Annals of Nuclear Energy 36 (2009) 103–113

Contents lists available at ScienceDirect

Annals of Nuclear Energy

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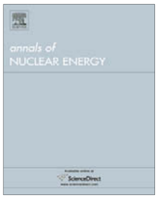

Experimental study on two-phase flow instability of natural circulation under rolling motion condition

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ARTICLE INFO

Article history:
Received 28 February 2008
Received in revised form 2 September 2008
Accepted 30 September 2008
Available online 29 November 2008

ABSTRACT

Two-phase flow instability of natural circulation under a rolling motion condition is experimentally studied. The experimental results show the rolling motion induces a fluid flow fluctuation. At the trough point of the flow fluctuation, rolling motion can cause the early occurrence of natural circulation two-phase flow instability, and this case is defined as trough-type flow oscillation. The system stability decreases with increasing rolling amplitude and effect of rolling frequency is nonlinear. The complex overlap effect of trough-type flow oscillation and density wave oscillation can enhance the system coolant fluctuation; this case is defined as complex flow oscillation. Complex flow oscillation may be divided into two types: regular and irregular complex flow oscillations. Irregular complex flow oscillation is a transition type from trough-type flow oscillation to regular complex flow oscillation. Under the same thermal hydraulic conditions, the marginal stability boundary (MSB) of regular complex flow oscillation is similar to that of density wave oscillation without rolling motion, and the influences of rolling parameters on the MSB are slight.

1. Introduction

As an important heat transfer process, natural circulation has extensive application in nuclear power engineering and other fields (Zvirin, 1981). In-depth study of natural circulation has been carried out for the transfer of heat generated in a core during either normal steady operation or an accident. A nuclear powered ship is often rocked by ocean waves, and thus there are special ship motions. A schematic of ship motion is shown in Fig. 1. If the ship rolls around the axis that is parallel to its cruise direction, the motion is called rolling. The ship motion could introduce an additional acceleration to the ship reactor (Wang et al., 1980). The additional inertia can cause the periodical fluctuation of primary coolant system flow and this destroys system stability.

The study of natural circulation flow instability has been carried out for decades and many achievements have been gotten (Boure et al., 1973; Gonella et al., 2007), however, such study under rolling motion is incomplete. In recent years, several research projects have been conducted for natural circulation under ocean conditions (e.g. Ozoe et al., 1974; Iyori et al., 1987; Murata et al., 1990, 2002; Ishida et al., 1990, 1994; Ishida and Yoritsune, 2002; Gao et al., 1995, 1997, 1999; Su et al., 1996; Kim et al., 2001; Yang et al., 2002a,b; Tan et al., 2005a,b, 2006, 2007; Tan and Gao, 2007). Ozoe et al. (1974), Iyori et al. (1987) and Kim et al. (2001) experimentally studied single-phase natural circulation flow under incline condition and analyzed the effect of incline angle. Murata et al. (1990, 2002), Tan et al. (2005a,b, 2006, 2007) and Tan and Gao (2007) experimentally studied single-phase natural circulation flow and heat transfer under rolling condition and their results showed that coolant mass flow rate changes periodically with the rolling angle due to the inertial force caused by the rolling motion; heat transfer is enhanced because of the internal flow also caused by rolling motion. The similar results were obtained by theoretical studies conducted by Gao et al. (1995, 1997, 1999), Su et al. (1996) and Yang et al. (2002a,b). Ishida and Yoritsune (2002) theoretically studied natural circulation flow instability under a heaving motion condition and the results indicate the overlapping of flow oscillation caused by heaving motion and self-excited oscillation easily result in the system to be more unstable.

However, the research mainly focused on single-phase natural circulation flow, and two-phase flow instability under rolling motion has been studied only by a few researchers. Furthermore, the theoretical studies were mainly carried out by using numerical calculation, and there is a lack of experimental research on two-phase natural circulation flow. The results of single-phase natural circulation flow under ocean conditions show the coolant flow always fluctuates in ocean conditions. As the flow rate varies, characteristics of thermal stability also change, such as the type of flow instability and the marginal stability boundary (MSB). Also two-phase

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doi:10.1016/j.anucene.2008.09.014

Nomenclature

g	gravitational acceleration (m/s^2)
N_{sub}	subcooling number
N_{pch}	phase change number
N_{pch}^{ave}	phase change number based on average mass flow rate
N_{pch}^{mi}	phase change number based on mass flow rate at trough point
P	system pressure (MPa)
Q	heating power (kW)
t	time (s)
t_0	rolling period (s)
T_{in}	inlet temperature of test section (°C)
ΔT_{in}	inlet subcooling of test section (°C)
W_{mi}	mass flow rate at the trough point (kg/s)

Greek letters

α	relative angle between a certain differential element of the loop and the relative horizontal axis (rad)
β	angular acceleration (rad/s^2)
θ	rolling angle (rad)
θ_m	rolling amplitude (rad)
ρ	density (kg/m^3)
$\Delta\rho$	density difference (kg/m^3)

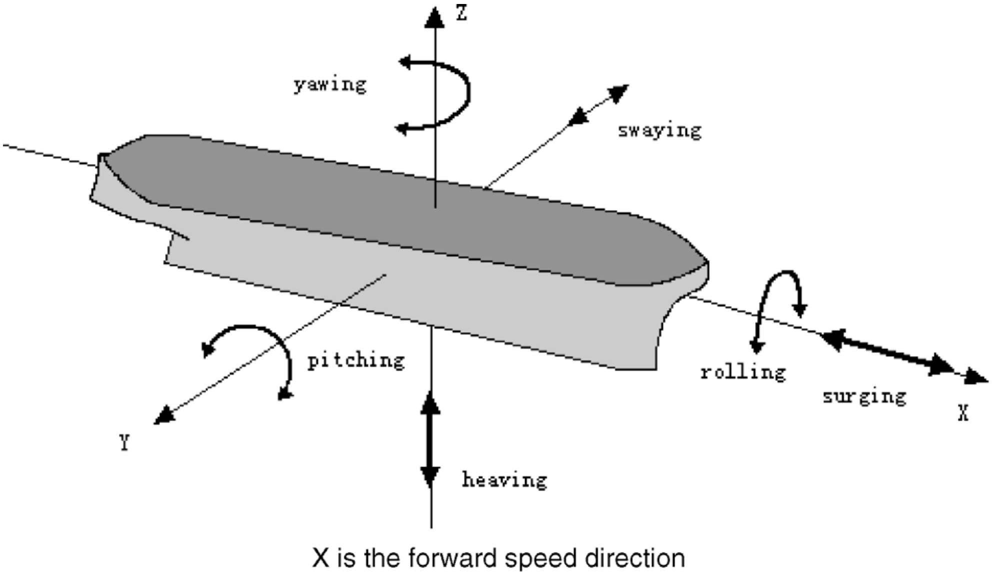


Fig. 1. Ship motions caused by ocean waves.

flow parameters analytical models are obtained based on static coordinate, two-phase flow under rolling motion is more complicated than single-phase flow and it is extremely difficult to describe any characteristics without experimental data. Therefore, experimental study is needed.

Compared with the effects of inclining and heaving motions, that of a rolling motion is more complicated. An inclining motion only result in a change in the effective height of the natural circulation flow; and a heaving motion only introduces an additional acceleration to gravitational acceleration. However, a rolling motion not only changes the effective height, but also introduces centripetal, tangential and Coriolis accelerations.

Therefore, advanced research of natural circulation flow instability under a rolling motion condition is needed. The present study focuses on the two-phase flow instability of natural circulation under a rolling motion condition based on experimental data.

2. Experimental apparatus

2.1. Experimental loop

The three-dimensional experimental apparatus is shown in Figs. 2 and 3. The experimental loop which is mainly symmetrical horizontally is shown in Fig. 4. In simple terms, the experimental apparatus is composed of the pressurizer, coolant pump, condenser, test section and preheater. The working fluid is distilled water.

The fluid is heated in the preheater until its temperature reaches the required inlet temperature of the test section, then it flows into the test section and is further heated. The two-phase mixture is generated in the test section and then flows into the condenser to be cooled, thus the two-phase flow changes into single-phase flow. Finally, the single-phase fluid returns to the preheater.

The pressurizer is a cylindrical vessel with a float level sensor. The system pressure is controlled by filling with nitrogen. Nine electrical heating elements heat the working fluid in the preheater, and the potential difference can be controlled from 0 to 380 V, with a maximum electrical power of 45 kW. The condenser is a shell-and-tube type heat exchanger. The total height of the loop is 3 m and the length is 2.2 m.

The system flow rate is measured by electromagnetic flowmeter and its uncertainty is 0.3%. The fluid temperature is measured by platinum resistance thermometer with uncertainty of 0.5% and the heated wall temperature is measured by thermocouple with uncertainty of 0.5%. The system pressure is measured by pressure sensor with uncertainty of 0.25%.

2.2. Rolling plate

The rolling plate is a 2 m × 2.5 m rectangular plane with a central horizontal axis. The rolling axis is the O–O axis, as shown in Figs. 3 and 5. The plate is horizontal, the test section is vertical and the working fluid flows upward in the non-rolling case. The

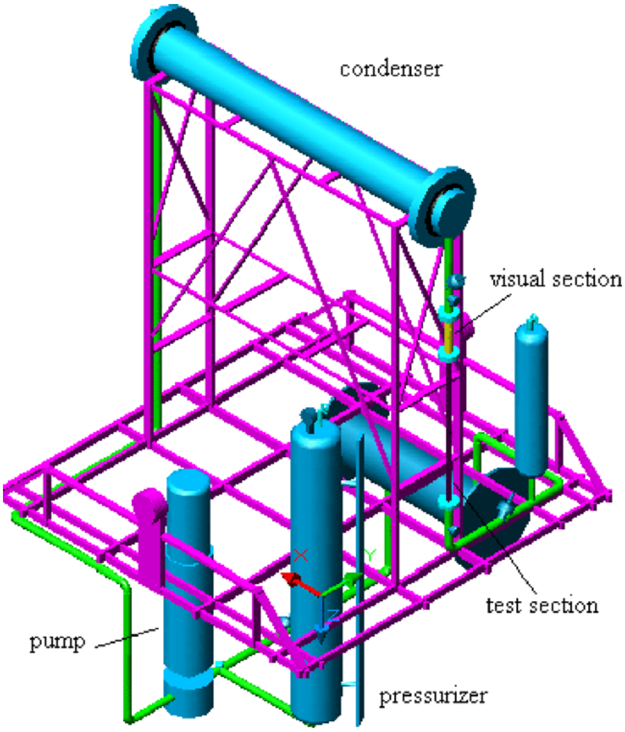


Fig. 2. Experimental equipment.

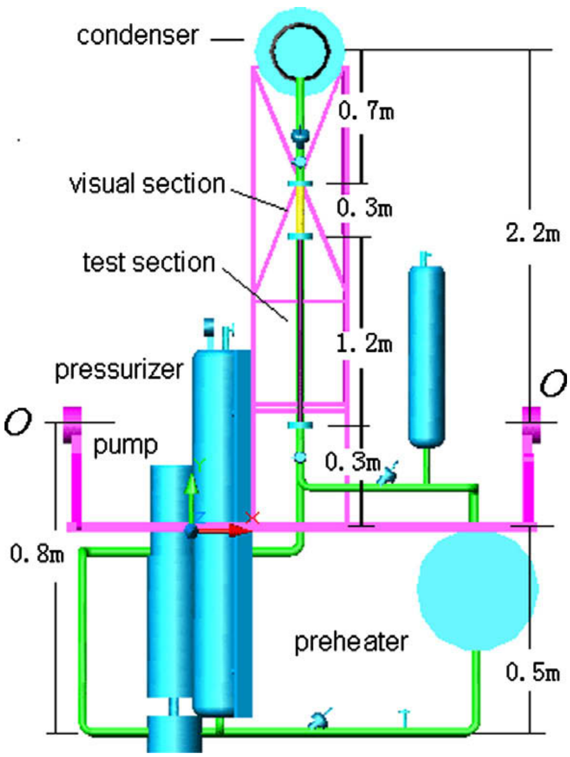


Fig. 3. Side view of experimental equipment.

rolling plate is driven by a crank and rocker mechanism, as shown in Fig. 6. Different rolling amplitudes can be obtained by changing the length of the rocker and linkage. The period of the rolling plate motion can be controlled by changing the frequency of the electromotor. The rolling motion is simulated by a sine wave. The rolling angle is approximated by

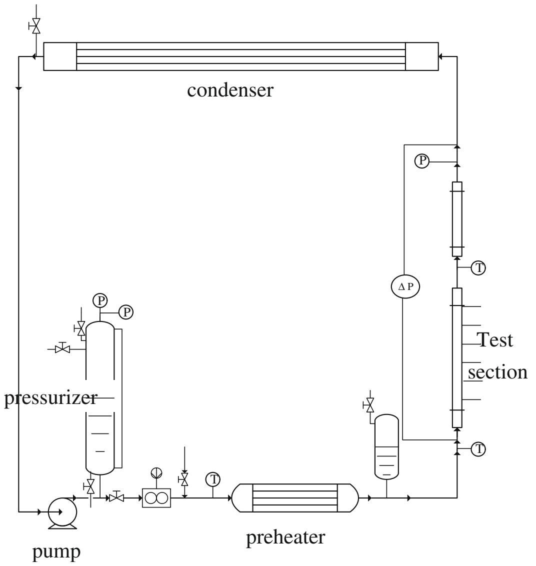


Fig. 4. Schematic diagram of experimental loop.

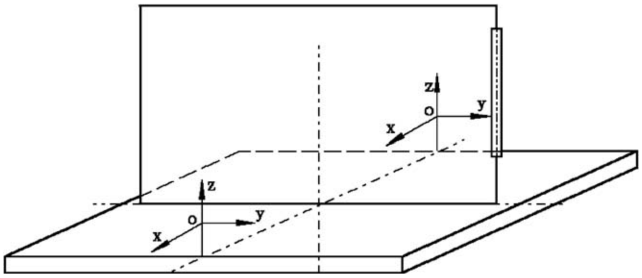


Fig. 5. Schematic rolling facility.

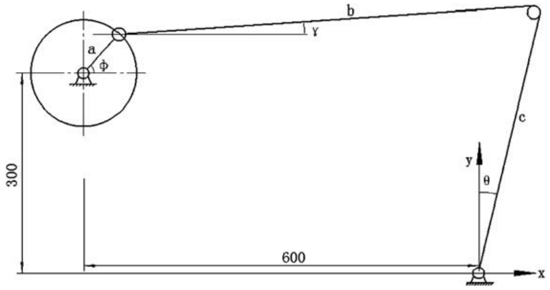


Fig. 6. Crank and rocker mechanism.

$$\theta = \theta_m \sin(2\pi t/t_0) \qquad (1)$$

where θ is the rolling angle in radians; θ_m is the rolling amplitude in radians; t_0 is the rolling period in seconds; and t is time in seconds.

2.3. Test section

The position of the test section is shown in Figs. 3 and 5. The test section is a stainless steel tube ($\varnothing 16 \times 1$ mm) that is directly heated using a DC power supply, and the working fluid flows inside the tube, as shown in Fig. 3. The length of the heated section is 1.2 m. There is a visual section at the outlet of heated section.

The ranges of experimental parameters are as follows: the inlet subcooling is 0–40 °C, the amplitude of rolling is 10°, 15° and 20°, the period of rolling is 5, 7.5, 10 and 12.5 s, and the system pressure is 0.1–0.4 MPa.

3. Experimental results

3.1. Density wave oscillation

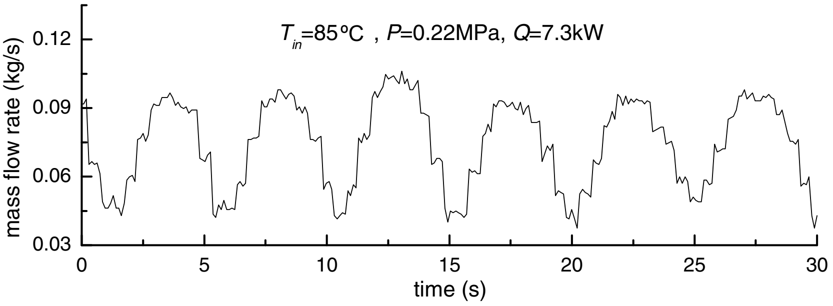
To compare with the phenomenon in the rolling case, experiments for the non-rolling case are carried out and a self-sustained oscillation is observed, as shown in Fig. 7a. This oscillation is a typical density wave oscillation (DWO) which is dominated by the gravitational pressure drop and is called type-I DWO (Fukuda and Kobori, 1979; Su et al., 2002). The oscillation curve agrees with that of such existing experimental results as Furuya et al. (2005) and Watanabe et al. (2008) as shown in Fig. 7b. The frequency of DWO in Fig. 7a is about 0.2 Hz. The frequency may reach at 0.3 Hz if the heating power is suitably increased. In this case, the experimental results are very similar with those presented by Krishnan and Gulshani (1987) and Delmastro et al. (1991). In the case with low inlet subcooling of the test section, the DWO does not occur, the flow is stable, the volumetric quality is high, and the flow pattern is annular.

3.2. Flow instability caused by sudden rolling motion

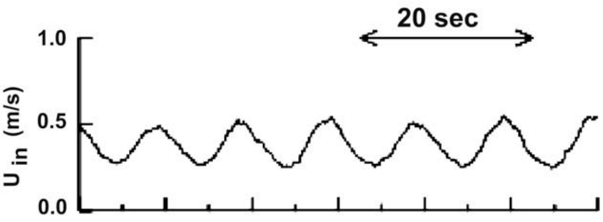
The sudden start of the rolling motion results in a large-amplitude flow fluctuation, such that the instability occurs in the low power case as shown in Fig. 8. In Fig. 8, the rolling motion begins at a time of 16 s, thus there is a jump in the mass flow rate immediately. The wall temperature increases obviously and a vapor bubble can be observed. After the rolling motion has proceeded for several periods, the system gradually becomes a regular single-phase fluctuation and the vapor bubble cannot be observed. The phenomenon is similar to that described by Murata et al. (1990). Because the flow rate varies, the relevant parameters always vary. The stable flow is destroyed by the sudden change in the acceleration caused by the rolling motion. The phenomenon is only observed in the case with short rolling period (5 s) and low inlet subcooling of the test section. When the inlet subcooling of the test section is high or the rolling period is long, this phenomenon cannot be observed.

3.3. Single-phase flow fluctuation caused by rolling motion

The mass flow rate may fluctuate due to the rolling motion and change in accordance with the sine wave as shown in Fig. 9. A vapor bubble cannot be observed. Therefore, the fluctuation is purely caused by the rolling motion, not by variations of thermal parameters. The wall temperature always changes; however, the outlet pressure, outlet temperature and system pressure do not vary obviously.



(a) present experimental result



(b)Watanabe's result (P=0.2MPa, ΔT_{sub}=5K, q=93.1kW/m^2)

Fig. 7. Natural circulation density wave oscillation.

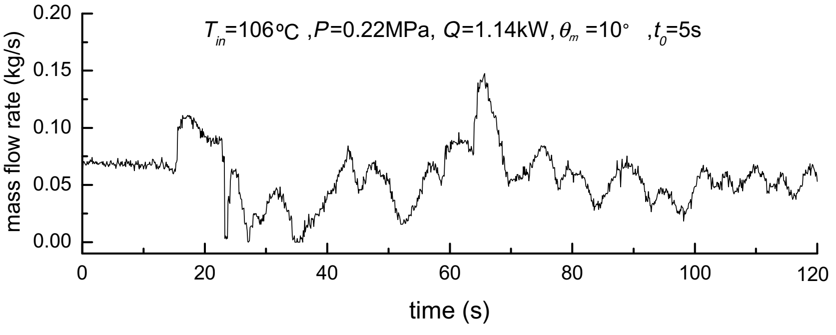


Fig. 8. Flow instability caused by sudden rolling.

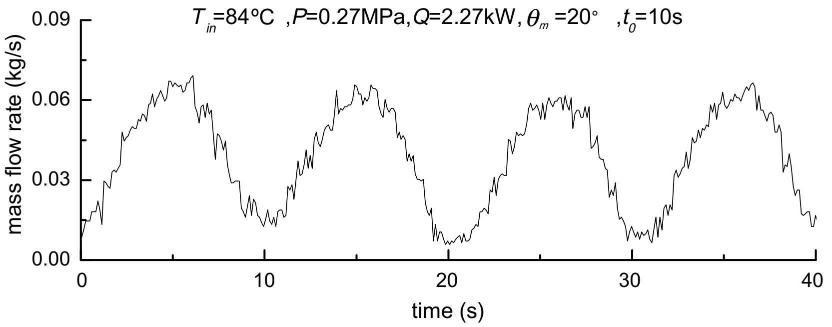
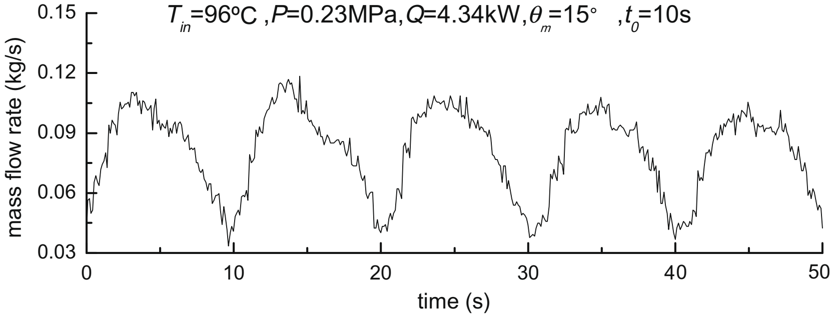


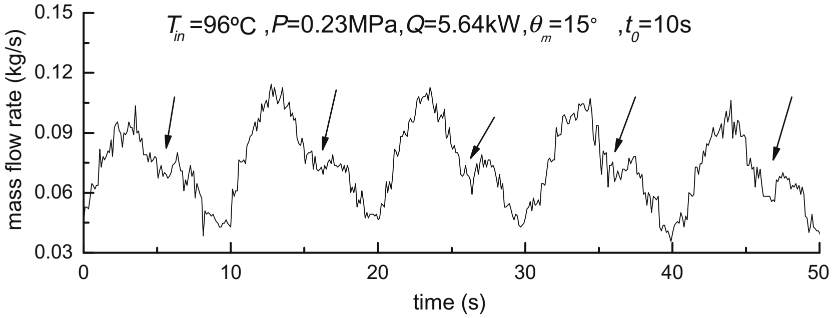
Fig. 9. Single-phase flow fluctuation caused by rolling motion.

3.4. Trough-type flow oscillation caused by rolling motion

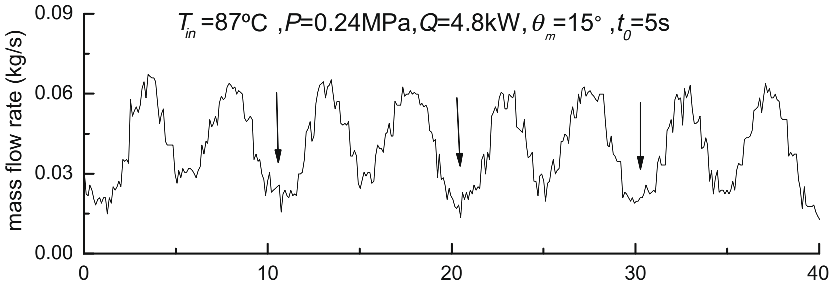
As the heating power increases, vapor bubbles generate when the mass flow rate is at its lowest. However, if the heating power increases sufficiently, more and more vapor bubbles generate immediately while the mass flow rate is at its lowest and liquid–vapor two-phase flow is alternatively observed when the mixture flows through the visual section. The period of vapor bubble generation is the same as the rolling period. This stage can be defined as the onset of flow instability (OFI). Because of the generation of the vapor, the flow resistance increases and the wave for the mass flow rate varies obviously, as shown in Fig. 10a. Flow oscillation caused by the rolling motion only occurs at the trough point of the flow fluctuation, thus it is defined as trough-type flow oscillation. If



(a) Pre-power increase



(b) Post-power increase



(c) Flow oscillation with the period of twice rolling periods

Fig. 10. Flow oscillation caused by rolling motion.

the rolling motion is stopped, the trough-type flow oscillation disappears and the flow becomes single-phase flow. With increasing the power continuously, vapor bubble will generate not only at the trough point but also at other point of the fluctuation curve. Thus there will be another oscillation in small scale during the oscillation of mass flow rate as shown by the arrowheads in Fig. 10b. That is to say, in the case with high power input, the system is easier to become unstable than the case with low power input. However, the mass flow rate at the point where the oscillation in small scale occurs is larger than that at trough point as shown in Fig. 10b, therefore, the effect of this oscillation in small scale is slight.

If the period of rolling motion is short (for example, 5 s) and the power is not sufficiently high, two-phase flow oscillation occurs once every two rolling periods, as shown in Fig. 10c. In Fig. 10c, the trough points marked by arrowheads are in two-phase flow, others are in single-phase flow. That is to say, the single-phase flow fluctuation and trough-type flow oscillation occur in turn when the input power is not high enough. Otherwise, the period of trough-type flow oscillation may be the same as rolling period.

3.5. Overlapping of trough-type flow oscillation and DWO

When the heating power increases sufficiently, the flow oscillation occurs at points of the fluctuation besides the trough point. The onsets (generation positions) of vapor bubbles are not only limited by the flow trough point. The flow oscillations are induced by the overlap of the trough-type flow oscillation which is caused by the rolling motion and the DWO; therefore, it is defined as complex flow oscillation. Complex flow oscillation is only observed in the case with high inlet subcooling of the test section. It can be divided into two types: regular and irregular complex flow oscillations. The complex flow oscillation is irregular initially and then becomes regular state with increasing heating power, as shown in Fig. 11.

If the rolling motion is shut down during regular complex flow oscillation, the flow becomes a DWO; in opposite, under the initial condition of irregular complex flow oscillation, the flow becomes stable two-phase flow; however, in the late case, DWO can be observed with a small increment of heating power. It can be concluded that regular complex flow oscillation cannot be observed under rolling motion without DWO in the non-rolling case with same parameters such as pressure, heat power and inlet temperature; and the irregular complex flow oscillation is a transition process from trough-type flow oscillation to regular complex flow oscillation.

Because the periods of trough-type flow and density wave oscillations are not the same, the period of the flow oscillation with the overlapping effect is neither that of the trough-type flow oscillation nor that of the DWO. The period of the overlapping fluctuation is the lowest common multiple of the periods of the two kinds of oscillations. In Fig. 12a, the rolling period is 10 s, the period of trough-type flow oscillation is 10 s, and that of DWO is 5 s, therefore, the superposition fluctuation period is 10 s. It should be noted that the waveform of trough-type flow oscillation in one period matches together with that of DWO in two periods. In Fig. 12b, the rolling period is 7.5 s, the superposition fluctuation with period of 15 s contains two oscillations: one with period of 5 s and another with period of 10 s. However, the period of the DWO decreases with increasing the heating power. According to the experimental observations, the period of DWO ranges from 3 to 5 s. The relationship between the periods of rolling motion and DWO is listed in Table 1. When the rolling period is 5 s, the period of DWO is also 5 s, the overlapping effect is obvious very much, and the system becomes more unstable.

3.6. High volumetric quality flow with slight amplitude

In the natural circulation flow with low inlet subcooling of the test section, as the heating power increases sufficiently, the overlapping effect weakens and the amplitude is slight, thus the system flow can be considered as having a fluctuation with slight amplitude and be considered stable compared with other cases (Figs. 7–12), as shown in Fig. 13. If the rolling motion is stopped, the flow pattern becomes annular.

From Figs. 9–13, it can be seen that the overlapping effect is influenced by the DWO. When the inlet subcooling is high and heating power is insufficient, no DWO is observed in the non-rolling case and no overlapping phenomenon (only the trough oscillation) can be observed for rolling motion. In addition, in the low inlet subcooling case, the DWO does not occur and the amplitude of the overlap fluctuation is small.

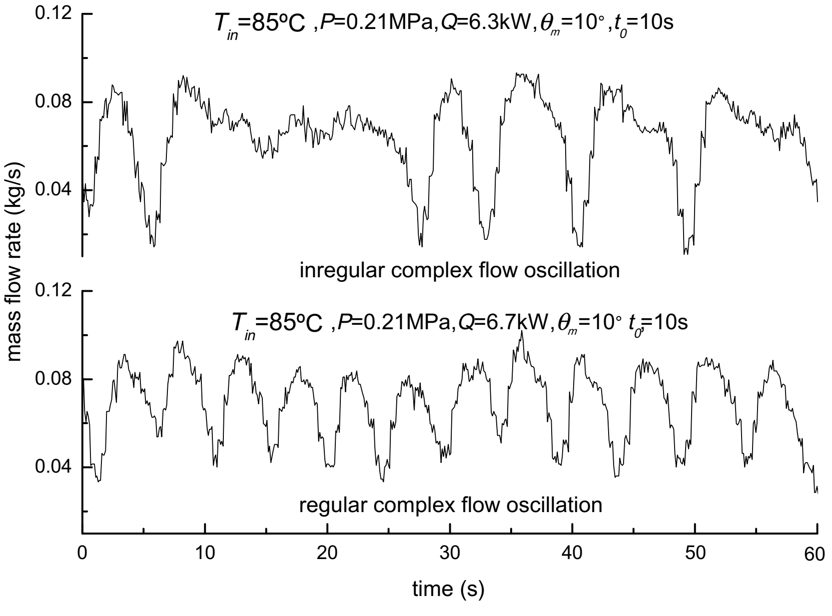
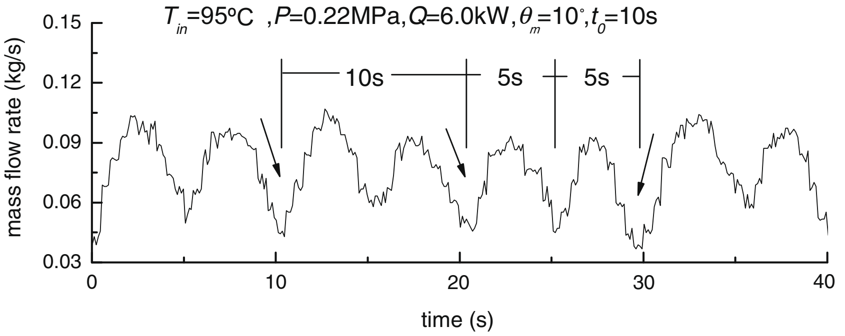
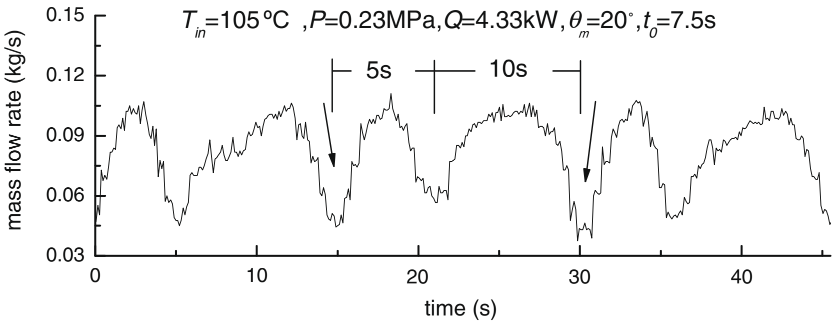


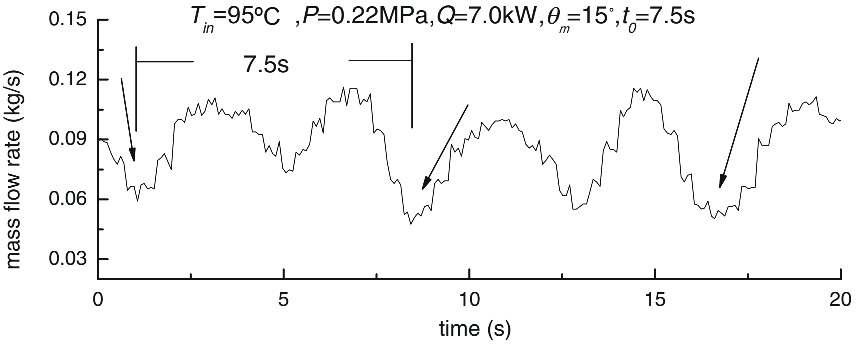
Fig. 11. Complex flow oscillation.



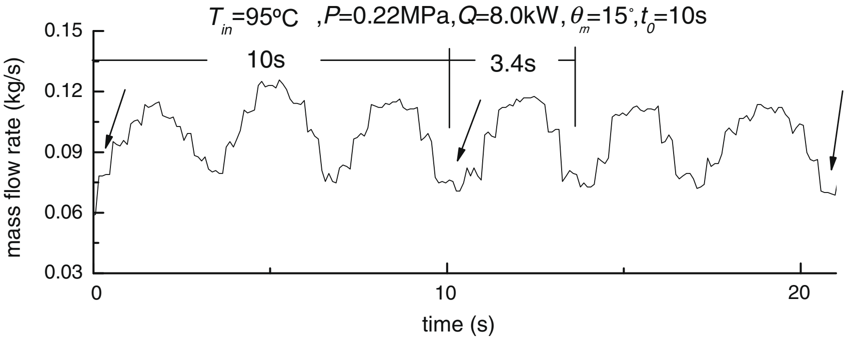
(a) Rolling period 10s



(b) Rolling period 7.5s



(c) Rolling period 7.5s



(d) Rolling period 10s

Fig. 12. Period of complex flow oscillation.

4. Discussion

4.1. Effect of rolling motion

Rolling motion can cause centripetal, tangential and Coriolis accelerations which may introduce additional pressure drop to natural circulation system. However, the Coriolis acceleration is perpendicular to the flow direction and thus it cannot cause any additional pressure drop. Theoretically, due to the centrifugal force, liquid column in the heated section is more easily pushed upward than the vapor phase causing mass flow rate larger than the case without the rolling motion. Unfortunately, the effects of

Table 1
Relationship between the periods of rolling motion and DWO.

DWO			
Period of rolling motion (s)	Number of DWO waveforms in one period of rolling motion	Period of DWO (s)	Note
5	1	5	System is easy to be unstable
7.5	1	5	Period of complex flow oscillation is 15 s (Fig. 12b)
	2	About 3.75	Fig. 12c
10	2 for low heating power	5	Fig. 12a
	3 for high heating power	About 3.4	Fig. 12d
12.5	3	About 4.2	

centripetal acceleration on different parts mostly counteract with each other. The effects of tangential acceleration on different parts can accumulate because the rolling axis is along the center line of the symmetrical loop (Fig. 3). Therefore, angular acceleration is the primary influence of rolling motion on the natural circulation within our experimental system and that is why the flow fluctuation is more like a sine wave.

The driven force of natural circulation is gravitational pressure drop and can be calculated by Eq. (2). The additional pressure drop caused by tangential acceleration can be calculated by Eq. (3):

$$\Delta p_g = \sum \Delta\rho_i g h \tag{2}$$

$$\Delta p_\beta = \sum \rho_i \beta r_i \cos\alpha h_i \tag{3}$$

where β is angular acceleration, α and r are employed to express the relative angle and distance between a certain differential element of the loop and the relative horizontal axis (O–O axis in Fig. 3).

Although the gravitational acceleration is much greater than tangential acceleration considering the density is always greater than density difference, the additional pressure drop has a strong influence on natural circulation flow and may induce additional flow. However, for forced circulation, the driven head is always larger than additional pressure drop. Thus the influence of additional pressure drop is not obvious and the amplitude of flow fluctuation is very small for forced circulation. For natural circulation, the most important influence of rolling motion is flow fluctuation which may induce the natural circulation flow instability early occurring and may affect characteristics of this instability.

4.2. MSB of flow instability

The MSB of flow instability is determined by experimental phenomenon and data. The MSB of the DWO without rolling motion was reported by Su et al. (2002).

In the rolling motion case, vapor bubbles generate firstly at the trough point of the flow fluctuation. This case has two effects: (a) The fluid density difference increases, then the driven head increases. Therefore, the mass flow rate at the trough point (denoted as W_{mi}) increases. (b) The two-phase flow frictional resistance also increases. However, if the heating power increases slightly, more vapor bubbles generate, and the second effect is larger than the first one. Thus, W_{mi} decreases, more and more vapor bubbles generate, and trough-type oscillation occurs.

The characteristic mass flow rates at the onset point of trough-type oscillation are the average mass flow rate and W_{mi} of pre-oscillation (just before oscillation occurs), and the characteristic heating power is the heating power of post-oscillation (just after oscillation occurs). Therefore, for a given fluctuation of mass flow rate and a given heating power, one can distinguish whether or not the trough-type oscillation occurs.

Based on the experimental data of OFI (Fig. 14) without rolling motion, an empirical correlation of the MSB of the DWO may be achieved:

$$N_{\text{sub}} = 1.223 N_{\text{pch}} \tag{4}$$

where N_{sub} is the subcooling number, $= \left(\frac{h-h_{\text{in}}}{h_{fg}}\right)\frac{v_{fg}}{v_f}$ and N_{pch} is the phase change number, $= \frac{Q}{Wh_{fg}}\frac{v_{fg}}{v_f}$ .The relative error is lower than 12.5%, as shown in Fig. 15.

An empirical correlation of the MSB of the trough-type oscillation under a rolling motion condition is also achieved. In the rolling case, the trough-type oscillation occurs at the trough point of flow fluctuation, the effect of the mass flow rate at trough point can not be neglected, thus following correlation may be obtained:

$$N_{\text{sub}} = 10.2327 + 1.3404 N_{\text{pch}}^{\text{ave}} - 0.0053 N_{\text{pch}}^{mi} \tag{5}$$

where $N_{\text{pch}}^{\text{ave}}$ and N_{pch}^{mi} are the phase change numbers based on the average flow rate and W_{mi}, respectively. The relatively error is lower than 20%, as shown in Fig. 15. Considering the coefficients in Eq. (5), the effect of the average flow rate is larger than that of W_{mi}.

It can be concluded from comparing Eq. (4) with Eq. (5) that the rolling motion causes earlier occurrence of flow instability under the same thermal parameters.

MSBs of flow instability under a rolling motion condition are shown in Fig. 16. MSBs of flow instability in Fig. 16a are described by heating power, and those in Fig. 16b are described by dimensionless number $N_{\text{pch}}/N_{\text{sub}}$, where N_{pch} under rolling motion is based on the average flow rate. The stable region under the rolling motion condition is made up of two parts. The first stable region

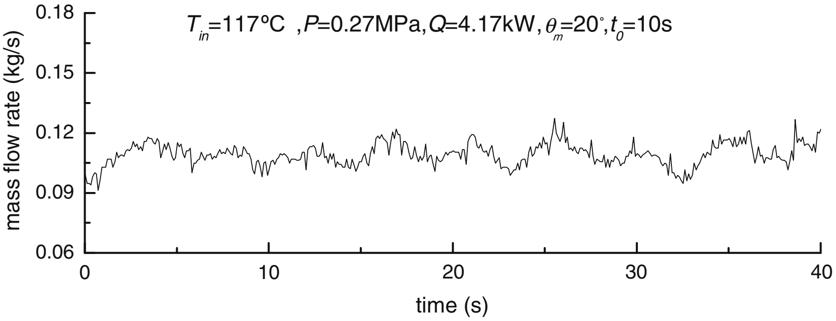


Fig. 13. High volumetric quality stable flow.

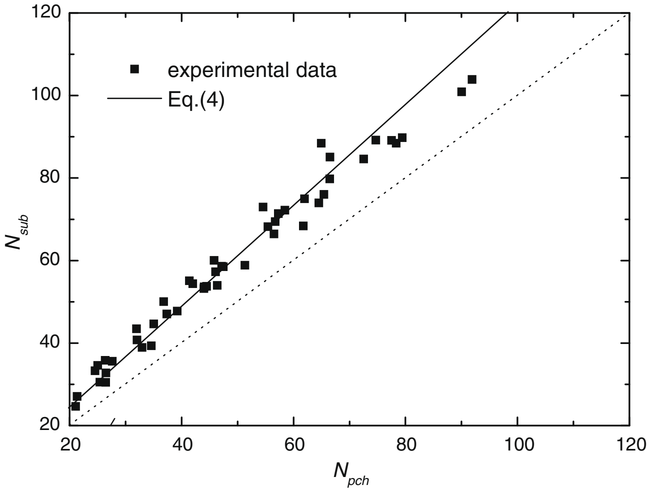


Fig. 14. Calculated MSB of density wave oscillation.

corresponds to single-phase flow or two-phase flow with low vapor volumetric quality. When the rolling motion is stopped, the flow becomes single-phase flow. The second stable region corresponds to the high volumetric quality two-phase flow with slight amplitude. When the rolling motion is stopped, the flow becomes annular two-phase flow. The unstable region lies between these two stable regions. It can be predicted that these two stable boundaries will meet if the inlet subcooling continues to decrease.

The unstable region can be divided into two parts: (a) when the inlet subcooling of the test section is low, the complex flow oscillation cannot be observed, and (b) when the inlet subcooling of the test section is high, the complex flow oscillation can be observed. In this case, the complex flow oscillation can also be divided into two types: regular and irregular complex flow oscillations. Under the same thermal hydraulic conditions, the MSB of regular complex flow oscillation is similar to that of DWO without rolling motion.

It is also seen that the fluctuation caused by rolling motion exacerbates the system instability, and decreases the power of the OFI by 30–45%.

4.3. Effect of rolling parameters on flow instability

Effects of rolling amplitude and period on trough-type flow oscillation are shown in Fig. 17. The power at the OFI decreases

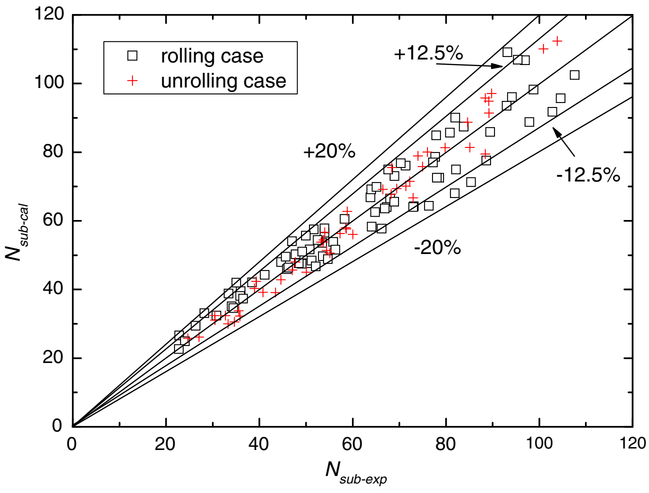
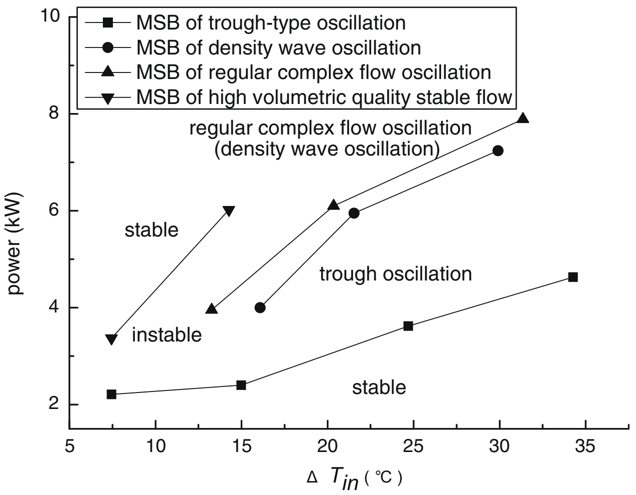
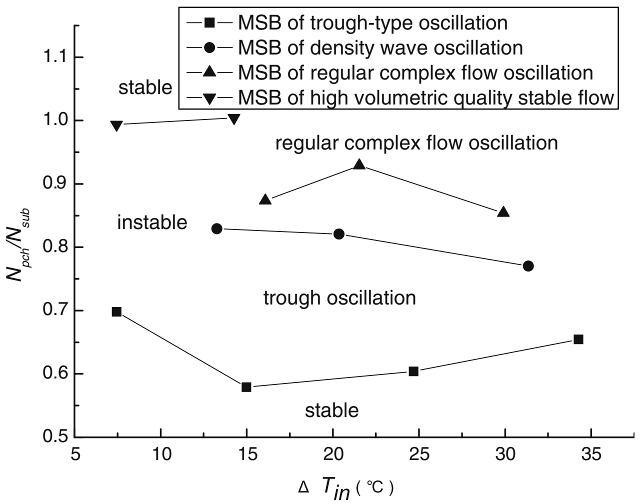


Fig. 15. Calculated MSB of trough-type oscillation and density wave oscillation.



(a) Power



(b) N_{pch} / N_{sub}

Fig. 16. MSB of flow instability under rolling motion condition.

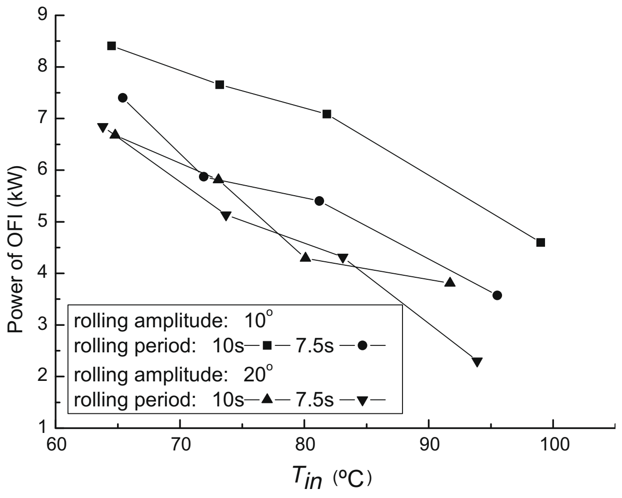


Fig. 17. Effects of rolling parameters on trough-type oscillation.

with increasing rolling amplitude. This is because the amplitude of the fluctuation increases with increasing rolling amplitude (Tan et al., 2005). Additionally, the mass flow rate is lower at the trough point; therefore, the trough-type flow oscillation occurs more easily. The effect of rolling period is nonlinear, the power at the OFI decreases with increasing rolling frequency in many cases, however, the difference between the periods of 7.5 and 10 s is not obvious when rolling amplitude is large (20°) or system pressure is low (0.22 MPa). Furthermore, the effect of the rolling period is more obvious when the rolling amplitude is smaller.

The effect of system pressure on the power at the OFI is shown in Fig. 18. The system stability increases with increasing pressure because the saturated temperature increases and vapor bubbles are difficult to occur. The effect of the rolling period is more obvious when the system pressure is higher.

Comparisons between OFI powers of DWO and those of regular complex flow oscillation with different rolling parameters are shown in Fig. 19. Considering the relative error, the OFI of DWO can be considered the same as that of regular complex flow oscillation. The influences of rolling amplitude and rolling period on the MSB are slight.

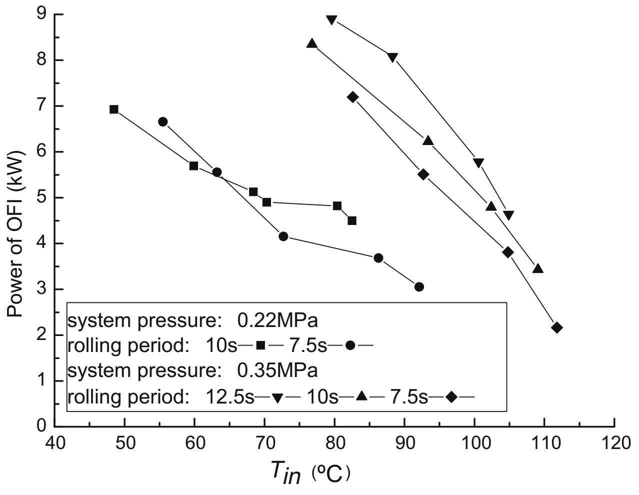


Fig. 18. Effects of system pressure on flow instability.

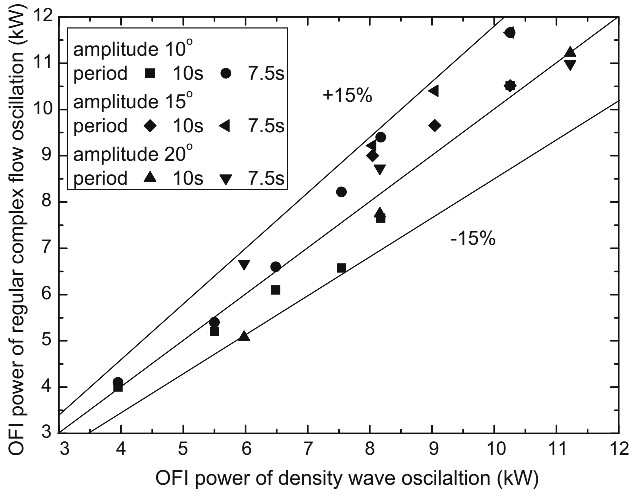


Fig. 19. Onset of density wave oscillation and complex flow oscillation.

5. Conclusions

An experimental study of two-phase flow instability of natural circulation is conducted and the following conclusions are obtained.

Rolling motion can cause the early OFI of natural circulation and change the types of flow instability, for example, to trough-type flow oscillation or complex flow oscillation. Rolling motion decreases the system stability of natural circulation, and the system stability decreases with increasing rolling amplitude and effect of rolling frequency is nonlinear. Complex flow oscillation is formed by the overlap effect of the rolling motion (trough-type oscillation) and DWO. The system becomes more instable because of the occurrence of complex flow oscillation. Complex flow oscillation only occurs in the case with high inlet subcooling, and can be divided into two types: regular and irregular complex flow oscillations. Under the same thermal hydraulic conditions, the MSB of regular complex flow oscillation is similar to that of DWO without rolling motion. The influences of rolling amplitude and rolling period on the MSB are slight.

Acknowledgements

This work is supported by the China Postdoctoral Science Foundation (No. 20060401002) and National Natural Science Foundation of China (No. 50806014) and supported by the Program for New Century Excellent Talents in University (NCET-06-0837).

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