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Theoretical investigation on the steady-state natural circulation characteristics of a new type of pressurized water reactor

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Abstract This article presents a theoretical investigation on the steady-state natural circulation characteristics of a new type of pressurized water reactor. Through numerically solving the one-dimensional steady-state single-phase conservative equations for the primary circuit and the steady-state two-phase drift-flux conservative equations for the secondary side of the steam generator, the natural circulation characteristics were studied. On the basis of the preliminary calculation analysis, it was found that natural circulation mass flow rate was proportional to the exponential function of the power and that the value of the exponent is related to the operating conditions of the secondary side of the steam generator. The higher the outlet pressure of the secondary side of the steam generator, the higher the primary natural circulation mass flow rate. The larger height difference between the core center and the steam generator center is favorable for the heat removal capacity of the natural circulation.

Key words Pressurized water reactor, Natural circulation characteristics, Height difference

CLC numbers TL33, $TL421^{+}.1$

1 Introduction

With respect to the inherent safety of nuclear reactors, application of passive systems/components including natural circulation phenomena as the main mechanism is intended to simplify the safety-related systems and to improve their reliability, to reduce the effect of human errors and equipment failures, and to provide more time to enable the operators to prevent or mitigate serious accidents. Natural circulation is the main mode of heat removal for removing decay heat from the primary system after the reactor trips. In some innovative designs, for relatively small- to medium-sized power reactors, natural circulation in the primary circuit is being used as the main means of heat removal under normal operating conditions including full-power operation[1]. In addition, these small and medium innovative reactors have many advanced design features such as the integrated layout of the core, the pressurizer, the main coolant pumps, and the steam generators in the reactor pressure vessel. Therefore, before the adoption of natural circulation as one of the main heat removal mechanism in a new type of pressurized water reactor, the natural circulation characteristics should be evaluated in detail at the conceptual design stage.

The steady-state natural circulation characteristics of the primary circuit are related to its geometry arrangement and circuit resistance characteristics as well as the operating conditions of the secondary circuit. To better understand the natural circulation characteristics of a new type of pressurized water reactor (PWR), a theoretical investigation was carried out in this article. Through numerically solving the one-dimensional steady-state single-phase conservative equations for the primary circuit and the steady-state two-phase drift-flux conservative equations

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tions for the secondary side of the steam generator, the natural circulation characteristics were studied.

2 Description of the reactor system

Fig. 1(a) schematically shows the layout of the new type of pressurized water reactor. The primary coolant system components, including a core, a pressurizer, 2 main coolant pumps (MCP), and 12 steam generators (SG), are contained in the reactor pressure vessel (RPV). This configuration results in an integral and compact system. The reactor core is located at the bottom of the RPV. The MCPs and the SGs are installed symmetrically in the annular space between the reactor barrel and the RPV. There is a long riser on top of the core outlet to enhance the natural circulation capacity. At the same time, a natural circulation by-pass valve, installed between the inlet and the outlet of each MCP, is designed to reduce the natural circulation form loss.

Under forced circulation conditions, the natural circulation by-pass valve is kept closed and the primary coolant is driven by the MCPs to circulate along the primary circuit. The primary coolant enters the core from the lower plenum. After been heated, the coolant flows out of the core and upward through the riser. Then, the coolant is pumped by the MCPs, located at the exit of the riser, and flows through the annular cavity on top of the primary entry of the SGs. Subsequently, it flows downward through the primary side of the SGs, cooled by the secondary coolant, and the downcomer until reaching the lower plenum. Finally, it flows back into the core and recirculates continually along the flow path. The heat transfer element of the SG has a straight annular channel composed of two concentric circular tubes with different diameters (see Fig. 1(b)). In the steam generator, the secondary coolant flows upward in the annular channel and is bilaterally heated by the primary coolant, which flows downward in the shell-side of the outer tube of the annular channel and the inner tube of the annular channel, respectively.

The core is cooled by natural circulation in the range from natural circulation power operation to residual heat removal. Under natural circulation conditions, the by-pass valves will be opened. The driving force caused by the density difference along the primary circuit is balanced by the friction and form losses, producing the adequate natural circulation flow rate with sufficient thermal margin to critical phenomena.

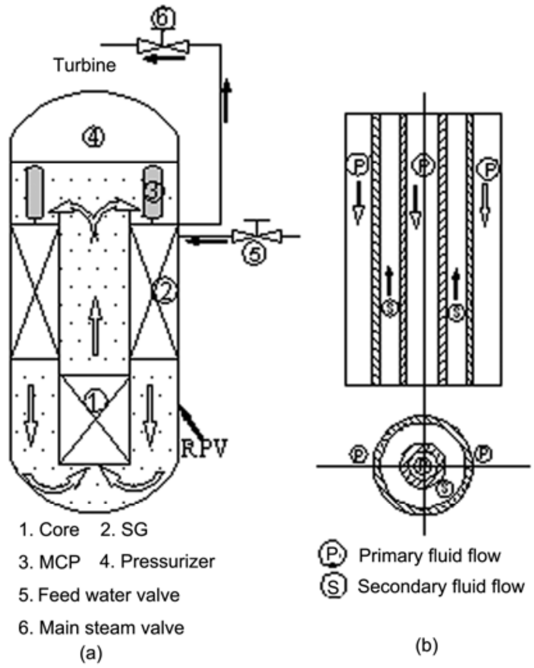

Fig. 1 Schematic diagram of the PWR.

3 Theoretical model

The model is based on the fundamental conservation principles, i.e., the mass, momentum, and energy conservation equations. Under steady-state operation conditions, single-phase conservative equations are applicable to the subcooled primary coolant flow. For the secondary coolant, it varies from subcooled fluid at the inlet of the SGs to superheated steam at the outlet of the SGs. Thus, both single-phase and two-phase conservative equations are applicable to the secondary coolant flow. The following assumptions are necessary to establish the theoretical model.

(1) The flow is one-dimensional.

(2) The axial heat conduction of the fuel, the clad, and the tube wall is negligible.

3.1 Single-phase Conservative equations

The single-phase mass continuity equation is

$$W = \text{const} \tag{1}$$

The single-phase momentum conservation equation is

$$\frac{\partial p}{\partial z} = -\frac{\partial}{\partial z}(\frac{W^2}{\rho A^2}) - \rho g - \frac{fW^2}{2\rho D_e A^2} \tag{2}$$

The single-phase energy conservation equation is

$$\left(\frac{W}{A}\right)\frac{\partial h}{\partial z} = \frac{qU_h}{A} \tag{3}$$

For the closed primary circuit, through integration of Eq. (2) with the primary circuit, the natural circulation momentum equation is also given by

$$B_n = \Delta P_t \tag{4}$$

where B_n and ΔP_t are expressed by

$$\begin{cases} B_n = -\oint \rho g \, \mathrm{d}z \\ \Delta P_t = W^2 \sum_{i=1}^{n} \left(\frac{c}{2\rho A^2}\right)_i + W^2 \oint f \frac{1}{2D_e \rho A^2} \mathrm{d}z \end{cases} \tag{5}$$

3.2 Two phase conservative equations

In this paper, the drift-flux flow model is adopted. The steady-state mass and energy continuity equations of two-phase flow are the same as those of the single-phase flow. The two-phase momentum conservation equation is

$$\frac{\partial p}{\partial z} = -\frac{\partial}{\partial z}(\frac{W^2}{\rho A^2}) - \rho g - \frac{f_{tp} W^2}{2\rho_f D_e A^2} - \frac{\partial}{\partial z} S_{DG} \tag{6}$$

3.3 Heat transfer of fuel and tube wall

Plate-type fuel elements are used in the new type of pressurized water reactor that is shown in Fig. 2(a). Ignoring the gap between the fuel and the clad, the heat transfer equation of the fuel and the clad are expressed by

$$k_u \frac{\partial^2 T_u(x)}{\partial x^2} + q_u = 0, \quad 0 < x < L_1 \tag{7}$$

$$k_c \frac{\partial^2 T_c(x)}{\partial x^2} = 0, \quad L_1 < x < L_2 \tag{8}$$

The boundary conditions are as follows:

$$\begin{cases} \partial T_u(x)/\partial x = 0, & x = 0 \\ T_u(x) = T_c(x), & x = L_1 \\ k_u \frac{\partial T_u(x)}{\partial x} = k_c \frac{\partial T_c(x)}{\partial x}, & x = L_1 \\ k_c \frac{\partial T_c(x)}{\partial x} = \alpha(T_f - T_c(x)), & x = L_2 \end{cases} \tag{9}$$

Fig. 2(b) shows the heat transfer process of the SG tube wall. Because the thickness of the tube wall is very less, the lumped parameter method is used to calculate the wall heat transfer. Ignoring the axial heat conduction, the tube wall heat transfer equation is

$$\alpha_1 A_1 (T_1 - T_w) = \alpha_2 A_2 (T_w - T_2) \tag{10}$$

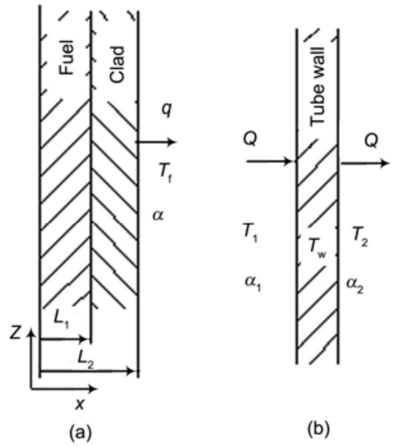

Fig. 2 Schematic diagram of the PWR.

3.4 Local pressure drop of the MCP

As mentioned above, under natural circulation operation conditions, the MCPs stop and the by-pass valves are opened to enhance the natural circulation. Because the local form loss coefficient of the by-pass valve is much less than that of the MCP, most of the primary coolant flows through the by-pass valve. The relationship between the local pressure drop of the MCP and the by-pass valve is expressed by

$$\Delta p_p = \Delta p_v \tag{11}$$

that is

$$\frac{1}{2} c_p \frac{W_p^2}{A_p^2 \rho} = \frac{1}{2} c_v \frac{W_v^2}{A_v^2 \rho} \tag{12}$$

whereas

$$W = W_p + W_v \tag{13}$$

Applying Eq. (12) and Eq. (13) in Eq.(11), the local pressure drop of the MCP is

$$\Delta p_p = \frac{1}{2} c_p \frac{W^2}{\left(1 + A_v \sqrt{c_p / c_v} / A_p\right)^2 A_p^2 \rho} \tag{14}$$

3.5 Constitutive correlations

The thermophysical properties of water and vapor are calculated using the correlations chosen from the international standard IAPWS-IF97[2]. The dominant heat transfer of the primary circuit is single-phase mode, and the modes of the secondary circuit are single-phase and boiling heat transfer in the SG. According to the corresponding flow regimes, appropriate heat transfer and frictional coefficient correlations are selected. Two-phase frictional multiplier is used to calculate the two-phase flow pressure drop, that is:

$$f_{\mathrm{tp}} = f_{\mathrm{lo}} \cdot \Phi_{\mathrm{tp}}^{2} \tag{15}$$

The heat transfer and frictional coefficient correlations are listed in Table 1 [3].

Table 1. Heat transfer and frictional coefficient correlations

Flow regime	Heat transfer coefficient	Frictional coefficient
Single phase		
Laminar flow	Collier	Darcy
Transition flow	Interpolation	0.048
Turbulent flow	Sieder-Tate	Blasius
Two phase		Chisholm
Subcooled/saturated boiling	Chen	
Transition boiling	Groenveld	

4 Solution procedure

In the range of normal power operation conditions, the average temperature of the primary coolant and the outlet pressure of the SG secondary side (steam pressure) are kept constant. Through iteratively solving the above-mentioned theoretical model, the coupled thermal hydraulic parameters under different natural circulation operation conditions are obtained. In fact, the iterative solving process is to determine the difference between the natural circulation driving force B_{n} and the total pressure loss $\triangle P_{\mathrm{t}}$ in the primary circuit. For a closed circuit, the difference equals zero (see Eq. (4)), that is, the natural circulation driving force is balanced by the total pressure loss. Fig. 3 is the flowchart describing the solution procedure, which is also summarized as follows.

(1) Determine the local friction coefficients of the primary circuit using the rated operation parameters to eliminate the accumulated error due to the uncertainty of them.

(2) Set the values of the operation power (N), the average temperature (T_{av}) of the primary coolant, and the outlet pressure (P_{SGO}) of the SG secondary side.

(3) Make an initial assumption for the mass flow rate of the primary circuit to solve the coupled thermal hydraulic parameters under the given conditions.

(4) Check if the natural circulation driving force equals to the total pressure loss in the primary circuit. If not, assume the initial value of the primary mass flow rate again. Steps (3)–(4) are repeated.

(5) Output the calculated results.

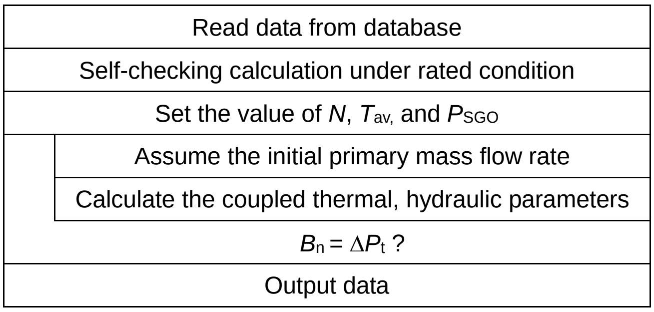

Fig. 3 N–S flowchart of the solution procedure.

5 Results and discussion

5.1 Analytical solution of the natural circulation mass flow rate

For single-phase primary coolant flow, the density is assumed to vary linearly with the temperature (i.e., the Boussinesq approximation) in this calculation. That is

$$\rho = \rho_r \left[1 - \beta (T - T_r)\right] \tag{16}$$

Using the inlet temperature and coolant density of the core as the reference temperature and density, respectively, the natural circulation driving force of the primary circuit is also given by

$$B_{\mathrm{n}} = \rho_{\mathrm{in}} \beta g \left(T_{\mathrm{out}} - T_{\mathrm{in}}\right) l_{\mathrm{hc}} \tag{17}$$

where l_{hc} is the height difference between the SG center and the core center.

At the same time, the total pressure drop of the primary circuit can be simplified as

$$\Delta P_{\mathrm{t}} = W^2 \sum_i^N \left[\frac{1}{2\rho A^2} \left(\frac{fL}{D_{\mathrm{e}}} + c \right) \right]_i \tag{18}$$

By combining Eq. (17) and Eq. (18), the primary mass flow rate is calculated as follows:

$$W^2 = \frac{\rho_{\mathrm{in}} \beta g \left(T_{\mathrm{out}} - T_{\mathrm{in}} \right) l_{\mathrm{hc}}}{R} \tag{19}$$

where R is

$$R = \sum_i^N \left[\frac{1}{2\rho A^2} \left(\frac{fL}{D_{\mathrm{e}}} + c \right) \right]_i \tag{20}$$

Ignoring the heat transfer loss in the primary circuit, the heat generated in the core is totally transferred to the primary coolant, that is

$$Q = W\bar{C}_{\mathrm{p}} \left(T_{\mathrm{out}} - T_{\mathrm{in}} \right) \tag{21}$$

Combining Eq. (19) and Eq. (21), the primary mass flow rate is expressed by

$$W = R_1 Q^{1/3} \tag{22}$$

where R_1 is given by

$$R_1 = \left(\frac{\rho_{\mathrm{in}} \beta g l_{\mathrm{hc}}}{R\bar{C}_{\mathrm{p}}} \right)^{1/3} \tag{23}$$

It can be seen from Eq. (20) and Eq. (23) that R_1 mainly depends on the mass flow rate and the thermophysical properties for a given geometry arrangement of the primary circuit. Therefore, by introducing another coefficient R_2, which does not depend on the mass flow rate, Eq. (22) is changed to

$$W = R_2 Q^n \tag{24}$$

Eq. (24) shows that the natural circulation mass flow rate is proportional to the exponential function of the power. The value of the coefficient R_2 and the exponent n are both related to the operation conditions.

5.2 Numerical results and discussion

It is noted that this numerical calculation method used as the main tool for the natural circulation characteristics analyses of the new type of pressurized water reactor at the conceptual design stage still needs to be continuously improved. Thus, experimental verification of the theoretical calculation is expected to continue in the future because currently, there is no experimental data that can be adopted. Furthermore, this numerical calculation method has been successfully adopted in some previous investigations[4-10]. In particular, in a calculation code, MISARS, developed by our research team in Xi'an Jiaotong University, the same numerical method is adopted to simulate the natural circulation characteristics of loop-type pressurized water reactors. The comparison of the calculated results of MISARS with those of RETRAN-02 showed good agreement[5,6]. Therefore, the use of this numerical method in the natural circulation characteristics analyses for the new type of pressurized water reactor is feasible and rational.

The natural circulation mass flow rates of the primary circuit under different core powers are shown in Fig. 4. It indicates that, for a given geometry arrangement of the primary circuit, the primary mass flow rate relies on the core power as well as the operation condition of the SG secondary side. The tendency of the primary mass flow rate to vary according to the core power is consistent with the analytical solution. The higher the steam pressure, the higher the natural circulation mass flow rate.

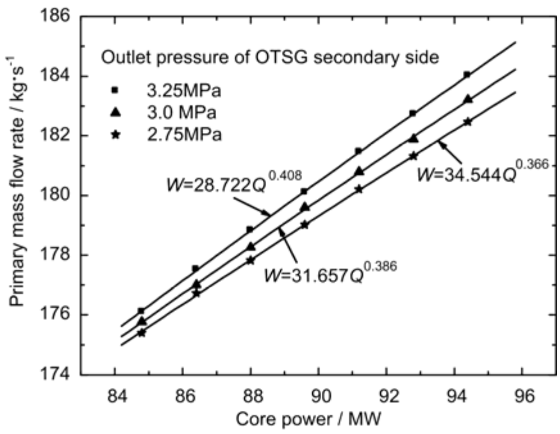

Fig. 4 Primary mass flow rate according to the core power.

Fig. 5 shows the inlet and outlet temperature of the core and the natural circulation mass flow rate of the primary circuit at different steam pressure. As mentioned above, the average temperature of the primary circuit is maintained a constant under normal operation conditions. Therefore, for a given core power, because of the higher natural circulation mass flow rate of the primary circuit under conditions of increased steam pressure, the inlet temperature of the core increases with the increase in steam pressure, whereas the outlet temperature of the core decreases with the increase in steam pressure.

The difference in height between the core center and the SG center is a very important parameter affecting the heat removal capacity of the natural circulation. It can be seen from Fig. 6 that the larger height difference causes the increase in natural circulation mass flow rate due to the corresponding greater natural circulation driving force. Consequently, the larger height difference between the core and the steam generator center is favorable for the heat removal capacity of the natural circulation.

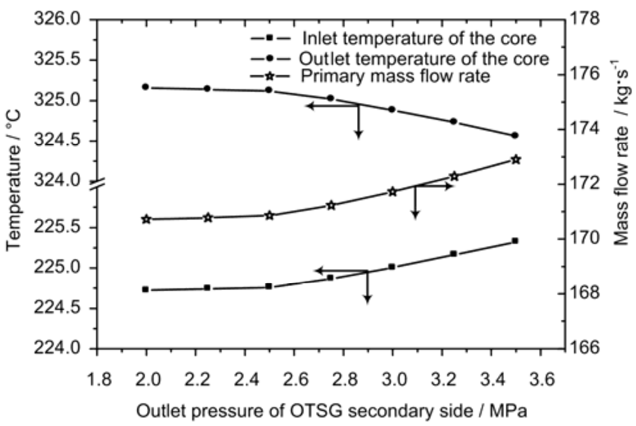

Fig. 5 The core inlet and outlet temperatures and primary mass flow rates at different steam pressures.

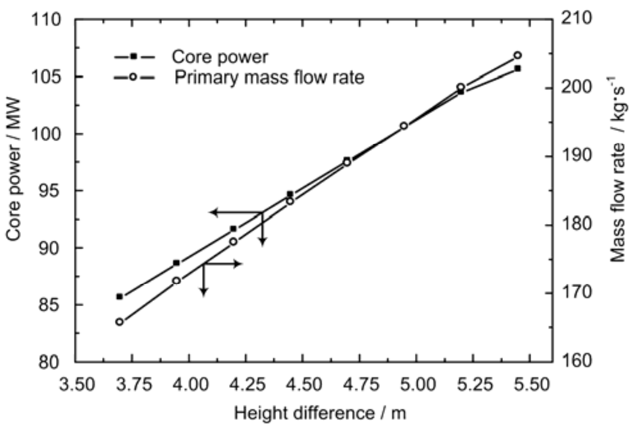

Fig. 6 The core power and primary mass flow rate as functions of the height difference.

6 Conclusions

The application of natural circulation, which is a promising means for heat removal after the tripping of a reactor as well as under normal operation conditions including full power operation, in innovative reactor designs improves the inherent safety and the reliability of the nuclear system. The natural circulation characteristics of the primary circuit are related to its geometry arrangement and circuit resistance characteristics as well as the operating conditions of the secondary circuit. This article presents a theoretical investigation on the natural circulation characteristics of a new type of pressurized water reactor. Through numerically solving the one-dimensional steady-state single-phase conservative equations for the primary circuit and the steady-state two-phase drift-flux conservative equations for the secondary side of the steam generator, the natural circulation characteristics are studied. On the basis of the preliminary calculation analysis, it is found that natural circulation mass flow rate is proportional to the exponential function of the power, and the value of the exponent is related to operating conditions of the steam generator secondary side. The larger the outlet pressure of the SG secondary side, the higher the primary natural circulation mass flow rate. The larger height difference between the core center and the steam generator center is favorable for the heat removal capacity of the natural circulation.

Nomenclature

A Cross-section area of the flow channel (m^2)
B Natural circulation driving force (Pa)
C_p Specific heat (kJ·kg^{-1}·K^{-1})
c Local friction coefficient
D_e Equivalent diameter of the flow channel (m)
f Friction coefficient
g Gravitational acceleration (m·s^{-2})
h Specific enthalpy (kJ·kg^{-1})
k Heat conductivity (kW·m·$^{-1}$K^{-1})
l_{hc} Height difference between the core center and the SG center (m)
p Pressure (Pa)
q Heat flux (kW·m^{-2})
q_u Volume heat generation rate (kW·m^{-3})
S_{DG} Drift flux pressure drop (Pa)
T Temperature (K)
U_h Heated perimeter of the flow channel (m)
W Mass flow rate (kg·s^{-1})

Greek letters

ρ Fluid density (kg·m^{-3})

α Heat transfer coefficient (kW·m^{-1}K^{-1})

β Expansion coefficient (K^{-1})

Subscripts

1 The primary circuit

2 The secondary circuit

c Clad

f Saturated liquid

in Core inlet

lo Total flow assumed liquid

n Natural circulation

p Pump

t Total

tp Two phase flow

u Fuel

v By-pass valve

w Tube wall

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