Numerical simulation of thermal-hydraulic characteristics in a closed natural circulation system

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Abstract. In order to enhance the safety of nuclear energy, natural circulation served as a passive technology is widely used. Accordingly, an investigation associated with thermal-hydraulic characteristics for natural circulation system is made in this work. Numerical simulation based on RELAP5 code is performed especially for flow instability phenomenon. The results indicate that flashing and condensation are two important factors for low pressure natural circulation two-phase system. For all this, the tolerance of natural circulation to flashing oscillation could be enhanced effectively with the increase of system pressure. Under high pressure condition, the flowrate might shrink to a new equilibrium state from flashing-induced oscillation. The simulation results and analysis could contribute to a more extensive utility of natural circulation mechanism for nuclear energy.

1. Introduction
Energy and environment protection have received considerable attention on a global scale in recent decades. The demand of energy becomes a hot issue with the development of world economy structure and diverse culture. Nuclear energy as a clean energy is one of the most high-efficient method for energy utility.

However, the radioactivity is a serious problem which restricts the development of nuclear energy. When severe accident occurs at NPP (nuclear power plant), the leakage of radioactivity is the most harmful threat to the society. Thus, the integrity of nuclear system should be guaranteed in both normal and accident transient operation modes. In the new generations of nuclear reactor, passive safety technology is adopted in many subsystems to enhance its inherent safety. Natural circulation (NC) served as rather effective and update method has been investigated in the design of nuclear system[1]. In fact, it has a more extensive use in other fields including, boiler cycle system, solar related system, some chemical processing systems etc[2-3]. It is worth mentioning that flow instability is more likely to take place in a two-phase natural circulation system[4-5]. It is a rather complex problem in the design and operation of many industrial systems and equipments. In general, it is necessary to make a further research on natural circulation mechanism in nuclear field.
In this paper, a numerical simulation of NC thermal hydraulic behaviors is accomplished based on experimental system. The aim of this research is to gain the insight of natural circulation and lend some empirical supports for a better use of natural circulation.

2. Methodology
Numerical and experimental investigations are performed to explore the NC mechanism. RELAP code is adopted in the analysis based on the empirical experimental results. It is turned out to be an efficient method to complete the simulation.

2.1. Description of NC experimental system
The experiment facility, which was set up at Harbin Engineering University in 2012 is shown in Figure 1. It is established to study various mechanisms behind the phenomena that appear in natural circulation loop. Apart from flow instability, many other important experiments including axial non-uniform heating, transition between NC and FC (forced circulation), coupled neutronics and thermal-hydraulic simulation are carried out in this system as well.

The height difference between the thermal centers of heat sink is over 4.0m. It could ensure the natural circulation ability as NC relies on the density difference between vertical hot legs and cold legs. As shown in Figure 1, the loop is mainly consisted of a direct current power supply(A), test section(B), adiabatic riser(C), condenser(D), downcomer(E), circulation pump(F) and pressurizer(G). A bypass pipe is set along with the pump. In order to reduce flow resistant, the circulation pump will shut down and be isolated when natural circulation is established.

In the experiment, inlet subcooling $\Delta T_{in,sub}$ is kept as a constant while heating power increases stepwise. The thermal parameters such as pressure drop, wall temperature, mass flux will oscillate once flow instability occurs. If wall heat flux $q$ remains constant, a self-sustained pulsation is obtained. With the increase of heating power, the flow instability will exhibit quite different variation principles.

![Figure 1. Natural circulation experimental apparatus.](image)

![Figure 2. RELAP5 Models and nodalization of experimental system based on RELAP5 code.](image)

2.2. Simulation models
The numerical simulation is accomplished by RELAP5 code, which is a light water reactor transient analysis code developed for the U.S.Nuclear Regulatory Commission (NRC)[6-7]. This best estimated code could also be used in severe accident analysis for NPP.

A natural circulation calculated model is established on the basis of the experimental apparatus. Figure 2 shows the main components that correspond to Figure 1. The nodalization for different sections is marked out as well.
A one-dimensional, transient, two-fluid model based on a non-homogeneous and nonequilibrium model is applied in RELAP5 code. In fact, the basic field equations are the fundamental for two-phase natural circulation. The three sorts of fluid equations are as follows,

**Mass Continuity:**

\[
\frac{\partial}{\partial t} (\alpha_g \rho_g A) + \frac{1}{A} \frac{\partial}{\partial x} (\alpha_g \rho_g v_g A) = \Gamma_g
\]

\[
\frac{\partial}{\partial t} (\alpha_l \rho_l A) + \frac{1}{A} \frac{\partial}{\partial x} (\alpha_l \rho_l v_l A) = \Gamma_l
\]

**Momentum Conservation:**

\[
\alpha_g \rho_g A \frac{\partial v_g}{\partial t} + \frac{1}{2} \alpha_g \rho_g A \frac{\partial^2 v_g}{\partial x^2} = -\alpha_g \frac{\partial P}{\partial x} + \alpha_g \rho_g B, A - (\alpha_g \rho_g A)FWG(v_g) + \Gamma_g (v_g - v_l)
\]

\[
\alpha_l \rho_l A \frac{\partial v_l}{\partial t} + \frac{1}{2} \alpha_l \rho_l A \frac{\partial^2 v_l}{\partial x^2} = -\alpha_l \frac{\partial P}{\partial x} + \alpha_l \rho_l B, A - (\alpha_l \rho_l A)FWF(v_l) - \Gamma_g (v_g - v_l)
\]

**Energy Conservation:**

\[
\frac{\partial}{\partial t} (\alpha_g \rho_g U_g) + \frac{1}{A} \frac{\partial}{\partial x} (\alpha_g \rho_g U_g A) = \frac{\partial}{\partial t} (\alpha_g \rho_g v_g A) + P \frac{\partial}{\partial x} (\alpha_g \rho_g v_g A) + Q_g + Q_g - \Gamma_g h_g + \Gamma_g h_g
\]

\[
\frac{\partial}{\partial t} (\alpha_l \rho_l U_l) + \frac{1}{A} \frac{\partial}{\partial x} (\alpha_l \rho_l U_l A) = \frac{\partial}{\partial t} (\alpha_l \rho_l v_l A) + P \frac{\partial}{\partial x} (\alpha_l \rho_l v_l A) + Q_l + Q_l + \Gamma_g h_l + \Gamma_g h_l
\]

3. Results and discussion

A series of flow instabilities phenomena are observed in the experiment and simulated by RELAP5 code. Figure 3 shows the flow oscillation under low heat flux and low pressure condition. The inlet temperature is almost constant \((N_{sub} = 50.2\sim58.9, P_{sys}=0.3\text{MPa})\), the flow instability occurs when heating power reaches 7.19 kW. Two types of oscillations captured under low heat flux condition: sinusoidal oscillation and irregular oscillation. The period changes from 47.5s to 6.9s. Flashing and condensation play a dominant role in the flow instability under this condition.

![Figure 3. Typical natural circulation flow instability phenomenon.](image)
In natural circulation system, the mass flux is tightly combined with fluid density difference, which induces the NC driving forces. It is because the driving mechanism is based on the net pressure difference between the two ends of horizontal section. Under the effect of gravity, the fluid is pushed into the heated channel intermittently during flow rate oscillations. As the fluid absorbs the energy from solid wall continuously, flow boiling might occur and induce a great decrease of average density in hot legs. When NC driving forces which caused by this density difference and flow resistance could not match with each other, the flow rate will change. Under certain heat flux, self-sustained oscillation emerges as a result.

Initially, a self-sustaining sinusoidal oscillation is observed under medium heat flux. Periodic variations of flow rate, outlet void fraction of heated channel and riser, pressure drop $\Delta P$ are displayed in Figure 4. The period is between 8.1~9.5s, which is about 4.2~4.5 times of $\tau$ (the propagation time in the riser). It belongs to low-frequency fluctuation. Actually, flashing effect still exists when riser inlet is two-phase fluid. Boiling and flashing contribute to natural circulation driving forces. The average value of void fraction varies smaller. The variation between flowrate and outlet void fraction of heated channel is out-of-phase. However, it is in-phase for flowrate and void fraction of riser outlet.

The flashing is weaken and the boiling is likely to be a key factor for this instability[8]. For two-phase natural circulation issue, the void fraction is the crucial parameter in phase change. Therefore, to account for the mechanism, the distribution of void fraction in the riser is exposed in Figure 5. It changes between 0.1 and 0.38. When mass flow rate $M_0$ has a disturbance at the minimum ($M' = M_0 + \Delta M$), the pressure drop of heated channel ascends almost instantaneously ($\Delta P \propto \rho u^2$). It will cause a drop in the outlet pressure. Flashing is promoted since the average pressure of riser decreases. Figure 5 also indicates that condensation and flashing function together and saturated boiling also affect this instability. $M'$ increase will suppress both flashing and saturated boiling. Distribution of void fraction reveals driving force in natural circulation to some degree.

Figure 4. Variations of main parameters for sinusoidal oscillation.  

Figure 5. Variation of void fraction in adiabatic riser during flow oscillation.

It is found that under higher pressure conditions, natural circulation system could be stable again and eventually transits to another instability. As shown in Figure 6, when inlet subcooling reaches a threshold, flashing occurs and induces fluctuation ($Q = 12.9\text{ kW}$). The flashing oscillation shrinks and a new stable state is established. The flowrate is much larger than the previous equilibrium flow. It is a notable flow excursion. As inlet subcooling continues decreasing, flow instability occurs again and belongs to DWOs (density wave oscillations) [4]. The evolution involves two different types of dynamic instability and a static instability (flowrate drifts to a higher value).

Figure 7 implies the corresponding phase graph. Natural circulation flowrate and pressure drop have a nonlinear relationship. Comparing with flashing oscillation, the fluctuation amplitude is smaller and
the frequency is higher. However, the curves are both oblate for flashing oscillation and DWOs. The major axis of elliptical trajectory has a positive slope. It is known that DWOs always occurs on the boiling positive slope branch of the pressure drop versus flow rate curve[9]. Thus, this flashing oscillation belongs to DWOs. Mass flow rate falls behind void fraction for 1/4 period. It acknowledged that flow oscillation period is about 4.8s and still belongs to low-frequency pulsation.

Figure 6. Transition between different types of flow instabilities.  

Figure 7. Flow oscillation trajectories in the phase planes.

A summary of natural circulation flow instability related to flashing is presented in Figure 8. The emphasis placed on instability area, some stable points and other instabilities are not displayed in stability map. Flashing effect on natural circulation could be divided into following 4 parts: (1) stable flow with flashing, (2) periodic irregular oscillation, (3) new stable point, (4) flashing-induced DWOs. While \( N_{\text{pch}} = N_{\text{sub}} \), i.e. \( x_e = 0 \), flashing is more likely to happen[10]. With the dimensionless plane of \( N_{\text{sub}} - N_{\text{pch}} \), the region is described more clearly[11]. The amplitude of flow oscillation could be very large, which results in flow reversal. The fluid heated repeatedly and local heat transfer deteriorates. Under low-pressure and high heat flux conditions, such as start-up in natural circulation boiling water reactors, the instability area should be avoided as far as possible. In addition, flow excursion may occur as inlet subcooling decreases. It should be taken into consideration in reactor design as well.

Figure 8. Stability map for natural circulation instabilities.
4. Conclusions
Natural circulation flow instability experiments are conducted and RELAP5 code is adopted in the analysis. The following conclusions are obtained from the results.

(1) Two representative waveforms are observed under low heat flux condition: sinusoidal oscillation and irregular oscillation. They are suggested to be flashing-related flow instabilities. The nonlinear relationship between pressure drop and NC mass flux is obtained and analyzed in natural circulation issue.

(2) With the system pressure increases, flashing is likely to have weaker effect on natural circulation. On the basis of RELAP5 code, the natural circulation flow instabilities under higher pressure are simulated. The flowrate would shrink to a new equilibrium from flashing-induced oscillation.

(3) Flashing-induced density wave oscillation is captured as well. A stability map related to flashing instability is summarized. It could lend strong empirical support to nuclear reactor design and operation.

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