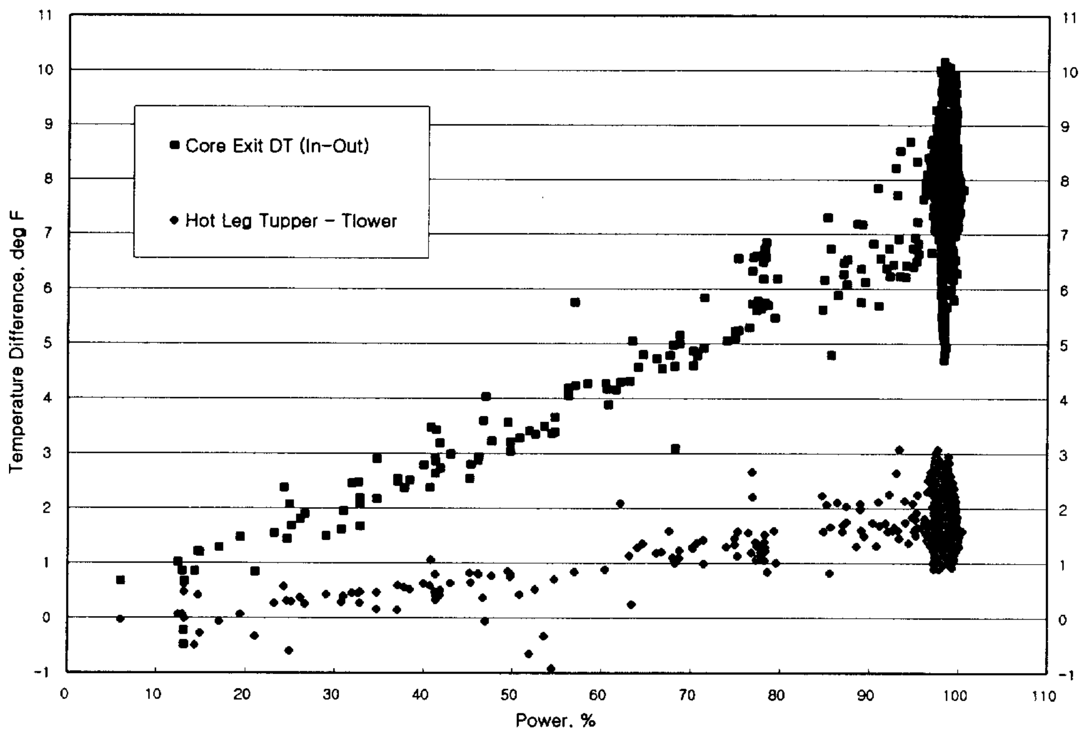

Figure 7. Temperature Differences at Core Exit and Hot Leg with Power (YGN 4) [4]