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Original Article

Effect of heat flux on temperature oscillation for two-phase natural circulation in a rectangular loop

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Abstract

The temperature oscillation of the heated water at the atmospheric pressure in the test loop where the ability to remove the heat was limited had been investigated. The flow instabilities were also visually observed. The results obtained from the study suggested that there were two frequencies for the temperature oscillation, which were affected by the heat flux applied to the system. By FFT analysis, these two major frequencies temperature oscillation were then identified. For the higher heat flux, the low frequency for the temperature oscillation was resulted since the hot water spilt into the condenser section. On the other hand, only the high frequency temperature oscillation next to the location of the heater section was then observed if the heat flux was low.

Keywords: temperature oscillation, flow instability, rectangular natural circulation loop, two-phase flow, Fast Fourier Transform (FFT)

1. Introduction

The two-phase natural circulation systems have found their places in many of the modern nuclear reactor designs and industrial processes because they possess three important features: passiveness, economics, and simplicity. The systems' passive nature allows less usage of valves and pumps for flow regulation. The production cost can therefore be reduced and become more economical, whereas the maintenances are generally simpler in comparison to the conventional active systems. In addition, the risk of failures associated with the usages of valves and pumps is also decreased. However, there can be the drawbacks for the system. Of a particular concern is the occurrence of various types of instabilities which can occur in the flow and thus prevent the two-phase natural circulation systems from being effectively implemented. The sources of the instabilities can be varied depending upon the systems' geometries and the operating conditions. These can cause the problems to the system operation and control and may reduce the thermal margin (Nayak, Dubey, Chavan, & Vijayan, 2007).

Both the theoretical and experimental studies have been conducted in order to understand the nature and the characteristics of various types of instabilities that occur in the natural circulation system (Fukuda & Kobori, 1979; Manera, Rohde, Prasser, & Van Der Hagen, 2005; Nayak, Vijayan, Saha, Venkat Raj, & Aritomi, 2000; Song, 2012; Yun *et al*., 2005). The scale-test facilities have been built to investigate these flow instabilities (Furuya, Inada, & Van Der Hagen, 2005; Jiang, Zhang, Wu, Bo, & Jia, 2000; Kuran *et al*., 2006). The results obtained from these facilities are mostly relevant to the problem in which they are designed to simulate and can be readily used for assessing the flow behavior in such problem. However, the construction and the operation costs of these facilities are expensive due to their sizes and complexities. Alternately, a simple circulation loop can also be employed for the study (Chiang, Aritomi, Inoue, & Mori, 1994; Guanghui, Dounan, Fukuda, & Yujun, 2002; Suxia, 2009; Watanabe, Aritomi, & Kikura, 2008). For the fundamental study, this has an

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advantage over the scale-test facilities because of its simplicity, its low cost, and the adaptability for various configurations, especially on heating and cooling abilities.

One of the main interests in the study of the flow instability is the temperature oscillation. Such oscillation can generate significant thermal stress which can seriously compromise the structural integrity of the cooling system. This research attempted to investigate the temperature oscillation characteristics in a natural circulation loop where the ability to remove the heat from the system was limited. Such condition is expected in the event such as that of the ultimate loss of heat sink in a boiling water reactor (BWR). The experiment was performed using the small size rectangular natural circulation loop facility under various heating powers. The measured temperatures at the heater and condenser outlets were then analyzed by FFT method. The obtained experimental and analytical results provided the generic understanding of the event where as the data regarding the temperature oscillation in the natural circulation loop with the limited capability of heat sink can be used for further study. The images of the flow under the different unstable boiling conditions associated with the temperature oscillations were also recorded.

2. Materials and Methods

2.1 Experimental setup

A rectangular natural circulation loop was designed and constructed at the Department of Nuclear Engineering, Faculty of Engineering, Chulalongkorn University, Thailand, to study the natural flow occurred during the single and the two-phase natural circulation conditions. A schematic diagram of the rectangular test loop was as shown in Figure 1 and some of its parameters were also presented in Table 1. The test loop consisted of a vertical heating section, a riser, a condenser section and a downcomer section.

The vertical heating section was set at the bottom part of the riser. It was a glass tube with the inner diameter of 22 mm. This was chosen in order to allow for the visual observation and for the photography. In this section, a stainless steel heating rod with the diameter of 16 mm, the length of 750 mm and the maximum heating power of 3 kW, was installed at the bottom and along the vertical axis of the riser. The width of the gap between the heating rod and the glass tube was therefore 3.0 mm. At the top of the riser, an expansion tank with the inner diameter of 47 mm and the length of 200 mm was installed to allow for the expansion of the heated water. At the bottom of the expansion tank, there was also a glass tube that connected to the downcomer so that the water could flow from the riser to the downcomer directly. At the top of the expansion tank where the steam would flow separately from the water, it was connected to the downcomer via the condenser. The condenser was a tube-in-tube type with the cooling water flowing in the annulus between the inner copper tube and the outer polyvinyl chloride (PVC) tube. The outer diameter of the copper tube was 28.5 mm and the inner diameter of the PVC tube was 50 mm. The downcomer section was made of a copper tube with the inner diameter of 26 mm. At the bottom of the test loop, the downcomer was bended horizontally to connect with the heating section of the riser.

For the test loop, the sections containing the glass tubes were un-insulated to allow for the visual observation of the flow. The entire loop was in thermal contact with the atmosphere and was subjected to the heat loss to the ambient environment.

A total of 6 thermocouples were installed to measure the temperatures. Two thermocouples were placed across the condenser (T1 and T2). One was placed at middle of the downcomer (T3). Two were placed across the heater (T4 and T5) and the last one was put at the riser outlet (T6). The type-K bare wire butt-welded thermocouples with the diameter of 0.5 mm were selected for the measurement due to its fast response time. The uncertainty of the temperature measurement was within ±1 °C. The data were acquired and stored in a computer via the RS-232 interface as a text file. Two piezo-resistive pressure transducers were also installed to measure the gauge pressure levels at the heater outlet (P2) and at middle of the lower horizontal tube (P1). The heating rod was controlled by a slide regulator. The heating power was calculated from the electric current and voltage as measured by a digital AC ammeter and a voltmeter (Carlo Gavazzi, type DI3-72 AV5) respectively. The photographs of the bubbles at the middle of the riser were taken by a single-lens reflex (SLR) camera (Cannon EOS 550 D). The photographs were taken at the speed of 3 frames per second. Two 36 W fluorescent lamps were used as the light source for the photograph.

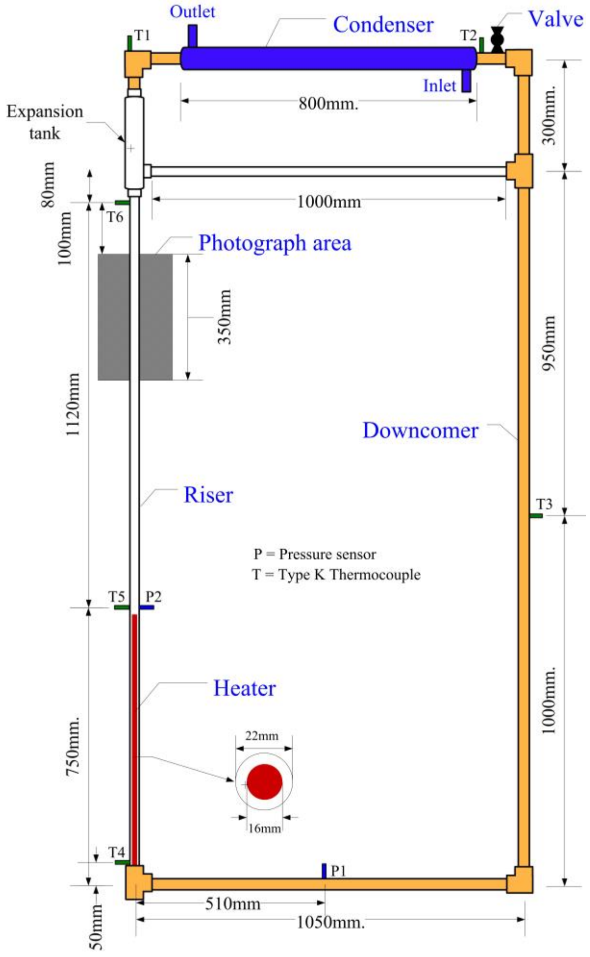

Figure 1. Schematic diagram of the rectangular test loop.

Table 1. System and geometry parameters.

Items	Values
Working fluid	Water
Maximum heating power (kW)	3
System pressure (MPa)	0.1
Heater section	
Heating rod	
Material	Stainless steel
Length (mm)	800
Outer diameter (mm)	16
Glass tube	
Inner diameter (mm)	22
Riser section	
Material	Glass
Length (mm)	1,120
Inner diameter (mm)	22
Downcomer section	
Material	Copper
Length (mm)	1,950
Inner diameter (mm)	26
Horizontal (Connecting tube)	
Lower	
Material	Copper
Length (mm)	1,050
Inner diameter (mm)	26
Upper	
Material	Glass
Length (mm)	1,050
Inner diameter (mm)	22
Condenser (Tube-in-tube type)	
Length (mm)	800
Outer diameter of copper tube (mm)	28.5
Inner diameter of PVC (mm)	50
Hydraulic diameter (mm)	21.5
Expansion tank	
Material	Glass
Length (mm)	200
Inner diameter (mm)	47

2.2 Experimental procedure

The water was chosen as the working fluid in order to reduce the possible side effects related to the different fluid properties so that the results would be relevant to that of a nuclear power plant (Lanz, Alobaid, & Epple, 2016). The challenges of using the water working fluid over refrigerants were the higher saturating temperature at the atmosphere pressure and the larger liquid/vapor density ratio which could result in the more susceptibility to instability (Lachner, Nellis, & Reindl, 2004; Zhang *et al*., 2011).

The test loop was filled with the water up to just cover the second horizontal tube, the tube below the tube connected to the condenser. To remove the gases dissolved in the water, the water in the test loop was pre-heated to just below the boiling temperature and then it was left simmering until the time of the experiment. The flow rate of cooling water (tap water) in the condenser was fixed at 8 liter per minute.

The single and two-phase natural circulation experiments were carried out in this loop at several heating power levels. The heating power was maintained at a constant level during the entire duration of an experiment. At the beginning of each experiment, before switching on the heating power, the system temperature was checked for uniformity and compared with the ambient temperature. The temperatures and pressures were recorded at every second. The experiment data were recorded until the steady flow behavior was observed.

3. Results and Discussion

3.1 The rectangular test loop characteristics

A total of 13 experiments were performed at various heat fluxes ranging from 13.9 - 39.0 kW/m^2. The results from two heat flux levels at 17.1 and 34.3 kW/m^2 are discussed here in this section as they represented the different temperature and pressure profile characteristics.

With the heat flux set at 17.1 kW/m^2, it was observed that the water at the heater outlet had achieved boiling, Figure 2(a). Overall, the water and the steam in the system were essentially saturated and the flow in the test loop was of the two phase flow, at least in the riser section (to be discussed in Flow visualization section). The temperature at the heater inlet (T4) at the steady state was just below the boiling point. Since the temperature at the condenser inlet (T1) was significantly increased but the temperature at condenser outlet (T2) was not much increased, this suggested that the condenser had performed well in condensing the steam. The profiles as shown in Figure 2(b) showed the fluctuation in the pressure levels at the heater inlet (P1) and heater outlet (P2), especially at time about 4,000 s after the turning on of the heater. At such time, the temperature at the heater outlet (T5) had reached the boiling point and the fluctuation of the pressure levels suggested that the boiling pattern had become fully developed.

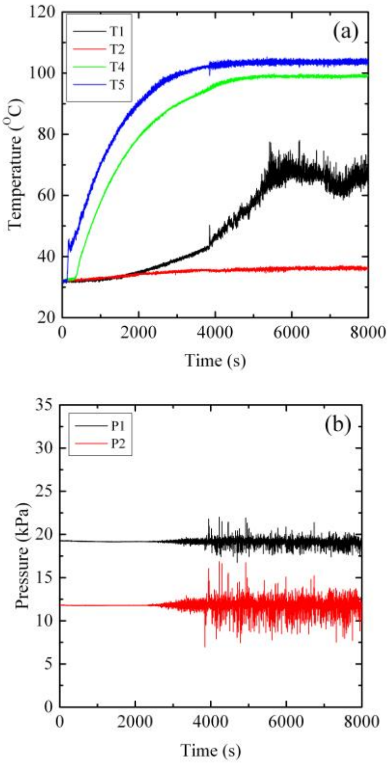

Figure 2. Temperature (a) and pressure (b) profiles at 17.1 kW/m^2 heat flux.

As the heat flux was increased to 34.3 kW/m^2, the steady state temperature at the heater inlet (T4) was observed to be periodically fluctuated near the boiling point. Similarly, the periodical fluctuations in temperatures were also observed at the heater outlet (T5) and also at the condenser inlet (T1) and outlet (T2). Profiles as shown in Figure 3(b) showed the same fluctuations in the pressure levels as observed in the case of the 17.1 kW/m^2 heat flux but with the higher magnitudes. For the fluctuation in the temperatures, it was visually observed that the boiling was very strong such that some of the water was spilt into the tube connecting to the condenser. Since the thermocouple was generally more sensitive to the liquid phase more than the vapor phase, the temperature measured at such point was actually the temperature of the spilt water. Therefore fluctuation of the temperatures was actually due to the presence of the spilt water in the condenser.

As seen in Figure 2(a) and 3(a), according to the temperature profiles measured at the heater outlet (T5), it was generally observed that when the heater was turned on, the temperature at the heater outlet was suddenly and sharply increased. This was because the water in the heating section had initially absorbed the heat from the heater whereas the flow had not been established. The natural circulation flow was soon initiated since the buoyancy force due to the density gradient at the heater outlet had become greater than the overall friction. With the flow established, the temperature at the heater outlet was then slightly decreased as the colder, unheated water then flowed into the heating section to replace the heated water. The temperatures at other locations (T1, T2, T4, and T5) were then gradually increased. It should be noted that the fluctuated temperature observed at the heater outlet was due to the turbulent caused by the flow from the small channel to the larger channel.

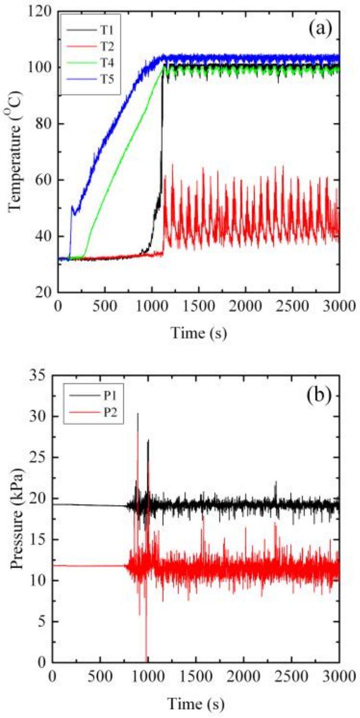

Figure 3. Temperature (a) and pressure (b) profiles at 34.3 kW/m^2 heat flux.

3.2 Temperature oscillations characteristics

From the study, after the flow had been fully developed, the temperature oscillations were observed and measured at various points on the test loop. Two types of the temperature oscillations could be generally identified; a high frequency observable at the heater outlet (T5) and a low frequency observable at the condenser outlet (T2). As shown in Figure 4 and 5, for heat flux level of 19.8 kW/m^2 and the heat flux level of 34.3 kW/m^2, the high frequency temperature oscillations were clearly identified from the profiles obtained at the heater outlet (T5) and at the condenser inlet (T1). The low frequency temperature oscillation, however, was only identified at the condenser outlet (T2) and the heater inlet (T4) in the case of heat flux level of 34.3 kW/m^2.

In order to analyze the frequency of temperature oscillations, the Fast Fourier Transform Analysis (FFTs) over the temperature oscillations were performed by MATLAB. The temperature oscillations at the heater outlet (T5) and the condenser outlet (T2) were selected for the analysis because the heater and the condenser were the major driving mechanisms

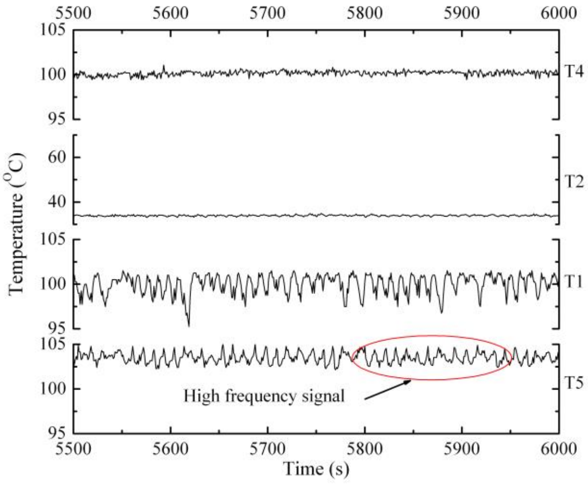

Figure 4. Temperature oscillations at 19.8 kW/m^2 heat flux.

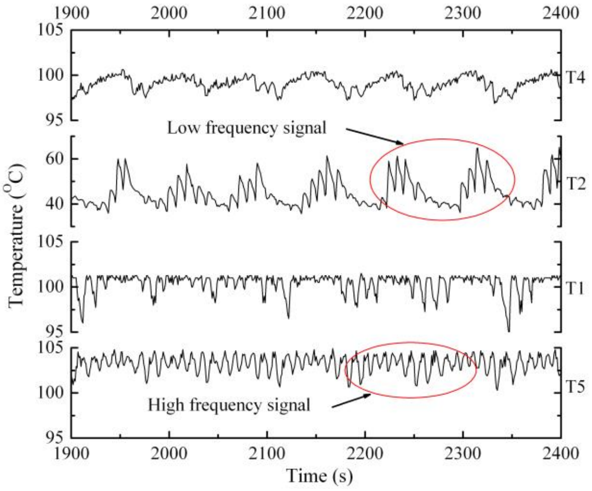

Figure 5. Temperature oscillations at 34.3 kW/m^2 heat flux.

for the temperature oscillations in the system. The FFT profiles of the temperature oscillations at the heater outlet (T5) and the condenser outlet (T2) for 19.8 kW/m^2 heat fluxes were as shown in Figure 6. According to the analysis, only one major frequency of 0.089 Hz was identified. Similarly, the FFT profiles of the temperature oscillations at the heater outlet (T5) and at the condenser outlet (T2) for 34.3 kW/m^2 heat fluxes were obtained as shown in Figure 7. For this case, the temperature oscillation frequency of 0.013 Hz was identified at the condenser outlet (T2) whereas the frequencies of 0.013 and 0.099 Hz were identified at the heater outlet (T5).

In the case of the lower heat flux (19.8 kW/m^2), it was expected that the temperature oscillation would have occurred with only one frequency as the oscillation was driven mainly by the heating mechanism. At the higher heat flux (34.3 kW/m^2), the oscillations were driven by the heating of the water and the cooling of the spilt water due to the condenser. By comparing with the case of the lower heat flux, it was considered that the high frequency was due to the heating process where as the low frequency was due to the cooling of the spilt water by the condenser.

Further FFT analyses were conducted on the other 12 tests. Due to the small values of obtained frequencies, it was considered more convenient to represent the results by the periods, which were essentially the inverse of the frequencies. For the low frequencies or the large period of the temperature oscillation, the results could only be obtained from 8 tests with the heat fluxes from 22.9 kW/m^2 or higher as shown in Figure 8. For the high frequencies or the small periods of the temperature oscillation, the results could be obtained from all 12 heat fluxes as displayed in Figure 9.

It was clear that the periods of the temperature oscillations became small (frequency getting high) as the heat flux was increased and that the small oscillation period (high frequency) was always observed as long as there was a boiling. However, the large oscillation period (low frequency) would only be observed with the strong boiling. The magnitude of the temperature oscillation might not represent any significant meaning as it might only be unique to the current system configuration. However, the transition in the oscillation period as the heat flux was increased at around 22 kW/m^2 was unique and this deserved to be further studied.

3.3 Flow visualization and instability mechanism

To better understand the temperature oscillation characteristic and its mechanism, the two phase flow at various heat fluxes were observed and the images of the bubbles formations were recorded at the riser. The examples of such records were displayed in Figure 10 and 11. It was generally seen that the two phase flow began with the formation of the very fine bubbles. The bubbles then rose upward, transformed and terminated their rising at the expansion tank. In such case, the heat content was transferred to the water in the riser. The size of the heat flux could affect this pattern by accelerating the process, magnifying the formation of the bubble or collapsing them into the churn flows as shown in Figure 10 and 11.

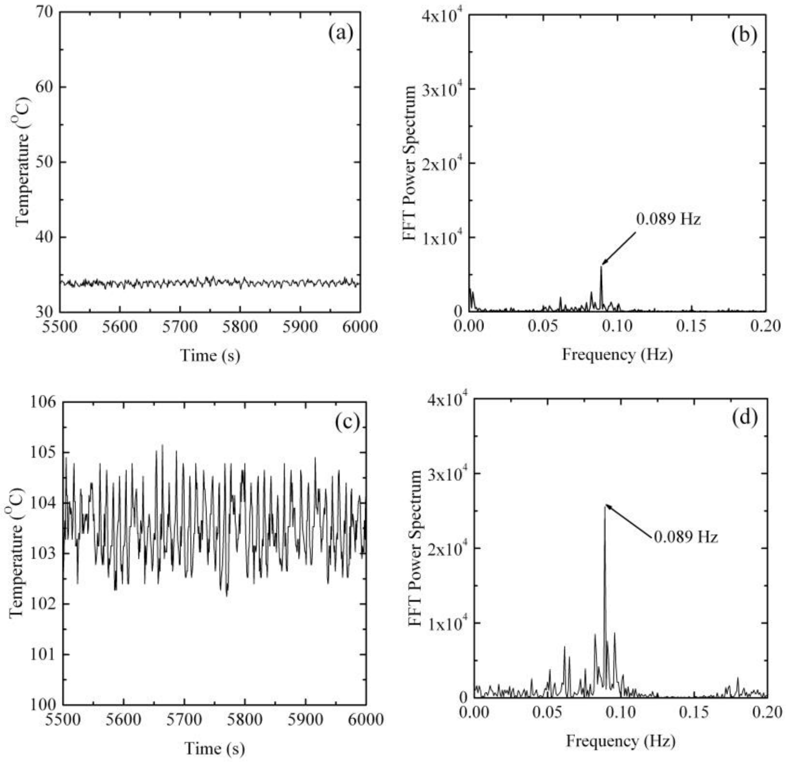

Figure 6. Temperature oscillation at 19.8 kW/m^2 heat flux: (a) temperature and (b) FFT power spectrum at condenser outlet (T2), (c) temperature and (d) FFT power spectrum at heater outlet (T5).

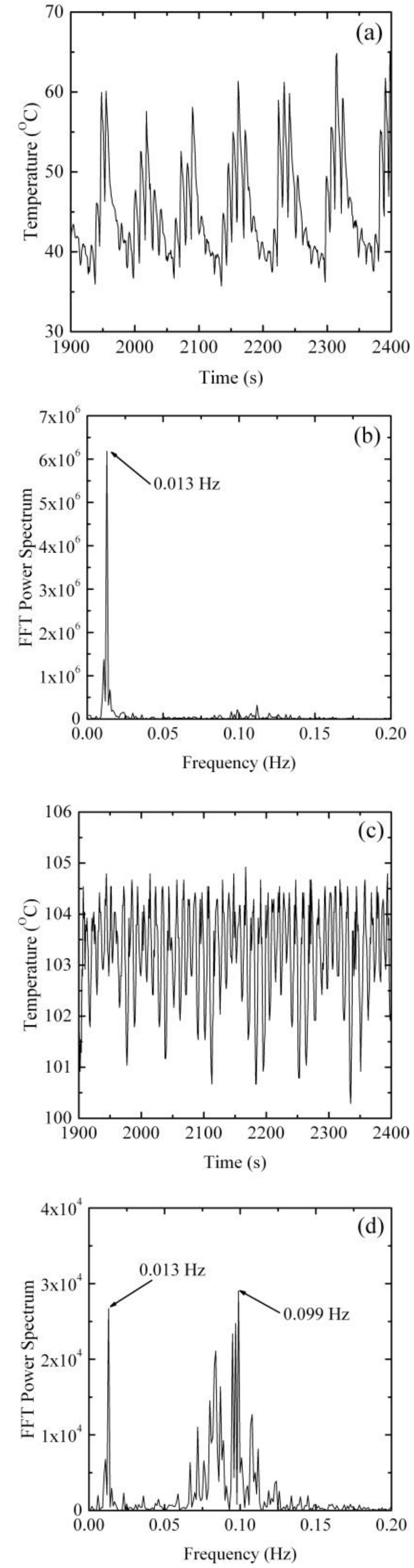

Figure 7. Temperature oscillation at 34.3 kW/m^2 heat flux: (a) temperature and (b) FFT power spectrum at condenser outlet (T2), (c) temperature and (d) FFT power spectrum at heater outlet (T5).

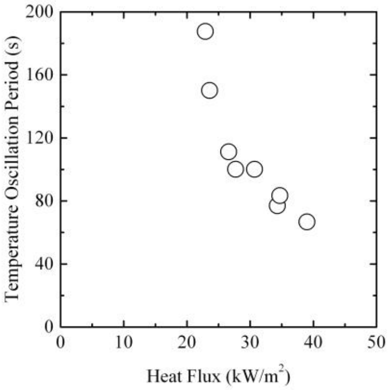

Figure 8. Large temperature oscillation period (low frequency) as the function of the heat fluxes, data obtained at the condenser outlet (T2).

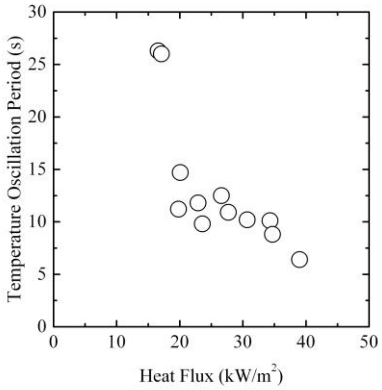

Figure 9. Small temperature oscillation period (high frequency) as the function of the heat fluxes, data obtained at the heater outlet (T5).

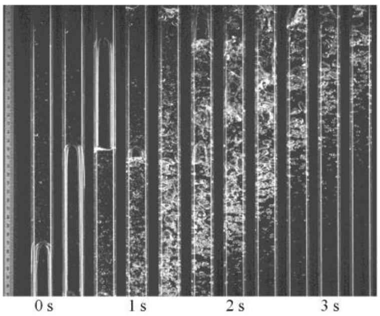

Figure 10. Flow instability images recorded at 20.1 kW/m^2 heat flux.

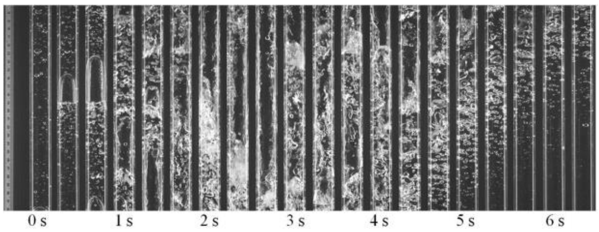

Figure 11. Flow instability images recorded at 39.0 kW/m^2 heat flux.

The observed flow was similar to the process of flashing-induced density wave oscillations as described by Furuya *et al*. (2005). In order to verify that the observed temperature oscillation in this rectangular loop design was driven by the similar mechanism, the stability map between the inlet subcooling and the heat flux was thus explored. The non-dimensional inlet subcooling, N_{sub}, was described as

$$N_{sub} = \frac{C_{pl}\Delta T_{sub}}{h_{gl}}\left(\frac{\rho_l}{\rho_g} - 1\right), \qquad (1)$$

Where C_{pl} was the heat capacity of liquid, ΔT_{sub} was the degree of subcooling, h_{gl} was the latent heat and ρ_l/ρ_g was the liquid to vapor density ratio.

Based on the parameters for the designed rectangular loop, the ΔT_{sub} was calculated to be a constant value of 10. When the heat fluxes used in this study were mapped together with the stability map by Furuya *et al*. (2005), as shown in Figure 12, it was seen that increasing the heat flux would shift the system into the instability region. Interestingly, the boundary between the stable and the unstable region occurred at about 20 kW/m^2, which was corresponding to the transition slope observed in temperature oscillation period of about 22 kW/m^2. It would thus be concluded that the effect of the heat flux on the temperature oscillation for the two phase natural circulation in this rectangular flow loop was possibly driven by the same mechanism as that of the flashing-induced density wave oscillations.

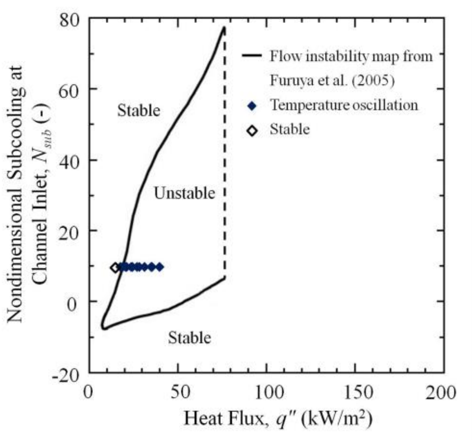

Figure 12. Temperature oscillation characteristic of rectangular loop from this study plotted against stability map proposed by Furuya *et al.* (2005) at 0.1 MPa.

4. Conclusions

In this study, the temperature oscillation in the rectangular natural circulation loop had been experimentally investigated and analyzed. The results were summarized as follows: (1) By the initial analyses of the obtained results on the fluctuation of the temperatures under various levels of the heat flux, there were evidences suggesting that the oscillations occurred at the specific frequencies depending primarily on the size of the heat flux. (2) By conducting the FFT analysis, two major frequencies for the temperature oscillation were identified. If the heat flux was just enough to cause the boiling, only one frequency would be resulted. If the heat flux was very strong such that the boiling caused the hot water to spill into the condenser section, it would cause the temperature to also oscillate at the low frequency. The details regarding the mechanism which affected these phenomena might be of interest for further study as the observed transition in the oscillation period with increasing heat flux was considered unique and deserved further study. (3) Flow instabilities were visually observed. The formations of the bubbly, slug and churn flows were identified. The effect of the size of the heat flux was postulated. The further study on the flow pattern in the test loop as affected by other parameters might be of interest.

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