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Development of a Power-Temperature Program for an Integral Reactor

Tae-Wan Kim, Jae-Kwang Seo, JuhyeonYoon, Chung-Chan Lee, Keung-Ku Kim
Korea Atomic Energy Research Institute, 150 Deokjin-dong, Yuseong-gu, Daejeon, taewan@kaeri.re.kr

1. Introduction

In order to assure the serviceability of a nuclear steam supply system (NSSS) and the generation of steam with required specifications, the NSSS parameter shall be controlled. For example, if the primary pressure varies in a wide range, it will be difficult to select the scram setpoint and the control rod will move a considerable distance due to the substantial Doppler reactivity effect. Therefore, it is important to choose the appropriate controlled parameters to minimize the control action.

In this study, the power-temperature program for an integral reactor was obtained to give the boundary conditions to the thermal hydraulic analysis under power maneuvering. Since the normal operation temperature has already been decided, the temperature at a hot-zero power was calculated for a constant primary pressure and a constant reactivity, respectively. The calculated temperature was verified with PZRTR[1] which is a program for the analysis of an integral reactor system with a gas pressurizer.

2. Criterion of the Constant Primary Pressure

In order to obtain the temperature at a hot-zero power for a constant primary pressure, several assumptions are introduced. At first, it is assumed that the variation of the water and gas in the end cavity of the pressurizer caused by the changes in the NSSS power are small and, therefore, it only slightly affects the primary pressure. The primary system can be considered as three regions which are the hot, cold, and average regions. The hot region includes the region from the core outlet to the steam generator inlet and the cold region consists of the region between the steam generator outlet and the core inlet. The average region means the inside of the core and the steam generator and the temperature in this region is assumed to be equal to the arithmetic average of the temperatures in the hot and cold regions.

The total mass in the primary system can be presented as the sum of the mass in each region.

$$M = M_h + M_c + M_m \tag{1}$$

In order to maintain a constant pressure during a power maneuvering, the mass of coolant should be constant. Therefore,

$$V_h \left.\frac{d\rho}{dT}\right|_{T=T_h} \frac{dT_h}{dn} + V_c \left.\frac{d\rho}{dT}\right|_{T=T_c} \frac{dT_c}{dn} + V_m \left.\frac{d\rho}{dT}\right|_{T=T_m} \frac{dT_m}{dn} = 0 \tag{2}$$

where, n is the reactor power.

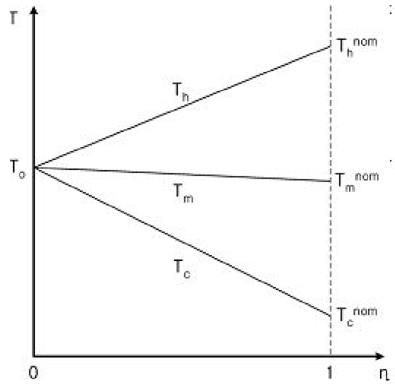

Fig. 1 Variation of the primary coolant temperature

The core outlet temperature is controlled as a constant and it is a maintained variable in a linear way depending on the power change. In this case, the dependency of the core inlet temperature is close to a linear function, as shown in Fig. 1, and the temperature variation with respect to the power can be written as,

$$\begin{aligned} \frac{dT_h}{dn} &= T_h^{nom} - T_o \\ \frac{dT_c}{dn} &= T_c^{nom} - T_o \\ \frac{dT_m}{dn} &= T_m^{nom} - T_o \end{aligned} \tag{3}$$

Substituting Eq. (3) into Eq. (2) and rearranging it, the following equation on the temperature at a hot-zero power is obtained.

$$T_o = \frac{V_h \left.\frac{d\rho}{dT}\right|_{T=T_h} T_h^{nom} + V_c \left.\frac{d\rho}{dT}\right|_{T=T_c} T_c^{nom} + V_m \left.\frac{d\rho}{dT}\right|_{T=T_m} T_m^{nom}}{V_h \left.\frac{d\rho}{dT}\right|_{T=T_h} + V_c \left.\frac{d\rho}{dT}\right|_{T=T_c} + V_m \left.\frac{d\rho}{dT}\right|_{T=T_m}} \tag{4}$$

3. Criterion of the Constant Reactivity

The change of a reactivity due to different temperature conditions of the core is related to the coolant temperature (T_w) and the fuel temperature (T_f).

$$\Delta\rho = \Delta\rho_w + \Delta\rho_f \tag{5}$$

The constancy of the reactivity can be written as

$$\frac{d\Delta\rho_w}{dT_w}\frac{dT_w}{dn} + \frac{d\Delta\rho_f}{dT_f}\frac{dT_f}{dn} = 0 \tag{6}$$

By definition, the derivatives of the reactivity with respect to the temperature are called as a temperature reactivity coefficient.

$$\frac{d\Delta\rho}{dT_w} = k_w \quad and \quad \frac{d\Delta\rho}{dT_f} = k_f \qquad (7)$$

Assuming that the heat transfer coefficient does not depend on the power, the derivatives of the temperature with respect to the power can be written as

$$\frac{dT_w}{dn} = T_w^{nom} - T_o$$
$$\frac{dT_f}{dn} = T_f^{nom} - T_o \qquad (8)$$

From Eqs (6), (7), and (8), the temperature at a hot-zero power for a constant reactivity can be obtained.

$$T_o = \frac{k_w T_w^{nom} + k_f T_f^{nom}}{k_w + k_f} \qquad (9)$$

4. Verification of Power-Temperature Program

Using the parameters listed in Tables 1 and 2, the temperatures at a hot-zero power were calculated. The calculated values are verified with PZRTR for the power range from 20 % to 100 %. The estimated temperature for a constant primary pressure is 299.97 ℃. In this case, the maximum pressure variation is 0.32 % of a normal operation pressure. This difference comes from the prediction of the temperature of the upper annulus cavity. The actual temperature of the upper annulus cavity is predicted to be 307.0 ℃ by PZRTR. However, it was assumed that the upper annulus cavity is included in the hot region. Thus, the temperature in the upper annulus cavity is considered to be equal to the core outlet temperature, 310.0 ℃. The volume of upper annulus cavity is 21.4 % of the hot region volume. Therefore, it is expected that the temperature at a hot-zero power will have lower value when the actual temperature in the upper annulus cavity is considered. In order to find an improved value, an additional sensitivity test was performed. As a results of the sensitivity test, the temperature at a hot-zero power is decided to be 299.5 ℃ and the pressure variation of 0.12 % is predicted as shown in Fig. 2.

The estimated temperatures for a constant reactivity are 295.41 ℃ and 297.59 ℃ for the beginning and end of cycle, respectively. As shown in Fig. 3, the maximum pressure differences calculated by PZRTR are 2.83 % and 1.35 %, respectively. This is a very large value compared with the method of a constant primary pressure. Therefore, from the thermal hydraulic point of view, the temperature from the method of a constant primary pressure is selected as the temperature at a hot-zero power and a small movement of the control rods is expected during a power maneuvering.

Table 1. Thermal hydraulic parameters

Region	Hot	Cold	Average
T^{nom} (℃)	310.0	272.4	291.2
Pressure (MPa)	14.7		
Volume (m^3)	8.6347	3.8117	1.8374
$d\rho / dT$	-2.3301	-1.6315	-1.8811

Table 2. Reactivity coefficients

Cycle	T_w^{nom} (℃)	T_f^{nom} (℃)	k_w (pcm)	k_f (pcm)
BOC	293.18	339.70	47.686	2.403
EOC			43.706	4.574

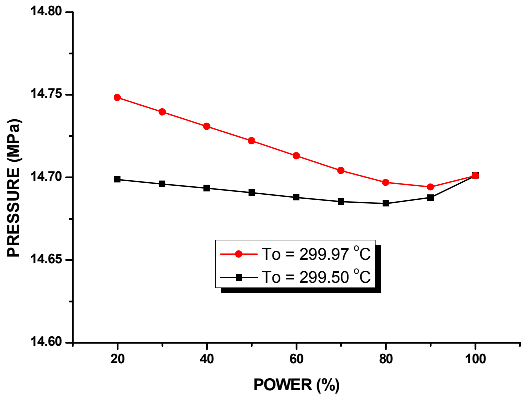

Fig. 2 Primary pressure variation (constant pressure)

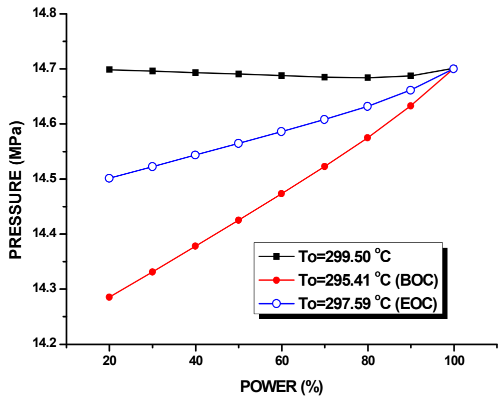

Fig. 3 Primary pressure variation (constant reactivity)

5. Conclusion

In order to determine a power-temperature program, the temperature at a hot-zero power was calculated. As a result of the calculation and sensitivity test, the temperature at a hot-zero power is decided to be 299.5 ℃. From the verification by PZRTR, the maximum pressure variation during a power maneuvering is predicted to be 0.12 % of the normal operation pressure. This result can be utilized as one of the boundary conditions in the thermal hydraulic analysis for an integral reactor system.

REFERENCES

[1] J. K. Seo and J. H. Yoon, Development of a Computer Code, PZRTR, for the Thermal Hydraulic Analysis of a Multi-cavity Cold Gas Pressurizer for an Integral Reactor, SMART-P, KAERI/TR-2632/2003, Korea Atomic Energy Research Institute, 2003.