Numerical and experimental investigations on transient behaviors in a low-pressure natural circulation system

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Abstract: During the start-up of natural circulation BWRs, the system need to operate under low-pressure condition. However, some abnormal phenomena might occur such as flashing-induced instabilities, lag increment of flowrate, transient burn-out caused by flow oscillations. The objective of this work is to investigate the transient behaviors in low-pressure natural circulation system by numerical and experimental research methods. Two types of experiments were conducted, including a transient process with step disturbance of given power signal and a self-sustaining flow oscillations process. RELAP5 code is adopted in the simulation. The calculated results are validated against the experimental data and show a good agreement with experimental results. Time lag caused by material and fluid properties is hard to simulate by RELAP5 original code. The variation of driving forces plays a dominant role in transient natural circulation. A series of flow instabilities experiments, which related to flashing, are analyzed with the help of numerical code. It is a good method to illustrate the flow instability mechanism.

Keyword: natural circulation; transient behaviors; flow instability; RELAP5

1 Introduction

In the design of advanced reactors, such as AP1000[1,2], ESBWR [3], SWR1000[4], passive safety technology has received more and more attention. The full reliance upon natural force is the primary characteristic of passive safety system. Natural circulation is widely used in normal core cooling, passive residual heat removal and shutdown cooling. A lot of work has been done to study the natural circulation behaviors [5, 6] not only in research reactors, but also in some commercial reactors [7,8]. However, the complexity of natural circulation system is doomed because of the complicated relationship between thermal parameters and its operating mechanism. Flow instability is one of the most undesirable phenomena in natural circulation system. During the transient oscillations which caused by flow instabilities, the system is faced with many kinds of hazards, such as mechanical fatigue, control failure, heat shock and transient burn-out. These problems should be avoided in the design and operation of nuclear power plant.

A clear classification of flow instability was firstly discussed by Boure [9] and improved with coupled thermohydraulic neutronic instabilities by March Leuba and Rey [10]. Several kinds of dynamic instabilities such as DWOs (density wave oscillations), geysering, flashing-induced DWOs, are more likely to occur in a low-pressure natural circulation system. Many theoretical and experimental investigations on these instabilities were reported in the literatures [11,12,13]. In natural circulation experiments, configurable and thermal–hydraulic parameters are turned out to make a great impact on natural circulation mechanism. Masanori Aritomi[14] investigated the influence of geometrical parameters and found that flashing instability principle was closely related to the size of non-heated riser. In general, flow instability is still a key and complicated issue.

In recent decades, the focus of analytical work has been put more and more to the simulations using

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best-estimate codes. FLOCAL, RELAP5, TRACE and RETRAN-3D are typical numerical codes in the analysis in time domain [15]. The light water reactor transient analysis code, RELAP5, was developed at the Idaho National Engineering Laboratory (INEL) for the U.S. Nuclear Regulatory Commission [16]. It shows an excellent performance on steady and transient simulation [17], which is adopted in this paper to analyze the dynamic process under natural circulation condition.

During the start-up process, natural circulation system will undergo several transient events and flow instabilities as natural circulation BWRs might operate in low-power and low-pressure condition (start-up condition) [18]. Meanwhile, natural circulation transient behaviors are quite different between low-pressure and high-pressure conditions. Thus, the investigations under low-pressure has been done in this paper. Two kinds of transient experiments are conducted in this condition. In the power step experiment, an inevitable factor, namely time lag, was taken into account. During flow instability experiments, the physical mechanisms are illustrated with the help of RELAP5 code. This paper is aimed to gain an insight into the nature of transient natural circulation behaviors under low-pressure condition.

2 Description of natural circulation experiment

2.1 Experiment apparatus

The experiments were carried out in a natural circulation system, which was established in Harbin Engineering University. Figure 1 shows the main components and the auxiliary systems, including secondary cooling system, nitrogen stabilized pressure system and data acquisition system. The primary loop consists of heating section, riser, condenser, downcomer, pump, preheater and pressurizer. Lots of experiments, which related to natural circulation are conducted in this facility, such as thermal-hydraulics simulation coupled with neutron dynamic, natural circulation transition process, flow instabilities.

The working fluid is demineralized water, which will be heated when it flows into the heated channel. A long adiabatic riser is installed above the heated channel. A shell and tube heat exchanger with counter cooling is arranged at the top of the loop. The water is cooled in this condenser and flows down. At the bottom, the fluid is preheated by an electronic heat exchanger. The inlet temperature is controlled as an expected value by the preheater. A pressurizer connected to the horizontal pipe is used to maintain system pressure. As shown in Fig.1, a parallel bypass pipe is set to change the operation from forced circulation to natural circulation.

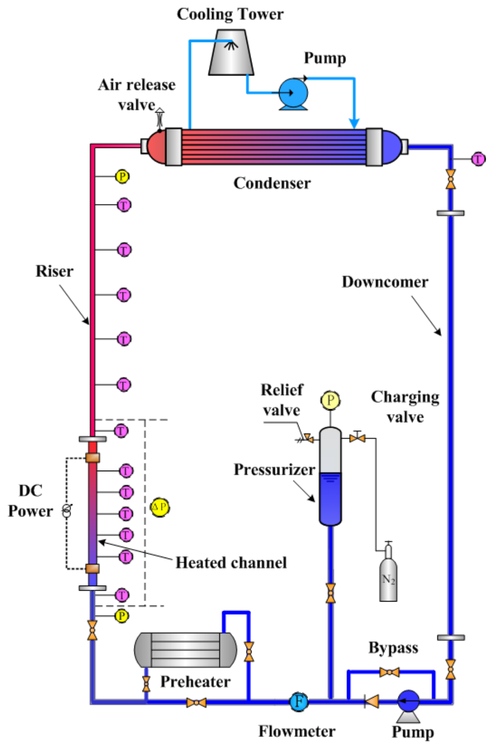


Fig.1 Schematic of natural circulation experimental system.

A direct current power(DC) is applied in the heated section. The stainless tube heats the fluid with the method of ohmic heating. The single-phase fluid absorbs the energy from the wall and may change to two-phase flow under some conditions. The hot fluid flows through adiabatic riser and cooled in condenser. The height between the center of heater and cooler is about 3.7m. Natural circulation flow is enhanced effectively by the loop height and density difference between the fluid in hot leg and cold leg.

2.2 The measurement and operating conditions

The stainless tube is used to simulate reactor core. It is served as heat source with the effective heating length of 1.6 m, inner diameter of 14.0 mm and thickness of 1.0 mm. There are 21 N-type thermocouples, whose accuracy is ±0.1%, attached to the outer surface of the wall. The response of wall temperature is measured by these thermocouples. Besides, several armored thermocouples, which inserted in the main pipes, are used to acquire the fluid temperature at key positions (see Fig.1).

An electromagnetic flowmeter (±0.2%) that installed at the bottom is used to measure the flowrate in steady and transient state. Several pressure transducers (±0.1%) and pressure sensors (±0.15%) are used to monitor pressure signal of main components. The operating ranges of primary parameters are listed in Table1.

Table 1 Experiment ranges for natural circulation.

Parameters	Ranges
Heating Power	0 ~ 25 kW
System pressure	0.1~0.5 MPa
Heat flux	0 ~ 355.4 kW/m^2
Inlet subcooling	35 ~ 75 ℃
Flow circulation	natural circulation

After the preparations, forced circulation is established initially. Then direct current power is brought into operation. The pump rotary speed begins to decrease gradually until flowrate reaches natural circulation level (about 0.1~0.2m^3/h). It is controlled by a VFD (Variable-frequency Drive). Then the main pump is shut down. The bypass valve turns on and the pump is isolated. A preliminary natural circulation is established.

On the basis of a steady natural circulation, the power steps with different variations of heat flux. The responses of wall temperature, fluid temperature and circulation flowrate are recorded during the transient process. Furthermore, flow instability experiments are conducted as well. It can be regarded as a special transient process which is characterized by periodic oscillations. In the experiment, heating power increases step by step with a constant inlet subcooling. Flowrate begins to oscillate when heat flux reaches a threshold. The dynamic oscillations for main parameters are obtained by the data acquisition system.

3 Numerical simulation

RELAP5 code is used in this work. It is a light water reactor transient analysis code developed by the U.S. Nuclear Regulatory Commission. In some transient accident conditions, such as LOCA (Loss of Coolant Accident), ATWS (Anticipated Transients without Scram), LOFA (Loss of Flow Accident), RELAP5 has shown a good performance [19] in the simulation.

3.1 Models and options

3.1.1 Hydrodynamic models

A one-dimensional, transient, two-fluid model serves as its hydrodynamic model. The two-fluid nonequilibrium model is based on basic phasic continuity equations, phasic momentum equations, and phasic energy equations.

1) Mass continuity

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

$$\frac{\partial}{\partial t}(\alpha_l\rho_l)+\frac{1}{A}\frac{\partial}{\partial x}(\alpha_l\rho_l v_l A)=\Gamma_l \tag{2}$$

2) Momentum conservation

$$\begin{aligned}&\alpha_g\rho_g A\frac{\partial v_g}{\partial t}+\frac{1}{2}\alpha_g\rho_g A\frac{\partial v_g^2}{\partial x}\\&=-\alpha_g A\frac{\partial P}{\partial x}+\alpha_g\rho_g B_x A-(\alpha_g\rho_g A)FWG(v_g)+\Gamma_g A(v_{gI}-v_g)\\&-(\alpha_g\rho_g A)FIG(v_g-v_l)-C\alpha_g\alpha_l\rho_m A[\frac{\partial(v_g-v_l)}{\partial t}+v_l\frac{\partial v_g}{\partial x}-v_g\frac{\partial v_l}{\partial x}]\end{aligned} \tag{4}$$

$$\begin{aligned}&\alpha_l\rho_l A\frac{\partial v_l}{\partial t}+\frac{1}{2}\alpha_l\rho_l A\frac{\partial v_l^2}{\partial x}\\&=-\alpha_l A\frac{\partial P}{\partial x}+\alpha_l\rho_l B_x A-(\alpha_l\rho_l A)FWF(v_l)-\Gamma_g A(v_{lI}-v_l)\\&-(\alpha_l\rho_l A)FIF(v_l-v_g)-C\alpha_l\alpha_g\rho_m A[\frac{\partial(v_l-v_g)}{\partial t}+v_g\frac{\partial v_l}{\partial x}-v_l\frac{\partial v_g}{\partial x}]\end{aligned} \tag{5}$$

3) Energy conservation

$$\begin{aligned}&\frac{\partial}{\partial t}(\alpha_g\rho_g U_g)+\frac{1}{A}\frac{\partial}{\partial x}(\alpha_g\rho_g U_g v_g A)\\&=-P\frac{\partial\alpha_g}{\partial t}-\frac{P}{A}\frac{\partial}{\partial x}(\alpha_g v_g A)+Q_{wg}+Q_{ig}+\Gamma_{ig}h_g^*+\Gamma_w h_g^{'}+DISS_g\end{aligned} \tag{6}$$

$$\begin{aligned}&\frac{\partial}{\partial t}(\alpha_l\rho_l U_l)+\frac{1}{A}\frac{\partial}{\partial x}(\alpha_l\rho_l U_l v_l A)\\&=-P\frac{\partial\alpha_l}{\partial t}-\frac{P}{A}\frac{\partial}{\partial x}(\alpha_l v_l A)+Q_{wl}+Q_{il}+\Gamma_{ig}h_l^*+\Gamma_w h_l^{'}+DISS_l\end{aligned} \tag{7}$$

3.1.2 Energy partition and assumptions

It is worth mentioning that heat transfer terms nearby wall region and bulk interface are treated separately in the code. Figure 2 provides an overview of the energy transfer in RELAP5. The energy partitioning shows the relationship in different energy exchange terms.

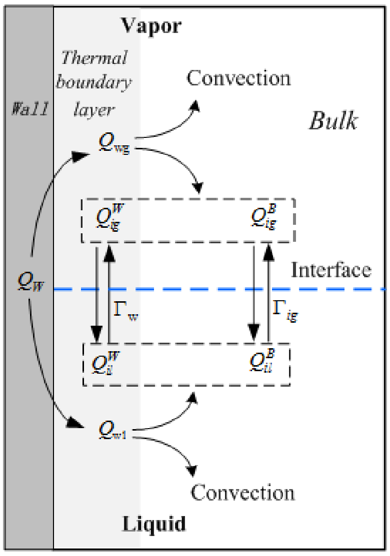


Fig.2 Energy partitioning in RELAP5.

In Eqs. (6) and (7), the last five terms represent wall heat transfer (Q_{wg}, Q_{wl}), interfacial heat transfer (Q_{ig},Q_{il}), interfacial latent heat in the bulk, interfacial latent heat near the wall and dissipation terms. The term Q_w is the sum of Q_{wg} and Q_{wl}. The mass transfer terms associated with bulk energy exchange(Γ_{ig}) and wall energy exchange(Γ_w) are related to the phasic continuity equations by

$$\Gamma_g = \Gamma_{ig} + \Gamma_{wg} \tag{8}$$

$$\Gamma_l + \Gamma_g = 0 \tag{9}$$

Meanwhile, there are some assumptions in the energy processing. The interface contains no mass and energy storage. It is applicable for both near wall interface and bulk interface heat transfer terms. It means that,

1) The summation of total interface transfer terms is zero.

2) The interface energy exchange terms of near wall and bulk are zero respectively.

The assumptions can be summarized by Eq. (10) and Eq. (11) as follow.

$$Q_{ig} + Q_{il} + \Gamma_{ig}(h_g^* + h_l^*) + \Gamma_w(h_g^{'} - h_l^{'}) = 0 \tag{10}$$

$$\begin{aligned} Q_{ig}^{w} + Q_{il}^{w} + \Gamma_w(h_g^{'} - h_l^{'}) = 0 \\ Q_{ig}^{B} + Q_{il}^{B} + \Gamma_{ig}(h_g^* + h_l^*) = 0 \end{aligned} \tag{11}$$

3.2 Nodalization and sensitivity

According to the experiment facility, a simplified natural circulation numerical model is established, which is shown in Fig.3.

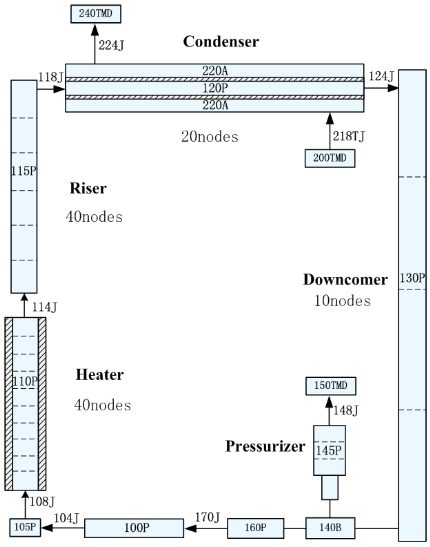


Fig.3 Nodalization for natural circulation loop.

The convergence and accuracy of the RELAP5 two-phase flow model have been investigated since 1991[20]. To solve nodalization sensitivities problems, several models are established, such as Edward's pipe problem. Following these methods, the number of nodes for different components has been checked in this paper. For instance, the value of z/D_H for heated channel ranges from 1.428 to 11.428, which corresponds to the nodes numbers from 10 to 80.

The independency of nodes should be checked at the beginning of each numerical calculation. The main components such as heater, riser, condenser are discussed in detail, while some horizontal pipes are set with coarse nodes. The nodalizations results are shown in Fig.3. Moreover, time step turns out to have an influence on the calculated results, especially for two-phase flow. The time step is set to below 0.0005s, which could solve the sensitivity problems.

4 Step disturbance of power

4.1 Natural circulation transient behaviors

In a nuclear power plant, some unplanned transients may lead to severely abnormal operation conditions. Such serious conditions are considered in the design and operation of a nuclear reactor. A step disturbance of power is a common operating sequence. It occurs more frequently in some accidents such as rod ejection accident, coolant inventory reduction, abnormal insertion of positive reactivity. Moreover, the power may also step during the start-up of a natural circulation BWR, which is in a normal mode.

In the single-phase natural circulation experiment, a designed transient power signal is imported in a steady state. The heating power increases from 6.25kW to 9.59kW in 3.1s. Meanwhile, this process is simulated in RELAP5 code. Figure 4 shows the responses of flowrate with this step power. To compare the variation of mass flowrate, it is set to change at the same time(t=70s). In fact, the power signal is imported at different points (t_{exp}=62.3s, t_{cal}=70.0s). It means that there is a time lag between the power and flowrate in the experiment(τ_1=8.3s). The time delay will be discussed in next section.

It is clear that the system flowrate will undergo two stages, a rapidly increasing process (τ_2=8.9s), a long-term and slowly increasing process (τ_3=60.7s). The calculated result shares high similarity with the experiment. A new steady state is obtained after 69.6s. The new balanced value does not exceed 3.6% of experimental result. The calculated flowrate agrees well with the experimental result.

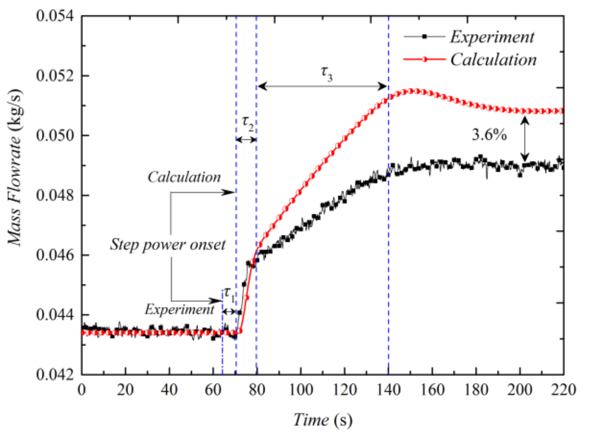


Fig.4 Responses of natural circulation mass flowrate with step power.

In natural circulation, the balance between driving and resisting forces is the primary influence factor of circulation flowrate. In single-phase experiments, the resisting forces changes a little. The total driving force is served as the major factor in analysis. It can be calculated by Eq. (12).

$$F_{total} = g\oint \rho dz = \int_0^H \rho_d gdz - \int_0^H (\rho_h + \rho_r)gdz \quad (12)$$

The driving forces caused by riser and heated channel are given by

$$F_{riser} = \int_0^{L_r} (\rho_d - \rho_r)gdz \quad (13)$$

$$F_{channel} = \int_0^{L_h} (\rho_d - \rho_h)gdz \quad (14)$$

where L_r represents the length of adiabatic riser, L_h is the length of heated channel. On the basis of RELAP5 code, the variation of driving forces is shown in Fig.5.

The process starts from a steady natural circulation state. The step power signal is imported from 70s, which is corresponding to Fig.4. The total driving force also experiences two stages. The flowrate variation could be illustrated by these two periods, which could be seen in Fig.5.

According to Eqs. (13) and (14), driving forces caused by riser and heated channel are discussed separately. As shown in Fig.5(b)~(d), the total driving force is divided into two parts. The fluid in heated section absorbs energy from the wall. The density decreases evidently and gives rise to the increase of circulation flowrate. Hot water flows into riser and heats the fluid in riser slowly. There is no heat source in riser. Moreover, its water inventory is greater than that of heated channel. Thus, it needs a longer time to change the circulation flowrate. The influence of this long-term should not be neglected as shown in Fig.5(b). In the long-term stage (transient stage II), flowrate variation approximately accounts for 60.8% of the total.

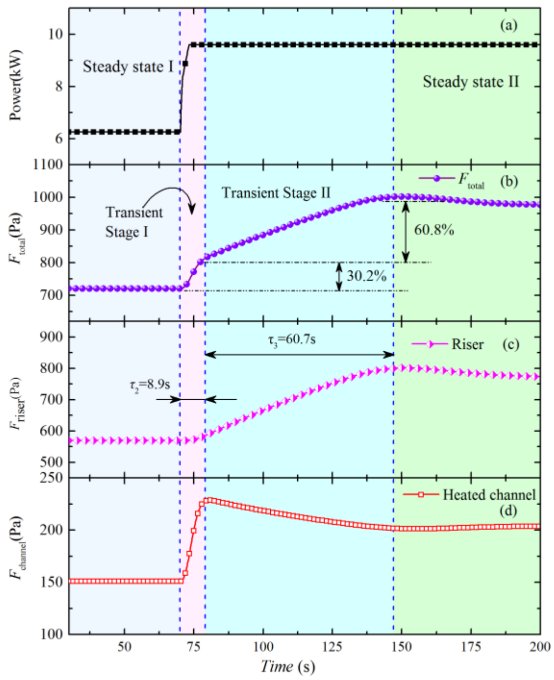


Fig.5 Variation of natural circulation driving forces by RELAP5 code.

Note that the driving force scale in Fig.5(d) is smaller than those in Fig.5(b) and Fig.5(c). The influence of riser is rather important in transient natural circulation. In transient stage II, mass flowrate rises slowly, which caused by fluid in riser. In this stage, a thermal equilibrium is established gradually in heated channel. The average density keeps decreasing with the increasing flowrate. The fluid thermal inertia causes the time lag and the time difference. The driving forces derived from different components are the basic reason of the staged flowrate variation.

4.2 Parameter effect on transient event

A series of transient natural circulation experiments are conducted under low-pressure conditions. As shown in Fig.6, the power changes from the same level with five variation magnitudes. The system keeps operating under single-phase condition even if the heating powers reaches 9.59kW.

The variation of mass flowrates under different conditions is shown in Fig.7, which corresponds to the five conditions in Fig.6. With the increase of heating power, flowrate ascends faster in the transient stage I. Meanwhile, it will take less time in transient stage II when the power or heat flux increases higher. In addition, it is more obvious that natural circulation flowrate variation could be divided into two parts.

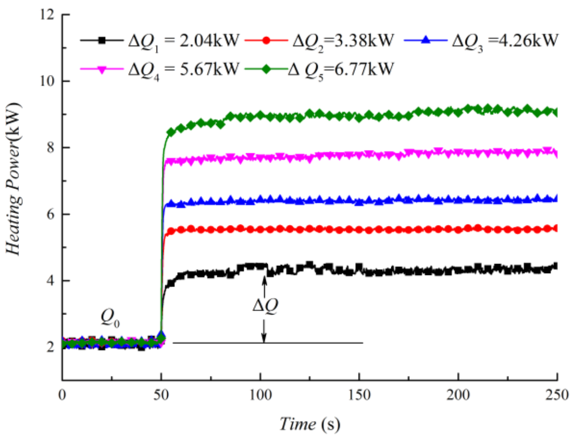


Fig. 6 Power steps with different magnitudes.

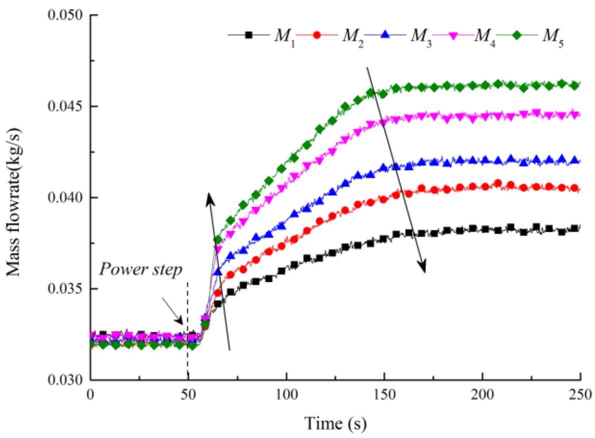


Fig.7 Variation of mass flowrate under different power step signals.

The response of outlet temperature is shown in Fig.8. The temperature overshoot appears when the power variation exceeds 4 kW. In the experiment, the maximum overshoot of outlet temperature is 3.7%. It can be calculated by equation (15).

$$\sigma\% = [T(\max) - T(\infty)] / T(\infty) \times 100\% \qquad (15)$$

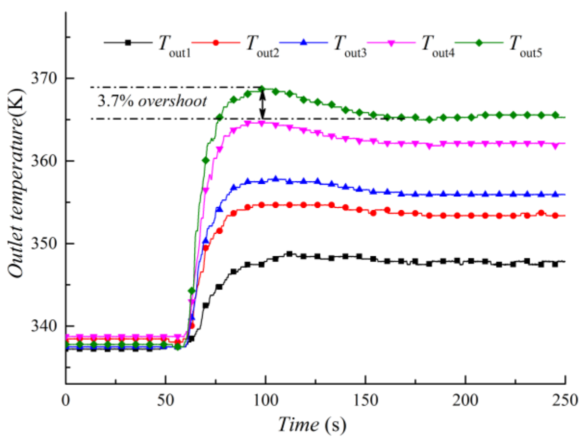


Fig.8 Response of outlet water temperature.

With the variation of power enlarges, the overshoot is more clear. It is because the heat flux rises rapidly in heated channel. The water absorbs larger amount of energy in a short time. The driving force derived from heated channel causes flowrate to arise faster. Thus, outlet temperature is higher when hot water flows through outlet. However, it is an nonequilibrium transient. The new steady temperature is lower than the maximum during this temperature variation.

As mentioned above, time lag is a crucial factor, which appears in the experiment. It is inevitable because the heat exchange needs time. There is a little difference in time lag in these five conditions. In Fig.9, with the increase of variation of heating power (ΔQ), it decreases slightly from 7.5s to 5.6s. It is calculated by time response difference between the input and output parameters, namely power signal and mass flowrate.

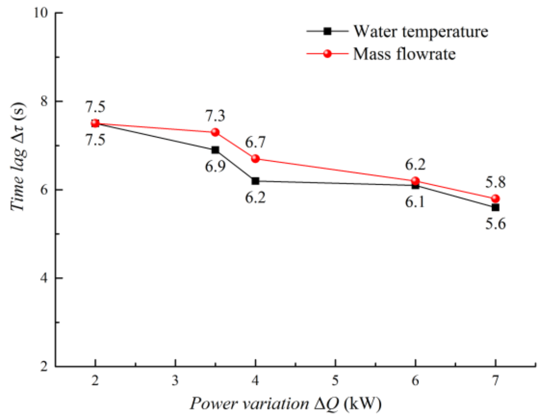


Fig.9 Time lag under different power variation conditions.

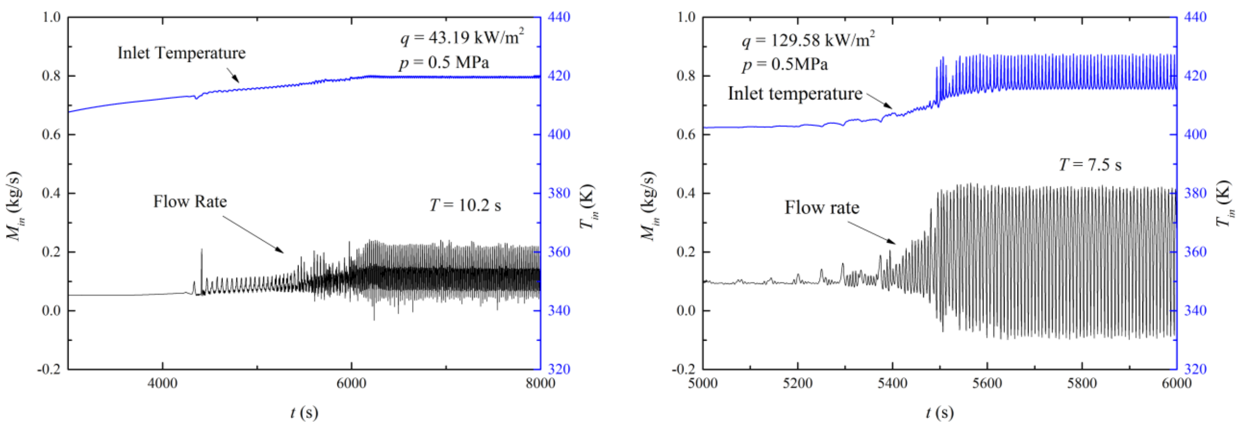
The time lag decreases with the increase of power variation, which is shown in Fig.9. It depends on the material character and fluid thermal properties. If the power increases, the molecules in solid wall generates more energy that derives from electricity. It contributes to conduction and convection between wall and fluid. But this energy exchange needs time to reach a new equilibrium. Therefore, time lag emerges in this transient event. Time lag is a key point in the modeling experiments, especially in the research of nuclear thermal coupling issue. Numerical simulation should take this factor into account according to practical conditions.

5 Flow instability

Flow instabilities always appear in a two-phase flow system [21-22]. Natural circulation flow instability is investigated by experiments and numerical calculations in this paper. It can be regarded as a special transient process.

In the experiment, heating power keeps increasing step by step until flow instability occurs. The boundary conditions such as inlet subcooling, system pressure are invariant. Considering the time lag of thermal parameters, the research emphasis is put on a self-sustained oscillation without power variation. It means that the heat flux will not change if flow instability occurs.

It has been found that the oscillation principles are different under low heat flux and high heat flux conditions. As shown in Fig.10(a) and (b), the higher heat flux is, the greater fluctuation amplitude and higher frequency will be. Inlet temperature is almost constant, *i.e.*, thermal parameter pulsation appears near the outlet. When heat flux is too high, inlet flow reversal may appear. It is a strong instability phenomenon with nonequilibrium but periodic heat exchange.



(a) Low heat flux (b) High heat flux

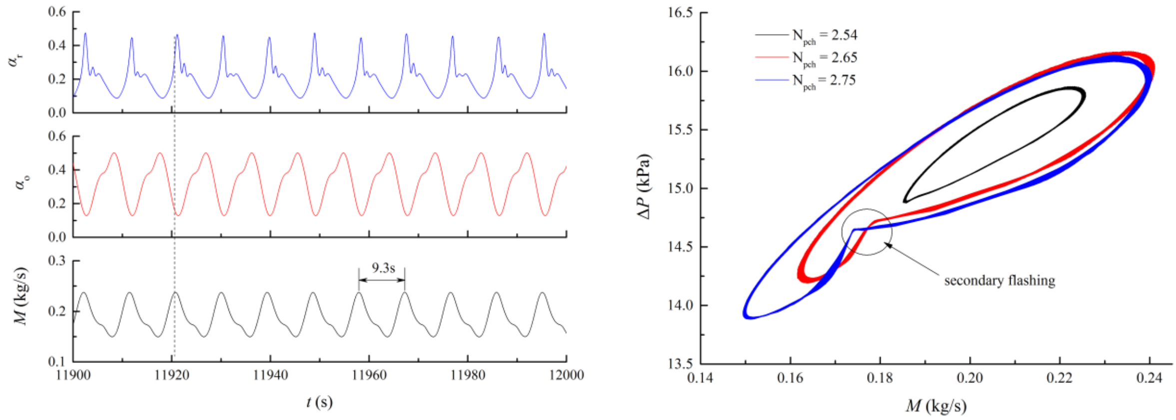
Fig.10 Flow oscillations under different heat fluxes.

5.1 Instability characteristics under low heat flux

An irregular oscillation is obtained under low heat flux condition. The period lasts about 8~11s. This irregular but periodic oscillation is illustrated in Fig.11. When driving force is not enough to offset the large resisting force, circulation flowrate begins to fall. Then the void fraction increases in heated channel as flowrate drops. A mass of gas which is generated by saturated boiling flows into riser. Two-phase flow resistance in riser keeps increasing. It will result in a great pressure drop in riser. The void is generated again if the outlet pressure is below local saturation pressure in riser. It is a secondary flashing, which slows down the flow decrease.

In the phase planes, the characteristic is more clear(Fig.11b). An oblate trajectory of flow rate and pressure drop(ΔP) is achieved. The pressure drop and circulation flowrate present a nonlinear relationship. It has a very similar regular with density wave oscillations. The dimensionless phase change number, which is defined by Ishii, is used in the instability. It could be expressed by Eq. (16). With the increase of phase change number N_{pch} [23], the curve covers a larger area and inner concave comes out. Secondary flashing-induced concave will expand if two-phase flow is stronger.

$$N_{pch} = \frac{Q}{Mh_{fg}} \frac{\rho_f - \rho_g}{\rho_g} \tag{16}$$



(a) Main parameters during flow oscillations

(b) Flow oscillation trajectories in the phase planes

Fig.11 Irregular oscillation under low heat flux condition.

5.2 Instability characteristics under high heat flux

When heat flux is high, the intense oscillation may lead to transient burn-out especially for natural circulation (low flowrate). This hazardous condition must be avoided. Mechanical breakdown caused by fluid shock even results in the release of radioactive materials in a reactor. Under high heat flux conditions, some low-pressure natural circulation experiments are performed(Fig.10b).

Based on RELAP5 code, this extreme condition has been simulated as well. Figure 12 shows the comparison results, which expose a good agreement.

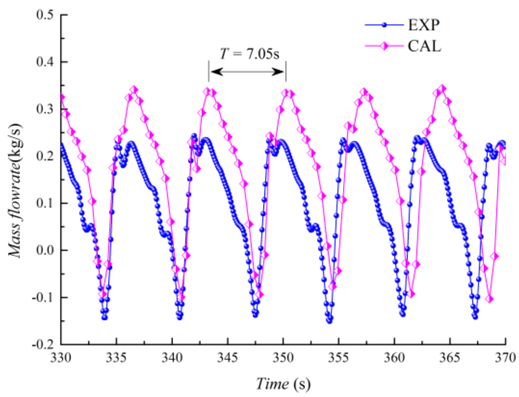


Fig.12 Comparison of experimental and calculation results.

The calculated mass flowrate is higher than experiment data, but they have similar waveforms. Negative flowrate appears during the oscillation. Fluid flows back to the inlet of heated channel and inlet temperature fluctuates(Fig.10b). It is heated again and might lead to wall thermal fatigue. Flow reversal always occurs under high heat flux.

Figure 13 shows the variation of main parameters including outlet void fraction of heated channel($\alpha_{h,out}$) and riser($\alpha_{r,out}$), mass flowrate(M_{in}). Void fraction is calculated by RELAP5 code. Single phase and two-phase fluid flow alternately through the outlet of heated channel. This flow instability occurs under low-pressure and high heat flux condition.

It belongs to a compound dynamic flow instability. It comprises three typical instabilities, including geysering, flashing, boiling instability. Density wave oscillation plays the dominant role. The oscillation period is about 1.5~2 times of fluid transport time [24-25]. In this paper, the calculation of transport time considers both heated channel and riser. The drift velocity, which is put forward by Zuber and Findlay [26], is adopted in two-phase flow in riser.

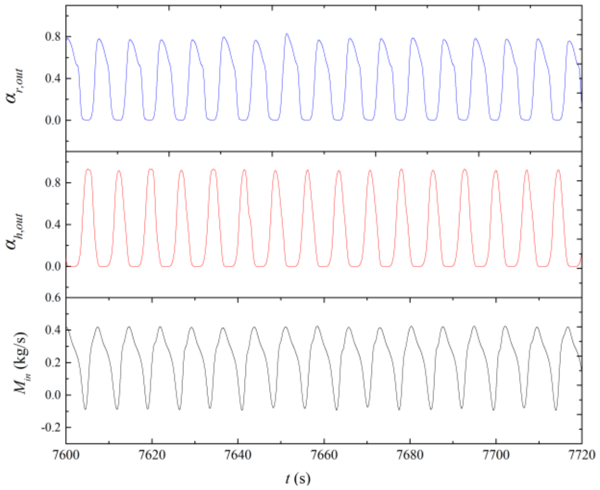


Fig.13 Main parameters during flow oscillations.

It can be concluded that the relation between mass flowrate and outlet void fraction of riser is in-phase. However, it is out-of for flowrate and void fraction of riser outlet. Flashing occurred at the end of adiabatic riser is the main factor according to the variation of void fraction.

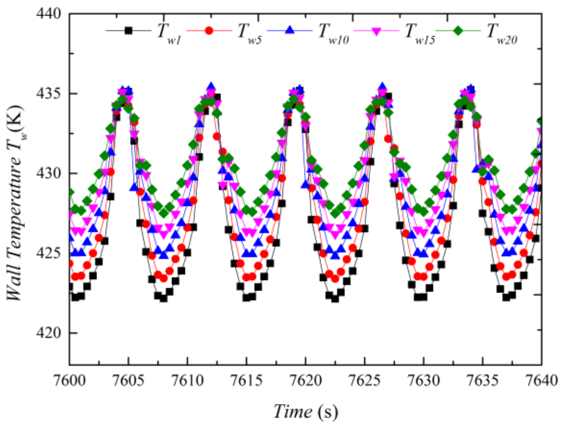


Fig.14 Variation of wall temperature.

During the oscillation, wall temperatures are obtained by the 21 N-type thermocouples. Figure 14 indicates the variation of wall temperature(T_w) at different positions. The inlet temperature(T_{w1}) varies stronger than that of outlet. It is because that two phase boundary moves in a large range when flowrate fluctuates. When wall heat flux is too large, heat transfer deterioration is more likely to cause transien burn-out. In natural circulation experiment, the oscillation might appear when average flowrate is low. A strong vibration always occurs in this condition. It must be avoided in the reactor.

The mechanism is illustrated in Fig.15. Parametric oscillations could be divided into four stages.

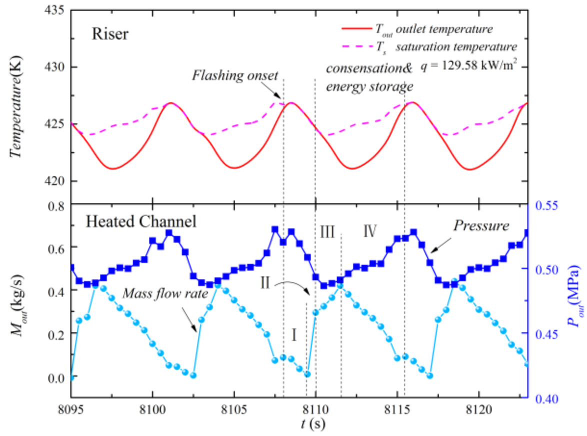


Fig.15 Staged irregular oscillation under high heat flux.

As shown in Fig.15, fluid satisfies flashing occurrence condition firstly at the outlet of riser in stage I. Then outlet pressure of heated channel descends and enhances flashing. The flashing front (onset of flashing) moves towards the inlet of adiabatic riser. In stage II, fluid average density decreases which is caused by flashing. It results in a fact that driving force exceeds loop resistance in a short time. Natural circulation flowrate increases dramatically. However, flashing is suppressed with the increase of flowrate and vanishes finally, which could be seen at the beginning of stage III. Condensation plays a dominant role in this stage. However, the pressure at the outlet of heated channel is low. It will drive flowrate continue increasing slowly. When system flow is large enough, resistance force will exceed driving force. It enters an energy storage state until flashing occurs again (stage IV).

6 Conclusion

Natural circulation transient behaviors are investigated by experiment and numerical method respectively. Two types of experiments are conducted including power step from steady single-phase natural circulation, two-phase flow instabilities. Based on RELAP5 code, the simulations are performed according to these experiments. A series of comparisons are made to validated the code. The mechanism is analyzed by natural circulation equations and numerical calculation results. The following conclusions are obtained.

(1) Natural circulation system will undergo two stages when the heating power steps. The short stage is dominated by heated channel. The long-term stage

relies on the fluid parameters in riser. The driving forces derived from different components are the basic reason of the staged flowrate variation.

(2) RELAP5 code could simulate the transient natural circulation behaviors very well. Time lag is hard for the code in the simulation. The code should be modified according to the practical problems such as the material characters and fluid thermal properties.

(3) Natural circulation flow instabilities present different characteristics under low heat flux and high heat flux. Secondary flashing is more likely to occur under low heat flux condition.

(4) The intense flow oscillations under high heat flux may result in flow reversal. Flashing in the riser plays a dominant role because of its in-phase relationship with flowrate. The instability must be avoided in the design of nuclear power plant.

Nomenclature

A	cross section of flow area
F	driving force
g	acceleration of gravity
H	height of loop
h_{fg}	latent heat
L	length
M	mass flowrate
p	pressure
Q	heating power
q	wall heat flux
T	period, temperature
t	time
U	internal energy
v	velocity
Greek letters	
α	void fraction
ρ	density
σ	overshoot
Γ	volumetric mass exchange rate
Subscripts	
cal	calculation
d	downcomer
exp	experiment
g	gas
h	heated channel
i	interface
in	inlet
l	liquid
out	outlet
r	riser
w	wall

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