Study on characteristics of steady natural circulation flow for external reactor vessel cooling

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Abstract: The In-Vessel corium Retention (IVR) through the External Reactor Vessel Cooling (ERVC) is known as an effective accident management strategy for maintaining the integrity of the reactor pressure vessel (RPV) during severe accidents. The natural circulation, which is adopted in design of IVR, not only determines the amount of heat carried off from corium pool, but also has significant influence upon critical heat flux (CHF) of wall of RPV lower plenum. Thus, characteristics of steady natural circulation flow under external reactor vessel cooling (ERVC) condition are investigated analytically. The analytical model for circulation velocity is established by proper hypothesis and simplification. The mass flow rate of the natural circulation and void fraction for different inlet temperatures, core corium powers, gap clearances and submersed depths are obtained through solving analytical model. The results show that established model is feasible to estimate the natural circulation flow rate. Capability of natural circulation is enhanced when core corium heat power increases or inlet temperature increases. The gap clearance between insulation and reactor vessel has few influences on circulation flow rate after it exceeds certain value. The circulation flow rate decreases as submersed depth increases and this influence is obvious when inlet temperature increases.

Keyword: severe accident; natural circulation; analytical model; external reactor vessel cooling

1 Introduction

The In-Vessel corium Retention (IVR) through the External Reactor Vessel Cooling (ERVC) is known as an effective accident management strategy for maintaining the integrity of the reactor pressure vessel (RPV) during severe accidents [1]. This measure has been adopted in many passive safety nuclear power plants such as the AP1000 and the CAP1400. Under hypothetical core melting accidents, the coolant submerging reactor cavity will boil as heat transferred through RPV wall from corium pool and form natural circulation flow along flow path between the external wall surfaces of RPV and thermal insulation. Decay heat then is continuously transported to environment so that integrity of the RPV is maintained [2]. Characteristics of natural circulation flow [3], which play an important role in design concept of IVR, not only determine the amount of heat carried off from corium pool, but also have significant influence upon critical heat flux (CHF) of wall of RPV lower plenum [4].

Thus, characteristics of steady natural circulation flow under ERVC condition are investigated analytically in this paper. The analytical model for circulation velocity is established by applying proper hypothesis and simplification to conservation equations for mass, momentum and energy. Natural circulation flow between insulation and reactor vessel is assumed as one-dimensional homogeneous flow along axis line of flow path.

2 Model of circulation velocity

The natural circulation flow between the external wall surfaces of RPV and thermal insulation under severe accident can be treated as one-dimensional steady flow shown in Fig.1. The flow path is consisting of gap clearance between reactor and insulation, passageway between insulation and concrete surface of sump.

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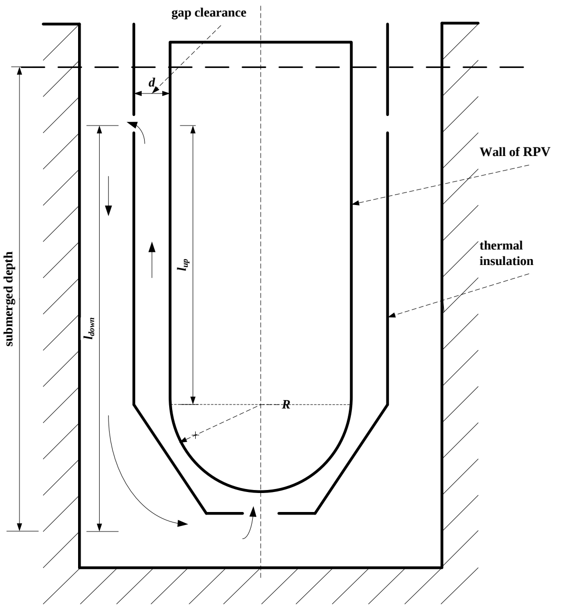

Fig.1 Schematic of natural circulation for ERVC.

The conservation equations of mass, momentum, energy can be expresses as [10]:

$$\rho_{\text{in}} u_{\text{in}} a_{\text{in}} = \rho_i u_i a_i = G \quad (1)$$

$$\sum_{i=1}^{N} \frac{\rho_i u_i^2}{2} \left(\frac{fl}{d_{\text{h}}} + K \right)_i = \left(\overline{\rho}_1 - \overline{\rho}_{\text{TP}} \right) L_{\text{th}} g \quad (2)$$

$$\rho_i u_i A_i \left(h_{\text{TP}} - h_{\text{in}} \right) = \dot{q}_s \quad (3)$$

where, ρ is density, u is velocity, a is cross-section area, G is mass flow rate, L_{th} is height difference between heat and cooling sources, g gravity acceleration, h is enthalpy, $\dot{q}_s$ is volumetric heat release rate of heat source, f and K are resistance coefficients, d_{h} is equivalent diameter. Subscript *in* means inlet, *i* means reference position, *l* means liquid, *TP* means two phase.

Quality based on thermal equilibrium and average density of two-phase flow is defined as follow:

$$\chi_{\text{e}} = \left(h_{\text{TP}} - h_{\text{ls}} \right) \gamma^{-1} \quad (4)$$

$$\overline{\rho}_{\text{TP}} = \rho_{\text{ls}} \left(1 + \chi_{\text{e}} \Delta\rho / \rho_{\text{gs}} \right)^{-1} \quad (5)$$

where, γ is latent heat, $\Delta\rho$ u is density difference.

Substituting Eq.(3) into Eq.(4) yields:

$$\chi_{\text{e}} = \left(\dot{q}_s - G h_{\text{sub}} \right) \left(G\gamma \right)^{-1} \quad (6)$$

where, h_{sub} is fluid enthalpy difference between inlet and saturated position.

Substituting Eq.(6) into Eq.(5) yiels:

$$\overline{\rho}_{\text{TP}} = \rho_{\text{ls}} \left(1 + \frac{\dot{q}_s - G h_{\text{sub}}}{G\gamma} \frac{\Delta\rho}{\rho_{\text{gs}}} \right)^{-1} \quad (7)$$

Substituting Eq.(7) and Eq.(1) into Eq.(2) yiels:

$$u_{\text{in}}^3 + u_{\text{in}}^2 \beta_1 + u_{\text{in}} \beta_2 - \beta_3 = 0 \quad (8)$$

where, β_1, β_2, β_3 are coefficients which are determined by heat power, fluid property and resistance. They are expressed as:

$$\beta_1 = \frac{\Delta\rho \dot{q}_s}{\left(\rho_{\text{gs}} \gamma - \Delta\rho h_{\text{sub}} \right) a_{\text{in}} \rho_{\text{in}}}$$

$$\beta_2 = \frac{2 L_{\text{th}} g \left[\rho_{\text{ls}} \rho_{\text{gs}} \gamma - \rho_{\text{in}} \left(\rho_{\text{gs}} \gamma - \Delta\rho h_{\text{sub}} \right) \right]}{\left(\rho_{\text{gs}} \gamma - \Delta\rho h_{\text{sub}} \right) \rho_{\text{in}}^2 F} \quad (9)$$

$$\beta_3 = \frac{2 L_{\text{th}} g \Delta\rho \dot{q}_s}{\left(\rho_{\text{gs}} \gamma - \Delta\rho h_{\text{sub}} \right) a_{\text{in}} \rho_{\text{in}}^2 F}$$

and

$$F = \sum_{i=1}^{N} \frac{1}{\rho_i} \left(\frac{fl}{d_{\text{h}}} + K \right)_i \left(\frac{a_{\text{in}}}{a_i} \right)^2 \quad (10)$$

Eq.(8) is the cubic equation to predict the flow velocity in a steady-state, two-phase fluid for both subcooled or saturated flow conditions. While the equation is highly implicit since the coefficients of the Eq.(8) include flow velocity terms. Therefore Eq.(8) cannot be analytically solved. As a result, Newton-Raphson Method [12] is utilized to obtain the solution in this paper. The formula in literatures [13] is used for calculation of friction coefficient.

3 Results discussion

3.1 Comparison of the model with experimental data

The model established above is verified by two experiments, the ULPU tests [4] and Reactor Pressure Vessel External Cooling tests (REPEC) [15]. The ULPU (Theofanous *et al.*, 1997) is a test loop which simulates a natural circulation flow and critical heat flux around a RPV of the advanced reactor, AP600. The length of the test loop is the same with the RPV and it simulates a slice of the vessel and flow domain around the vessel. The REPEC located in China is a test loop similar with ULPU.

The test data obtained under different power, inlet subcooling are compared with predictions with the present model as shown in Fig.2 and Fig.3. It is noted that the test data of ULPU in Fig.2 are obtained with inlet subcooling 9 ℃ and 10 ℃. It can be recognized from Fig.2 that the measured flow rates are well predicted by the present model for subcooling between 9 ℃ and 10 ℃. What is more, the accuracy of present model becomes worse when inlet subcooling is more than 20 ℃ by referring to Fig.3. This deviation is mainly caused by the hypothesis that two phase are at thermal equilibrium state. Thermal equilibrium state is used to model the two-phase flow in ERVC, but the subcooled boiling is occurring in fact. As a result, the driving force caused by density difference for natural circulation will be larger in test than that in calculation. So there is an obvious deviation under high subcooling conditions.

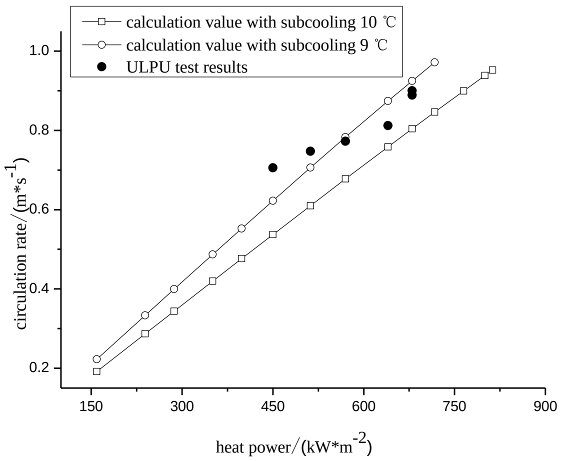

Fig.2 Comparison between analytical model and ULPU experiment results.

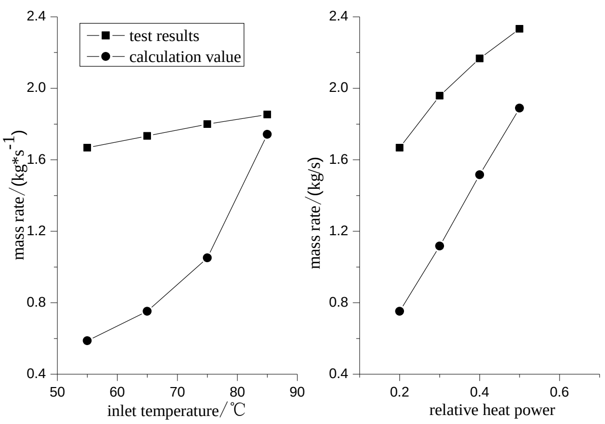

Fig.3 Comparison between analytical model and REPEC experiment results.

The comparison in Fig.2 and Fig.3 shows rationality and reliability of present model to predict circulation flow rates under different ERVC condition.

What is more, the inlet sub cooling should not be more than 20 ℃ so as to make sure accuracy of the calculation.

3.2 Influence of core corium power on natural circulation

The circulation rate and void fraction vs. inlet temperature under different core corium powers (5 MW, 10 MW, 20 MW and 50 MW) are studied, as shown in Fig.4 and Fig.5. The results show that circulation rate will increase as core corium power increases or inlet temperature increases. The void fraction for two-phase flow in upper region of path between the external wall surfaces of RPV and thermal insulation shows a similar characteristic as circulation rate. When the core corium power increases or inlet temperature increases, the vaporization occurring at bottom head of the RPV is enhanced. Therefore there is an augment in void fraction leading to a decrease in density of two-phase mixture in natural circulation. As a result, the density difference between heat source and heat sink increases which makes the driving pressure drop enlarged and circulation velocity increased.

Besides, the influences of core corium power or inlet temperature on circulation rate will be weakened when fluid is approaching saturated temperature. This conclusion is of importance for the fact that the temperature of fluid flooding the reactor cavity under accident condition will increase slowly as reflux condensation effects.

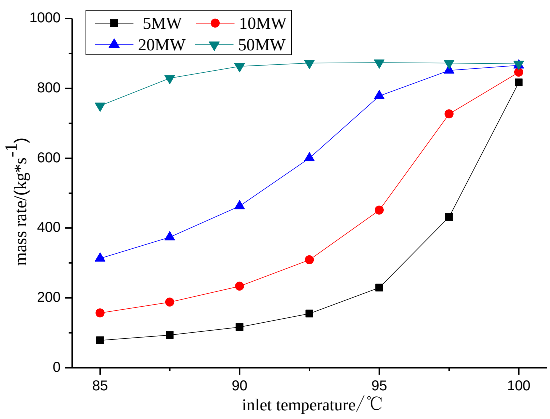

Fig.4 Effect of core corium power on mass flow rate.

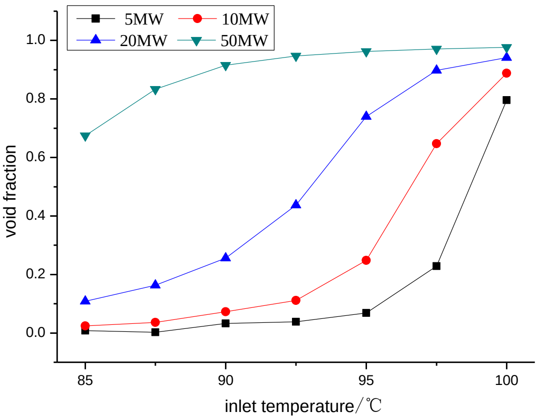

Fig.5 Effect of core corium power on void fraction.

3.3 Effect of gap clearance between reactor and insulation on natural circulation

The circulation rate and void fraction vs. gap clearance under different inlet temperature are studied, as shown in Fig.6 and Fig.7. It is convinced that circulation rate will increase as gap clearance or inlet temperature increases. The void fraction for two-phase flow in upper region of path between the external wall surfaces of RPV and thermal insulation will decrease as gap clearance increases. The influences of gap clearance on circulation rate and void fraction are relative small when the gap clearance exceeds 0.1 m.

The circulation rate and void fraction vs. inlet temperature under different gap clearance are studied, as shown in Fig.8 and Fig.9. It can be founded that the impacts of gap clearance on circulation rate has a close relationship with inlet temperature. When inlet temperature is below 90℃, the variations of gap clearance have little effects on circulation rate. While it is more than 90℃, the circulation rate will increase gradually as gap clearance increases. What is more, effects of inlet temperature on void fraction are not obvious.

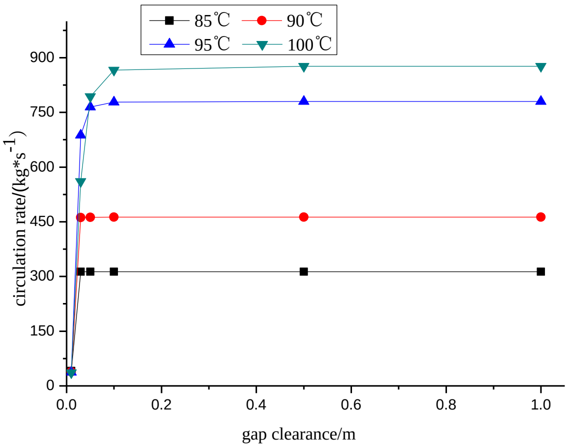

Fig.6 Effect of gap clearance on mass flow rate.

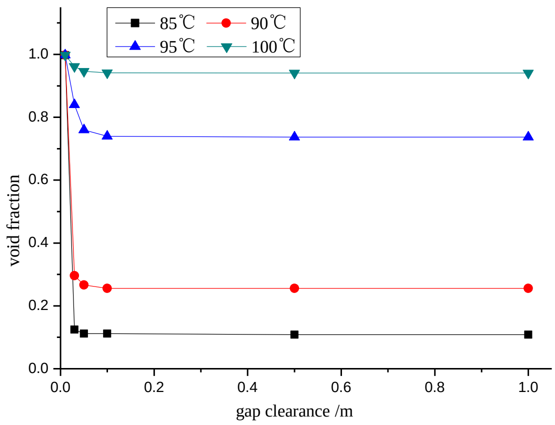

Fig.7 Effect of gap clearance on void fraction.

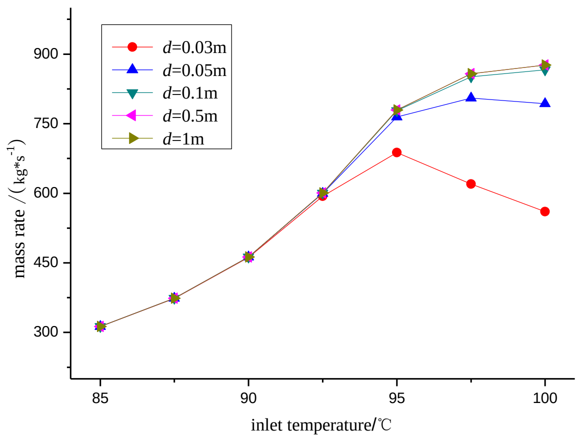

Fig.8 Effect of inlet temperature on void fraction.

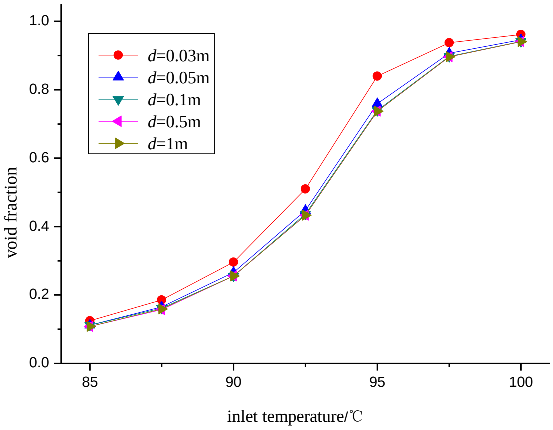

Fig.9 Effect of inlet temperature on void fraction.

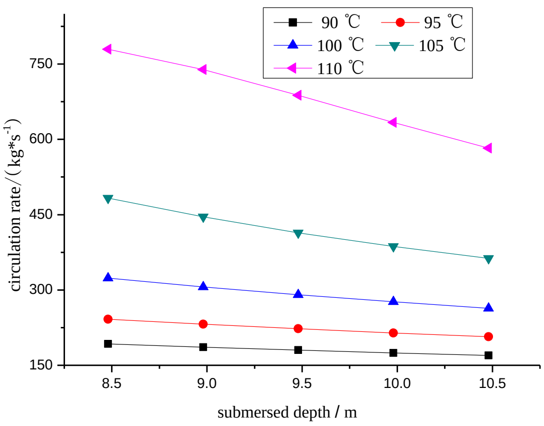

Fig.10 Effect of submersed depth on mass flow rate.

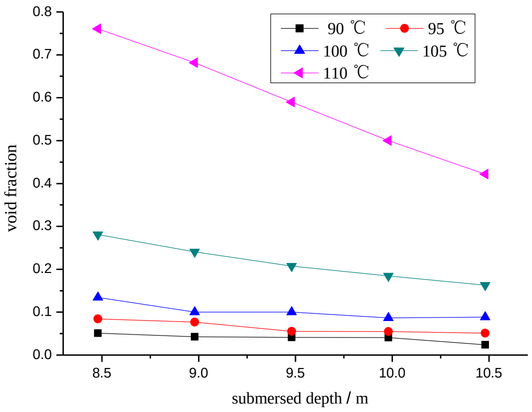

Fig.11 Effect of submersed depth on void fraction.

3.4 Effect of submerged depth on natural circulation

The circulation rate and void fraction vs. submerged depth under different inlet temperature are studied, as shown in Fig.10 and Fig.11. It is convinced that circulation rate will decrease as submerged depth increases. What is more, effect of submerged depth on natural circulation mainly rests with inlet temperature.

The void fraction for two-phase flow in upper region of path between the external wall surfaces of RPV and thermal insulation will decrease as gap clearance increases. The influences of gap clearance on circulation rate and void fraction are relative small when the gap clearance exceeds 0.1 m.

General speaking, the static pressure at inlet of flow path between reactor pressure vessel and insulation becomes larger as submerged depth varying from 8.48 m to 10.48 m. As a result, the saturation pressure becomes larger so that the saturation temperature for fluid in natural circulation goes up. Furthermore, the subcooling of fluid is increased owing to the rise of saturation temperature.

4 Evaluation of calculation model

The calculation model established in this paper could be used in quick estimation for natural circulation characteristics of ERVC. However, there are some hypotheses and limitations that should be evaluated before application.

a) The mathematical model is obtained based on steady natural circulation. The suitability for some condition, *i.e.*, set up process of natural circulation or circulation flow in which convective accelerations caused by evaporation and condensation should not be neglected, need further investigation.

b) One-dimensional homogeneous flow model are selected to describe the two phase flow in natural circulation of ERVC. Based on test results reported by literature [16], nucleate boiling is the main heat transfer mode. Thus the two phase flow, which flow through hemispherical annulus under the action of centrifugal force and gravity in the same direction, behaves an asymmetrical flow pattern in which gaseous phase build up in the region near the reactor pressure vessel wall while the liquid phase mainly flow through the region near the thermal insulation. Therefore, the calculation model present here has ignored distribution of steam bubbles along the flow direction and cross section of the flow channel. Optimized two phase flow model is needed to improve the deviation between calculation model and physical phenomenon.

c) The hypothesis that two phases have reached thermal equilibrium state is applied in homogeneous flow model. However, the subcooled boiling is occurring in fact. Consequently the predicting values for low subcooling conditions are consistent with test results while that for high sub cooling conditions show an obvious deviation.

5 Conclusions

Characteristics of steady natural circulation flow under ERVC condition are investigated analytically in this paper. The analytical model for circulation velocity is established by applying proper hypothesis and simplification to conservation equations for mass, momentum and energy. Natural circulation flow between insulation and reactor vessel is assumed as one-dimensional homogeneous flow along axis line of flow path. What is more, the circulation velocity model is verified with experimental results obtained in tests at ULPU facility and REPEC facility. Result of verification indicates the model established is feasible to estimate velocity or flow rate for natural circulation flow with low inlet subcooling in ERVC system. The mass flow rate of the natural circulation and void fraction for different inlet temperatures, core corium powers, gap clearances and submersed depths are then obtained through solving analytical circulation velocity model with Newton-Raphson method. The results show that capability of natural circulation is enhanced when core corium heat power increases. The gap clearance between insulation and reactor vessel has few influences on mass flow rate of the natural circulation after it exceeds certain value. However, there are increases in mass flow rate of the natural circulation and decrease in void fraction when the gap clearance is less than certain value. As submerged depth increases, the circulation flow rate and void fraction will decrease as augments of submersed depth leading to higher saturated temperature for water in insulation channel. Associating with saturated temperature of cooling water, inlet temperature has significant impacts on capability of natural circulation. Under low inlet temperature condition, the impacts of core corium heat power on circulation flow rate and void fraction are less. While that for submersed depth is enhanced. Besides, gap clearance has minimal impact on circulation flow rate and void fraction when inlet subcooling is more than 10℃.

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