KMRR Thermal Power Measurement Error Estimation

B.W. Rhee, B.S. Sim, I.C. Lim and S.K. Oh

Korea Advanced Energy Research Institute

Korea Advanced Energy Research Institute
P.O.Box 7, Daeduck-danji
Daejeon, Korea

KMRR Thermal Power Measurement Error Estimation

B.W. Rhee, B.S. Sim, I.C. Lim, S.K. Oh

Korea Advanced Energy Research Institute
P.O.Box 7, Daeduk-danji
Daejeon, Korea

Abstract

A thermal power measurement error of the Korea Multi-purpose Research Reactor has been estimated by a statistical Monte Carlo method, and compared with those obtained by the other methods including deterministic and statistical approaches. The results show that the specified thermal power measurement error of 5% cannot be achieved if the commercial RTD's are used to measure the coolant tempteratures of the secondary cooling system and the error can be reduced below the requirement if the commercial RTD's are replaced by the precision RTD's. Also, the possible range of the thermal power control operation has been identified to be from 100% to 20% of full power.

1. Introduction

Korea Multi-purpose Research Reactor (KMRR) is a research reactor being built by Korea Advanced Energy Research Institute [1]. It is an upward flowing, light water cooled reactor with an open chimney in pool arrangement. Fig. 1 shows a schematic flow diagram of the KMRR heat transport system. The light water primary coolant enters the inlet plenum, flows through the core and directs to the chimney. About 10% of the total primary flow returning from heat exchangers flows into the bottom of the pool, and slowly rises in the pool outside the reactor assembly. Then, it is drawn into the chimney and flows downward to the chimney bottom where both bypass flow and the flow from the core are sucked into the outlet nozzle. This primary coolant flows through pumps and heat exchangers, and comprises the closed loop.

In KMRR, the core thermal power is measured to provide the reference power for the continuous calibration of the fission chamber [2]. The error associated with the fission chamber is typically less than 1% over the power range of the upper two decades. But, the thermal power measurement error is usually dependent on the errors of the measuring devices of process parameters such as coolant flow rate and temperature and it is below 5% of the measured power in a typical commercial power reactor. On the design of thermal power measurement system of KMRR, the maximum allowable error associated with measuring the reactor thermal power is required to be below 5% for the whole range of the thermal power control mode.

The new method of estimating thermal power measurement error based on the Monte Carlo simulation has been introduced and it is applied to KMRR along with the deterministic and statistical linear perturbation methods. A series of analyses shows that the thermal power error requirement can be met if the commercial process RTD's are replaced by the precision RTD's. Also, the possible range of the thermal power control operation has been identified.

2. Thermal Power Measurement System of KMRR

The thermal power is measured from the secondary cooling system as shown in Fig. 1. This system reflects the design simplicity and provides the accessibility and installability of the associated instruments. The thermal power measured from the secondary cooling system is the sum of the core heat, the heat removed from the pool by the bypass flow, and the primary coolant pump heat. The bypass flow detouring the reactor via pool picks up the heat generated from the experimental sites and/or the spent fuels temporarily stored in the pool. The net core thermal power, Q, for a steady state operation can be expressed by Eq.(1).

$$Q = C_p W_s \ (T_o^s - T_i^s) - C_p W_{by} \ (T_{cm} - T_{by}) - Q_p \qquad (1)$$

The values of the process parameters for the full power steady state operating condition are obtained from the plant simulation study and are summarized in Table 1. The inlet temperature of the secondary flow to the heat exchangers is taken to be 32°C for the simplicity of the analysis. The temperature rise of the secondary coolant across the heat exchangers is only 8°C and its associated enthalpy rise is much smaller than that of a power reactor. The uncertainty range of the commercial RDT takes quite a fraction of the total temperature rise and it can be expected that the temperature measurement uncertainty will results in the large portion of the thermal power measurement error.

3. Thermal Power Measurement Error Analysis

As mentioned above, the error involved in the core thermal power estimation results from the errors of the associating measuring instruments and can be approximated as following equation using the principle of superposition of errors ;

$$\delta Q = \frac{\partial Q}{\partial W}\delta W_s + \frac{\partial Q}{\partial T_o^s}\delta T_o^s + \frac{\partial Q}{\partial T_i^s}\delta T_i^s + \frac{\partial Q}{\partial W_{by}}\delta W_{by} + \frac{\partial Q}{\partial T_{cm}}\delta T_{cm} + \frac{\partial Q}{\partial T_{by}}\delta T_{by} \qquad (2)$$

This equation can be further approximated to the following one considering that the heat load to bypass flow is much small as compared to the core power.

$$\frac{\delta Q}{Q} = \frac{\delta W_s}{W_s} + \frac{\delta T_o^s - \delta T_i^s}{T_o^s - T_i^s} - \frac{W_{by}}{W_s}\frac{\delta T_{cm} - \delta T_{by}}{T_o^s - T_i^s} \qquad (3)$$

Based on this equation, various methods have been applied to evaluate the thermal power measurement error as described in the following paragraphs. In Table 2, is shown the accuracy of the instruments used for the analysis.

Deterministic Perturbation Method

A rudimentary and conservative way is to assume that all the errors of individual instruments are summed in the most adverse way and to find the possible upper bound of the error. For this purpose, Eq.(3) can be modified as the following equation.

$$\frac{\delta Q}{Q} = \left|\frac{\delta W_s}{W_s}\right| + \left|\frac{\delta T_o^s}{T_o^s - T_i^s}\right| + \left|\frac{\delta T_i^s}{T_o^s - T_i^s}\right| + \left|\frac{W_b}{W_s}\right|\left|\frac{\delta T_{cm}}{T_o^s - T_i^s}\right| + \left|\frac{W_b}{W_s}\right|\left|\frac{\delta T_{by}}{T_o^s - T_i^s}\right| \qquad (4)$$

Using this method, the thermal power measurement error was 15.5% of the measured power at full power. Also, the analysis shows that the summation of the second and the third term of RHS in Eq.(4) is 8.4 times of the first, which means that the power measurement error is mainly due to the temperature measurement error.

Although this method is very straightforward in finding the possible maximum bound of the thermal power error and identify the major source of the error, it is too conservative to be used in practice.

Statistical Error Combination Method

To provide more practical result, the root mean square error method was applied to Eq.(2) to derive the following equation and the thermal power error value below which the actual error occurs with 95% probability was computed.

$$\frac{\delta Q}{Q} = \left[\left(\frac{\delta W_s}{W_s}\right)^2 + \left(\frac{\delta T_o^s}{T_o^s - T_i^s}\right)^2 + \left(\frac{\delta T_i^s}{T_o^s - T_i^s}\right)^2 \right]^{1/2} \tag{5}$$

where the errors from the bypass flow heat load are neglected due to small contribution.

The basic assumptions underlying this method are that the errors associated with each instrument are statistically independent and normally distributed, and the instrument accuracy specified by the manufacturer is the error bound value corresponding to the 95% probability of having the actual error within these values. In principle, the instrument accuracy cannot be used to characterize the error characteristics in this kind of statistical error analysis because it is usually not a statistically defined quantity regarding to the instrument error. In practice, however, this is usually the only information available from the manufacturer regarding to the instrument behavior. Thus, the first two assumptions are thought to be reasonable, but the last one is questionable. The thermal power error predicted by this method was significantly reduced from that of the previous method and was 6.8% of the measured power at full power.

Monte Carlo Method

Recently, Monte Carlo method was applied to improve the confidence on this error estimation. The mean and standard deviation of the thermal power error have been estimated based on the 1000 data points produced using the individual pseudo values of the parameters generated by the random numbers equally distributed over the instrument accuracy span. The equation for thermal power error is described below ;

$$\frac{\delta Q(j)}{Q(j)} = \frac{\alpha \delta W_s(j)}{W_s(j)} + \frac{\beta \delta T_o^s(j) - \alpha \delta T_i^s(j)}{T_o^s(j) - T_i^s(j)} - \frac{W_{by}(j)}{W_s(j)} \frac{\mu \delta T_{cm}(j) - \nu \delta T_{by}(j)}{T_o^s(j) - T_i^s(j)} \tag{6}$$

where the mean value is zero and the standard deviation is computed from the following equation ;

$$\sigma_{\delta Q/Q} = \left[\sum_{j=1}^{N} \left(\frac{\delta Q(j)}{Q(j)} \right)^2 \quad (N - 1) \right]^{1/2} \tag{7}$$

Since the random variable composed of linear combination of equally distributed random variables may have a histogram-like probability density distribution (pdf), the standard deviation derived from the 1000 random data should be interpreted according to the corresponding pdf distribution. In order to have the actual thermal power error inside an interval around the mean value with 95% probability, the half width of the the interval should be 1.645 times of the standard deviation for the equally distributed error and two times of the standard deviation for the normally distributed error. It is not clear what form of the pdf this thermal power error takes in practice. In this simulation method, however, the thermal power error is expressed as a function of at least 25 random variables in the case of using process RTD. This numbers are, at least to authors, thought to be large enough so that the central limit theorem may be applied to these cases. Thus, the pdf of the simulated thermal power error is assumed to be normal distribution and the error value below which the actual error occurs with probability of 95% on every measurement is determined to be two times of the standard deviation computed as above. The numerical result is 8.88% at full power. Note that this value is larger than that predicted by the statistical error combination method and this observation can be explained as follows. In the statistical method, the instrument accuracy is taken as the error value corresponding to 2σ value of the normally distributed random error whereas, in this method, it is taken as the boundary value of the uniformly distributed random error. As shown in Fig.2, the standard deviation of the equally distributed random error is greater than that of the normally distributed one. Furthermore, the equation for the thermal power error used in this method contains various multiplication of two equally distributed random variables and this operation is thought to have accentuated the discrepancy between the standard deviations predicted by these two methods. Therefore, the reason for the conservative prediction of this Monte Carlo method lies on the fact that the instrument errors are assumed to distribute uniformly over the accuracy span. This implies that a caution should be exercised when the random number is used to simulate a random instrument error because the pdf used to generate the random number can make a difference in the simulated result.

Statistical Monte Carlo Method

Another method, a blend of statistical and Monte Carlo method, was also tested to estimate the thermal power error. The basic equation of thermal power error used is as below;

$$\frac{\delta Q(j)}{Q} = \left[\left(\frac{\alpha\delta W_s(j)}{W_s(j)}\right)^2 + \left(\frac{\beta\delta T_o^s(j)}{T_o^s(j) - T_i^s(j)}\right)^2 + \left(\frac{\alpha\delta T_i^s\ (j)}{T_o^s(j) - T_i^s(j)}\right)^2 + \right.$$

$$\left.\left(\frac{W_{by}(j)}{W_s(j)}\right)^2\left(\frac{\mu\delta T_{cm}(j)}{T_o^s(j) - T_i^s(j)}\right)^2 + \left(\frac{W_{by}(j)}{W_s(j)}\right)^2\left(\frac{\nu\delta T_{by}(j)}{T_o^s(j) - T_i^s(j)}\right)^2\right]^{1/2} \quad (8)$$

This is essentially a kind of root mean square error version of Monte Carlo simulation ; i.e., all the square of each random number are summed and this summation is taken as a random number representing the thermal power error. After 1000 iterations, the mean and standard deviation of the most probable error can be obtained instead of just one value when computed by eq. (7). Thus, the mean of eq. (8) is equivalent to the standard deviation computed by eq. (7) while the standard deviation of eq. (8) provides the dispersion of error about its mean value. The range of thermal power error for the process RTD at full power becomes 8.32±2.56% which confirms that the thermal power errors calculated by the other methods fall within this range except the deterministic perturbation method. Thus, we have confidence in the various evaluation methods by the calculation of a range of the thermal power error.

4. Application of Thermal Power Error Analysis

Precision RTD

The thermal power errors evaluated by the various methods are given in Table 3. All these methods predicts that the thermal power measurement error is above the design requirement, of 5% and the major factor of this error is the temperature measurement error. The reason is that the KMRR is a low enthalpy rising system and the uncertainty range of the commercial process RTD takes quite a fraction of the total temperature rise.

As one option to resolve this problem, the replacement of the commercial process RTD by the precision RTD was proposed. The accuracy of the precision RTD is summarized in Table 2. The thermal power error was calculated using the above four methods and given in Table 3 with the results for the process RTD cases. As expected, the error was significantly reduced owing to the smaller value of "accuracy" of this precision RTD and the design requirement was satisfied.

Power Range of Thermal Power Control Mode

As the coolant temperature rise at the secondary cooling system falls off with the reduction of reactor power, one can easily expect that the thermal power error would increase with the reactor power decrease. In order to determine the range of thermal power control mode, it was necessary to investigate at which power the thermal power error begins to exceed the error limit given by design requirement. Thus, the thermal power error with precision RTD was calculated for the whole power range and its trend with power was investigated.

For Monte Carlo method, the error stays less than 5% for the power from 100% to 20% of full power but begins to increase sharply after the power drops below 20% of full power as shown in Fig.3. For the statistical Monte Carlo method, the trend of the mean error value is basically the same as that of the standard deviation of the previous method except the minor discrepancy in the error value. One new information generated in this method is the fluctuation of the error about its mean value. Based on this study, The range of the thermal power control mode was determined to be 20% to 100% of full power.

5. Conclusions

Four methods have been applied to evaluate the measurement error of the reactor thermal power for KMRR to meet design requirement and some design implications were drawn out. Throughout this study, the following were drawn as conclusions:

1) The deterministic perturbation method is useful in estimating the maximum error bound and identify the major source of measurement error. However it predicts too conservative value to be used for any practical design resolution.
2) The statistical error combination method provides the realistic estimation of the measurement error with reasonable amount of computing effort. Thus, it is most recommendable for this type of analysis.
3) The Monte Carlo method provides more realistic estimation of the measurement error provided the physically reasonable probability density function is used to describe the nature of the random measurement error. In this study, this method predicts more conservatively than the statistical error combination method because the uniformly distributed pdf over the accuracy span was used.
4) The statistical Monte Carlo method is useful in identifying the degree of fluctuation of the thermal power error about its mean value.
5) The replacement of the process RTD's by the precision RTD's was judged to be a good design resolution.

6) The power range of reactor thermal power control mode was found to be extendable to as wide as 20% to 100% of full power.

Acknowledgment

The authors express appreciation to C. Pappas of Candu Operation of Montreal, Atomic Energy of Canada Limited for his generous help in performing the Monte Carlo simulation.

Nomenclature

C_p - specific heat
j - iteration number
N - total number of iteration
Q - core power
Q_p - pump heat
T - temperature
W - coolant flow rate

<u>Superscript and Subscript</u>

by - bypass flow
cm - chimney
i - inlet
o - outlet
s - secondary coolant

<u>Greek</u>

α, β, γ, μ, ν - random number between [-1, +1]
δ - error
σ - standard deviation

References

[1] Kim D.H., The Korea Multi-purpose Research Reactor, J. of Korea Nucl. Soc., Vol.20, No.3 (1988)

[2] Grouard P. and Khang B.O., Design Requirements of the Reactor Regulating System, DR-KM-63700-001 (1986)

TABLE 1. Steady State Operating Conditions

Reactor Power (Q)	28.4 MWth
Secondary Flow Rate (W_s)	840. kg/s
HX Exit Temp. of Secondary Flow (T_o^s)	40.°C
HX Inlet Temp. of Secondary Flow (T_i^s)	32.°C
Bypass Flow Rate (W_{by})	72.5 kg/s
Chimney Inlet Temp. of Bypass Flow (T_{cm})	35.°C
Pool Inlet Temp. of Bypass Flow (T_{by})	35.°C
Pump Heat Generation Rate (Q_p)	0.4 MWth

TABLE 2. Accuracy of the Instrument Associated with Reactor Thermal Power Measurement[1)]

Flowmeter	
Flow element error	: 1 %
Flow transmitter error	: 0.25 %
Flow transmitter drift error	: 0.25 %
A/D conversion error	: 0.05 %
Process RTD	
Temperature element error	: 1 %
Temperature element drift error	: 0.2 %
Temperature transmitter error	: 0.2 %
A/D conversion error	: 0.05 %
Precision RTD	
Temperature element error	: 0.005°C
Temperature element stability error	: 0.01 °C
Temperature element selfheating error	: 0.002°C
Temperature element calibration error	: 0.005°C
Temperature transmitter error	: 0.005°C
A/D conversion error	: 0.005°C

1) The overall error of an instrument is also composed of the various sources. Here the individual errors are combined using root-mean-square error sum for the statistical error combination method and the following equations for the Monte Carlo method and statistical Monte Carlo method.

$$\delta Y = \sum_{i=1}^{N} \mu_i \cdot \delta X_i \qquad \text{for Monte Carlo method}$$

$$\delta Y = \left[\sum_{i=1}^{N} \left(\mu_i \delta X_i \right)^2 \right]^{1/2} \qquad \text{for statistical Monte Carlo method}$$

where μ_i is the random number whose range is [-1, 1].

TABLE 3. Comparison of the Thermal Power Measurement Error Predicted by Various Methods for the Cases with Process RTD and Precision RTD at Full Power Steady State Condition

Method	2σ (process RTD)	2σ (precision RTD)
Deterministic[1)]	15.5 %	2.40%
Deterministic with instr. error sum	10.73 %	1.46 %
Statistical error comb.	6.8 %	1.09 %
Monte Carlo	8.8 %	1.90 %
Statistrical Monte Carlo	(8.32±2.56)%	(1.8±0.72)%

1) The overall instrument error is calculated by multiplication of the constituent errors.

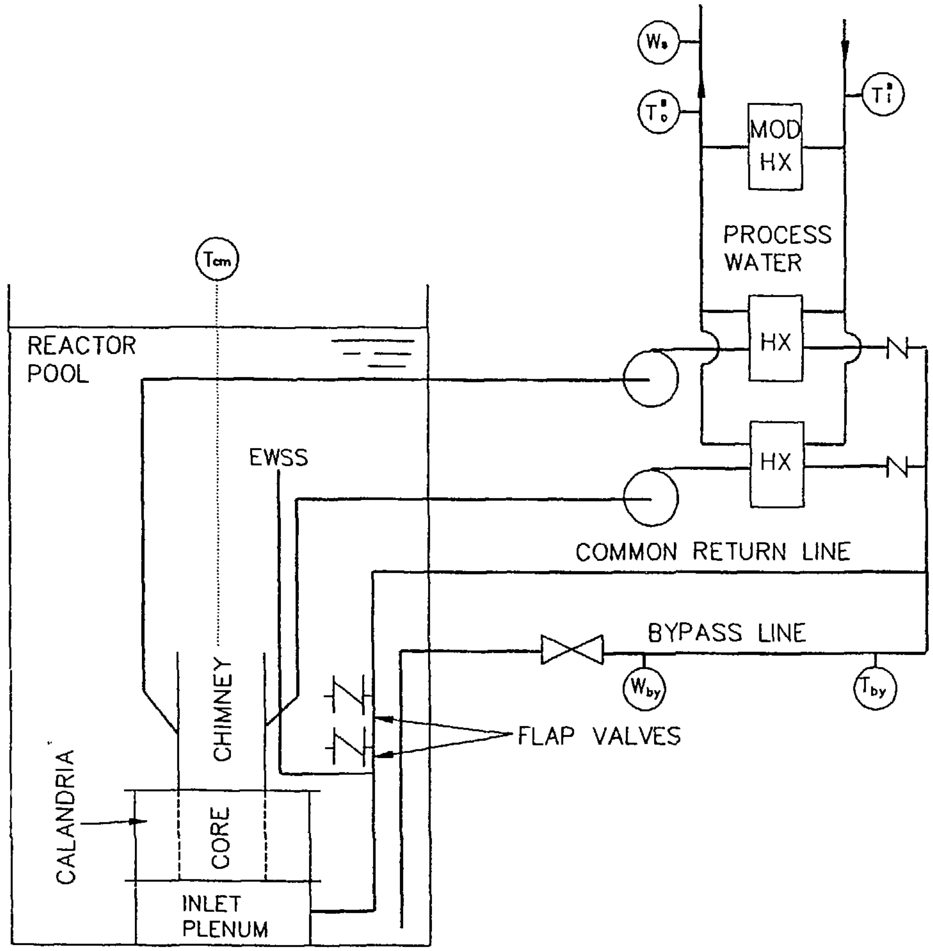

Fig. 1. KMRR Coolant Flow Schematics and Thermal Power Measurement System

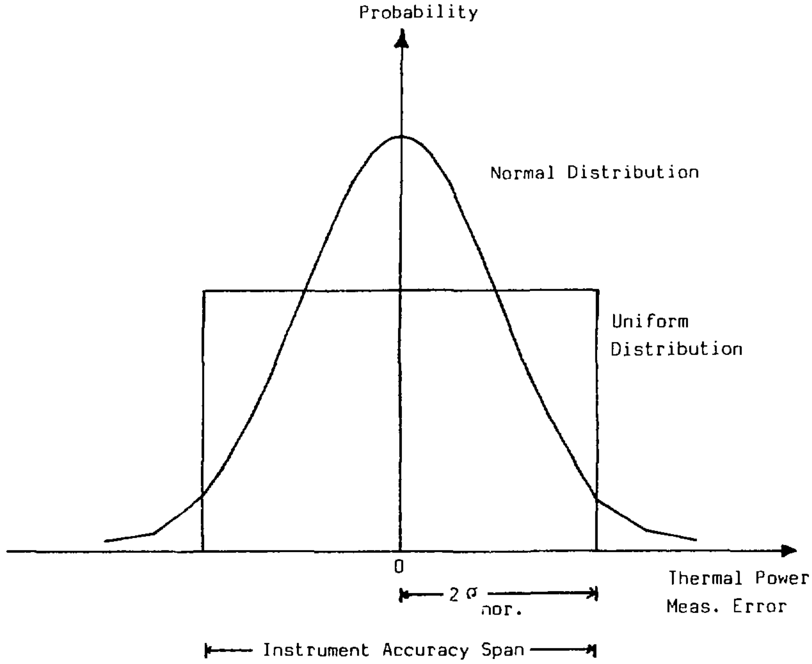

Fig.2. Two Probability Density Functions Used in the Error Simulation

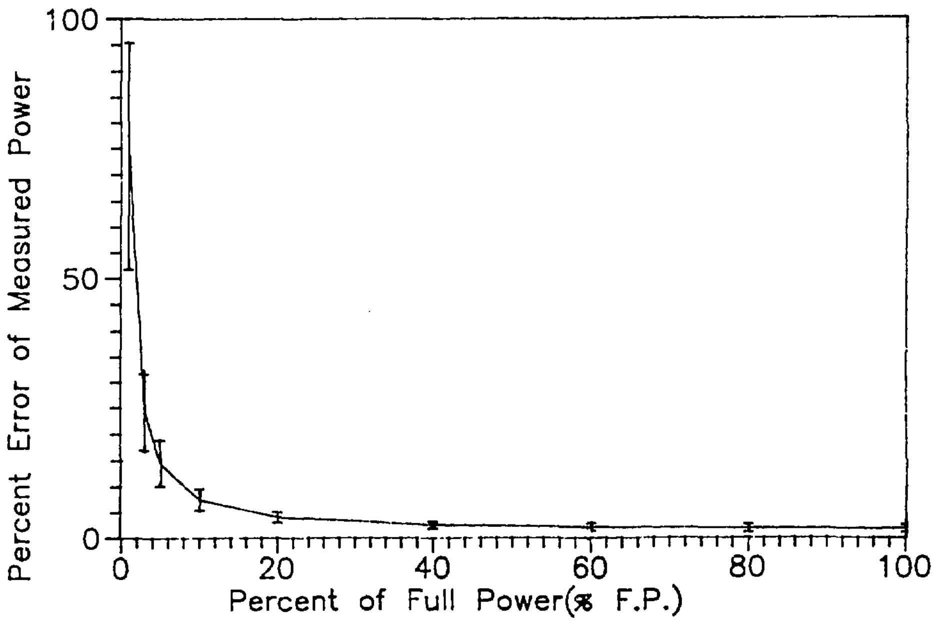

Fig.3. Thermal Power Measurement Error as Reactor Power with Precision RTD