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Thermal-Hydraulic Oscillations in a Low Pressure Two-Phase Natural Circulation Loop at Low Powers and High Inlet Subcoolings

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Abstract

The stability of a natural circulation boiling loop is of great importance and interests for both academic researches and many industrial applications, such as next generation boiling water reactors. The present study investigated the thermal-hydraulic oscillation behavior in a low pressure two-phase natural circulation loop at low powers and high inlet subcoolings. The experiments were conducted at atmospheric pressure with heating power ranging from 4 to 8 kW and inlet subcooling ranging from 27 to 75℃. Significant oscillations in loop mass flow rate, pressure drop in each section, and heated wall and fluid temperatures are present for all the cases studied here. The oscillation is typically quasi-periodic and with flow reversal with magnitudes smaller than forward flows. The magnitude of wall temperature oscillation could be as high as 60℃, which will be of serious concern for practical applications. It is found that the first fundamental oscillation (large magnitude oscillation) frequency increases with increase in heated power and with decrease in inlet subcooling.

1. Introduction

The stability of a natural circulation boiling loop is of great importance and interest for both academic researches and many industrial applications, such as next generation boiling water reactors. The natural circulation has been proposed as the major heat transfer mode for the next generation boiling water reactor under both normal and abnormal conditions.

Several earlier experimental studies had explored the stability characteristics of a two-phase natural circulaltion loop. Wissler et al.[1] studied periodic oscillations of the flow rate and fluid temperature in a two-phase natural circulation loop. Jain et al.[2] studied the self-sustained hydrodynamic oscillations in a high pressure natural circulation boiling water loop. Effects of several important parameter, such as system pressure, inlet subcooling, geometric aspects of riser and heater, on the magnitude and frequency of oscillations were thoroughly studied. However, their studies emphasized the density wave oscillations at relatively high pressures and powers. Chexal and Bergles [3] investigated the instability in a low pressure two-phase natural circulation loop similar to a reboiler.They reported several different types of instability at low powers in addition to the density wave oscillation at higher powers. Fukuda and Kobori [4] conducted experiments on two-phase flow instability in parallel channels under forced and natural circulation conditions. "Type-I" oscillations were indentified at low powers and lower exit quality. The existence of this type of instability could be predicted by using linear stability analysis [5]. Recently, Lee and Ishii [6] investigated the oscillatory flow behaviors in a two-phase natural circulation Freon loop, which was to simulate the hot-leg U-bend natural circulaltion flow in a PWR. More recently, Aritomi et al.[7,8] studied the thermal-hydraulic instabilies of a double-channel natural circulation loop, which is to simalate thermal-hydraulic phenomena during start-up in a natural circulation BWR. They reported three different kinds of instabilities at different power levels, namely, geysering induced by condensation, natural circulation instability induced by hydrostatic head fluctuation in steam separatos and density wave instability.

The objective of this study is to investigate the thermal hydraulic oscillation behavior in a low pressure two-phase natural circulation loop at low powers and high inlet subcoolings. Oscillatory characteristics of loop flow rate, pressure drop in each section and wall temperature were studied and reported.

2. Experimental Apparatus and Procedure

2.1 Apparatus

A rectangular two-phase natural circulation loop, as shown in Fig.1, was built to study the oscillation behavior. The loop includes annular heated section, riser, upper horizontal section, cooling section, downcomer and bottom horizontal section.

The annular heated section consisted of an electric heater, imbedded in a SUS-316 stainless steel tube with an outer diameter of 10.6mm, and an outer transparent PYREX glass tube with an inner diameter of 20.2mm. The thickness of the glass tube is 2.6 mm. The length of the heater tube is 1.1 m and only the lower 1.0m part is uniformly heated.

The riser is made of transparent PYREX tube with inner diameter of 20.2 mm, which is about 2.1 times of the equivalent diameter of the heated section, and thickness of 2.6 mm. The length of the riser is 3.5 m.

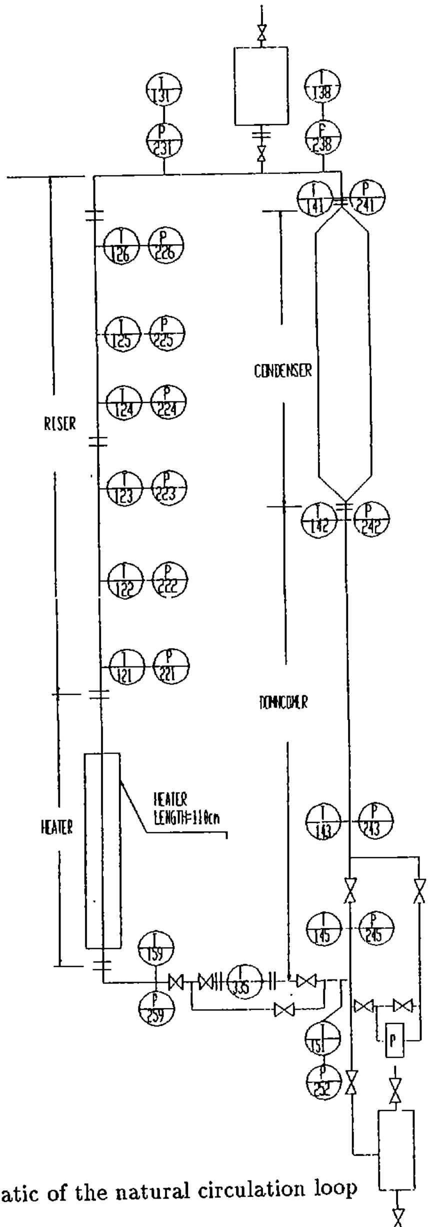

Fig.1. Schematic of the natural circulation loop

The component in the cooling section is condenser, which is 1.8 m height and is a shell-tube design. The cooling water, from the water tank on the roof of Nuclear Engineering Building, flows through the horizontal tube bank carrying heat from the shell side of the working fluid. The outlet temperature of primary side working fluid could be controlled by the flow rate of the second ycooling water to within ± 0.2℃. This outlet temperature is considered as the inlet temperature of the heated section.

The downcomer, upper and lower horizontal sections are made of stainless steel with inner diameter of 19.8 mm. The downcomer provides the gravity head to drive the loop flow. A control valve was installed in the downcomer region so that the flow resistance in the single phase region might be controlled. For the present study, it was fully open. An orifice flow meter was installed in the lower horizontal section to measure the loop mass flow rate. A pressure regulation tank was installed at the bottom horizontal sections, to regulate the loop pressure to a desired value. The heated power was provided by a DC power supply. It's maximum power output was 30 kW.

The whole loop, except the heated region and a very small part of the riser region, was insulated to minimize heat loss. The heat loss due to natural air convection from uninsulated heated section was estimated to be less than 2% of the heated power.

2.2 Instrumentation and Data Acquisition System

The layout of instrumentations is shown in Fig.2. In the heated region, the wall and coolant temperatures were measured every 10 cm with K-type thermocouples. The coolant temperature near the top of the riser, at the inlet and outlet of condenser, and near the inlet of heated section were all measured with the same type thermocouples. The pressure drop through each sections were measured by differential pressure transducers, which were set to zero by static liquid in the channel before experiments. The orifice flow meter, that was used to measure the loop mass flow rate, was calibrated for both forward and reversed flows. The coolant mass flow rate, inlet and outlet temperatures of the secondary coolant were measured by turbine flow meter and K-type thermocouples, respectively.

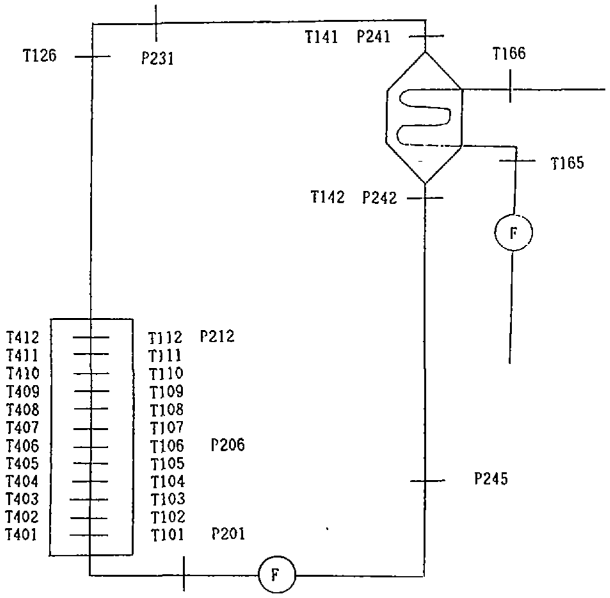

Fig.2. Layout of instrumentations

The output of thermocouples, flow meter and pressure transducers, were recorded and processed by a data acquisition system. It included a YOKOGAWA HR-2500 recorder, a personal computer (IBM-PC/AT compatible) and a printer. The recorder and the PC were linked by an interface card, GPIB (IEEE-488).

2.3 Experimental Procedure

Experimental procedures, including preparation, start up, operation and shut off procedures had been established to assure feasibility, reliability and safety of each experiment. Detailed procedures were given in ref.[9]. The working fluid, distilled water, was first heated at a desired power inside the loop with the top relief valve being open to boil off the noncondensible gases. Subsequently, the relief valve was closed and the loop becomes closed. The cooling water flow rate in the secondary side was subsequently adjusted so that the exit working fluid temperature in the primary side of the condenser was at the desired value. This temperature was treated as the inlet fluid temperature in the present study. The system pressure was regulated by nitrogen gas pressurizer such that the pressure at the loop bottom was at 1.5pm0.1 atm. Data were recorded for about 120 minutes after the initial transient had died out and quasi-steady state appeared. The sampling rate was 0.5Hz.

The experimental conditions are:

Heated Power (Heat Flux)	4 kW - 8 kW (127 - 254 kW/m^2)
Inlet subcooling	$27^0C - 75^0C$

3. REsults and Discussions

It was found that the cases studied here were all unstable. Significant oscillations in loop mass flow rate, pressure drop in each section, and heated wall temperatures are present. Figure 3 shows the temporal evolution of the mass flow rate at the bottom horizontal section of the loop for the case of Q = 6kW and Tin = 43.5 ℃. The starting time of data recording was arbitrarily selected after the system had reached the quasi-steady state; therefore, the flow rate at t = 0 being negative was possible. From Fig.3 it can be seen that the flow rate oscillates quasi-periodically between -160 kg/hr and 500 kg/hr ,i.e., the inlet velocity oscillates between -13.8 cm/s and 43.4 cm/s. The appearance of flow reversal was typical for the present study. However, the magnitude of the forward flows was typically 3 to 4 times the reversed flows. This was because during the instant of flow reversal, the gravity head in the downcomer region must be overrided and the fluid in the heated region was heated at the same time. Thus, the buoyancy force generated against the flow direction and the reversed flow was reduced. From Fig.3, it can also be seen that the oscillation is a type of quasi-periodic one with four fundamental frequencies. Three oscillations with smaller magnitudes follows an oscillation with larger magnitudes. The period of large magnitude oscillation was about 50 sec. Experiments under lower powers and/or higher inlet subcoolings indicate that the oscillations become chaotic.

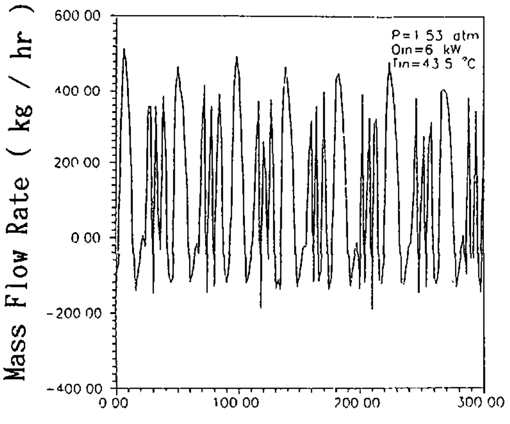

Fig.3. Temporal evolution of mass flow rate.

The flow oscillations result in the oscillations of heated wall temperature at various locations as shown in Fig.4. It can be seen that the wall temperature rises after a short while of flow reduction or reversal. The temperature rise is clearly due to reduction in heat transfer and the time lag is caused by the delay from the location of flow meter and points of wall temperature measurements. The variations of wall temperature are very significant. At the entrance point, in which single phase flow prevails, the temperature variation is as high as 50 ℃. At the point near the boiling boundary, the temperature variation is the highest and reaches about 60℃. The wall temperature variation at the exit point is qualitatively different from those at the entrance point and the point near the boiling boundary. This is because boiling at this point lasts longer than the point near the boiling boundary. Heat transfer coefficient during boiling period is usually not very sensitive to the flow rate and flow direction; Therefore, temperature variations during boiling period is relatively small.

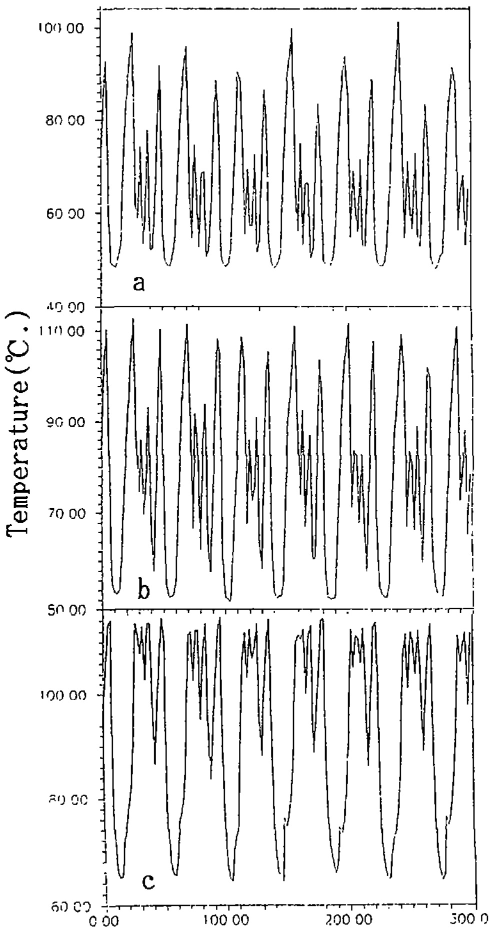

Fig.4. Temporal evolution of heated wall temperatures (a) at the entrance point; (b) at the point near the boiling boundary ; (c) at the exit $Q = 6KW, T_{in} = 43.5^oC$

The thermal hydraulic oscillation for this particular case may be well explained as follows. Comparing Fig. 3 and Fig.4 it is clear that, during the langth amplitude oscillation, when the flow rate rises, magnitude, heat transfer becomes very good; the wall temperature is decreased and boiling is suppressed. As boiling is suppressed, the driving buoyancy force and thus the flow rate becomes smaller; all temperatures are thus increased and boiling is reestablished and vapors are generated in the heated region and the flow is increased again. Void fraction measurements indicate that the loop flow rate increases following the increase in void fraction in the riser and upper heated region[10]. This process repeats itself. However, the flow rise may not be strong enough to suppress boiling in the upper part of the heated region as suggested by Fig.4b. This kind of small amplitude oscillatiions persist for three cycles. Thus, many vapor bubbles will be accumulated in the upper part of heated section and riser. This results in a very large driving force and an increase in loop flow rate of large amplitude is resulted. This large amplitude flow sweeps most of the vapor bubbles in the heated section and riser and the flow reversal is resulted if more vapor bubbles have transported to the cooling section than those stay in the heated and riser section. Moreover since there are not many vapor bubbles left in the riser and heated section after the large amplitude forward flow, such a larger amplitude flow is not possible until three smaller amplitude flow oscillations have appeared for this particular case.

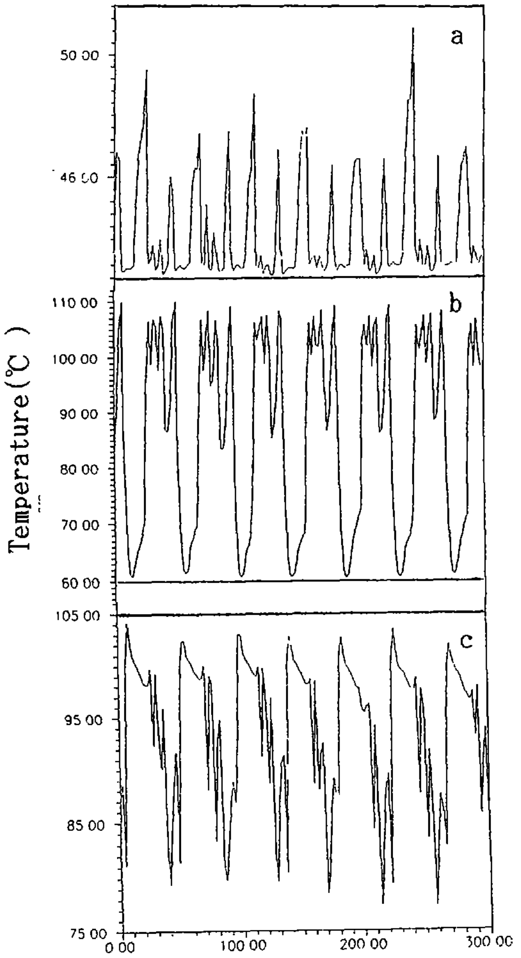

Fig 5. Temporal evolution of fluid temperature (a) at the entrance of the heated section;(b) at the exit of the heated section; (c) at the point near the exit of the riser. $Q = 6KW, T_{in} = 43.5°C$

Significant oscillations in coolant temperature prevail in the loop. Fig.5 shows the temporal evolution of fluid temperature at the entrance and exit of the heated section and at a point near the exit of the riser. It can be seen that for inlet temperature isolated peaks above the base value appear due to flow reversals. This is the reason why the fluid temperature at the exit of condenser, which is much more stable due to large condenser design and insignificant effect of flow reversal on this point, is referred to as the inlet fluid temperature in the present study. The fluid temperature at the exit of the heated section is quite similar to that of wall temperature at the same elevation. on the other hand, due to time lag and mixing effect in the riser the fluid temperature oscillation at the riser exit is quit different from that at the exit of the heated region.

The oscillation in flow rate and vapor void may cause the oscillation in pressure drops in each sections. Figure 6 shows the temporal evolution of pressuure drops for the lower and upper half part of the heated section, riser(including an elbow and a small portion of the upper horizontal section), upper horizontal section including an elbow and a small portion in the entrance region of the cooling section. It can be seen that the pressure drop in the upper horizontal section, which is mainly due to friction and an elbow form loss, is much smaller less than land heated section. This suggests that frictional pressure drop and elbow form loss are very small. This is to be expected for relatively low flow rates in the present study. The negative pressure drops in the upper horizontal section are due to reversed flows. Since the frictional pressure drop and elbow form loss are negligibly small, the pressure drop shown in Fig.6c is mainly due to gravitational pressure drop and the oscillation in pressure drop is mainly caused by the variation in void fraction. Figure 6(a) and 6(b) show that due to the presence of void oscillation the oscillation of pressure drops in the upper half portion of the heated section is more violent than the lower half portion.

Experiments under other conditions of power and inlet fluid temperatures had also been conducted. Figure 7 the sumarizes effects of power level and inlet fluid temperature on the average mass flow rate. It can be seen that the average mass flow rate increases with increased power level and/or inlet fluid temperatures. This results from that, in average, more vapors are generated under the conditions of high power levels and/or inlet fluid temperatures.

Figure 8 shows the effect of heated power and inlet fluid subcooling on the first fundamental frequency (the frequency of the largest amplitude oscillation). It can be seen that the frequency increases with increase in heated power and with decrease in inlet subcooling. Similar trends have been reported by Aritomi et al.[7] for geysering in a natural circulation loop. They found that for low inlet subcoolings the period of geysering could be correlated with the time period required boiling of subcooled liquid flowing into a heated chennel.

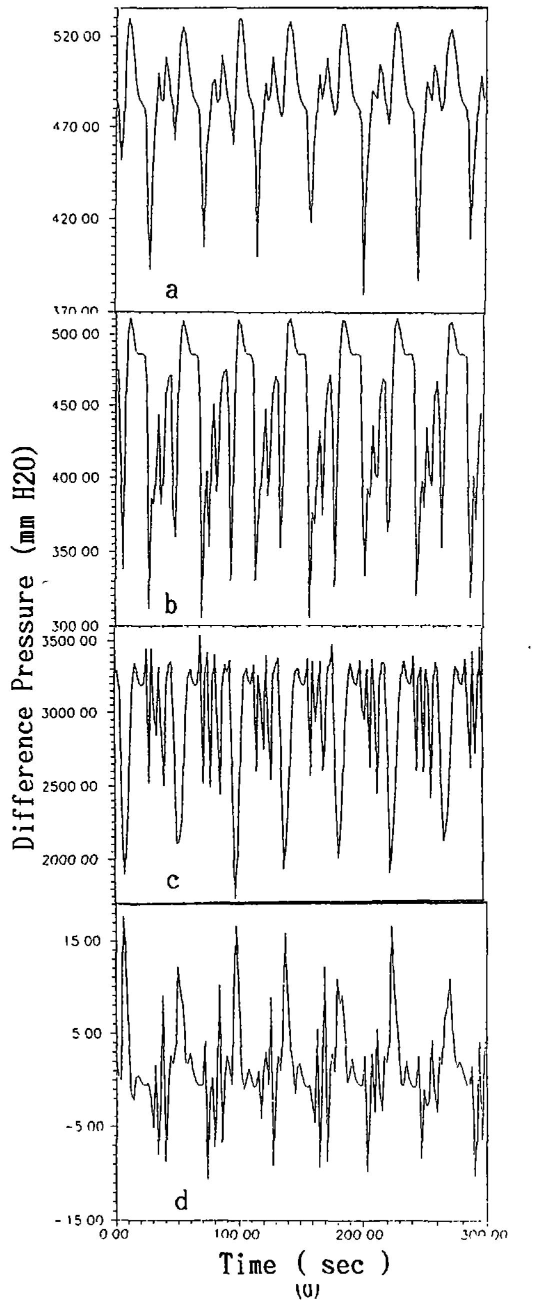

Fig.6. Temporal evoluation of pressure drops (a) in the lower half portion of the heated section (b)in the upper half portion of the heated section; (c)in the riser;(d) upper horizontal section. $Q = 6KW, T_{in} = 43.5^oC$

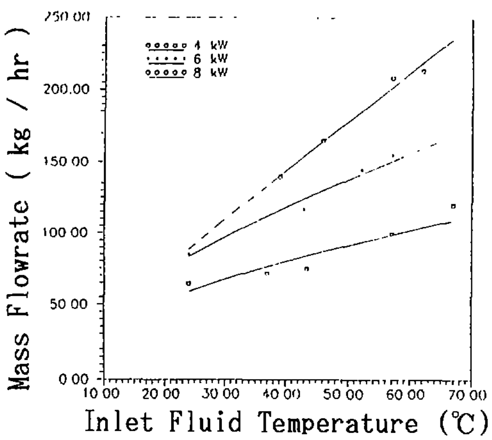

Fig.7. Effects of heated power and inlet fluid temperature on the averaged mass flow rate

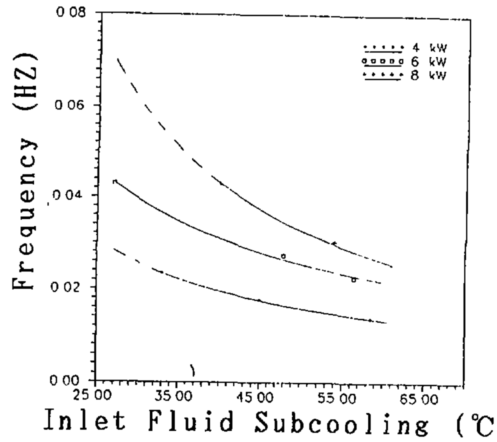

Fig.8. Effects of heated power and inlet fluid subcooling on the first fundamental frequency

4. Conclusions

The present study investigated experimentally the thermal hydraulic oscillation behavior in a low pressure two phase natural circulation loop at low powers and high inlet subcoolings. The following conclusions may be drawn from the study.

1. Quasi-periodic oscillations with flow reversals appear in the present low pressure natural circulation loop at relatively low powers and high inlet subcoolings. At even lower powers and/or higher inlet subcoolings the oscillations become chaotic. Physical explanations for such quasi- periodic oscillation were provided.

2. The magnitude of forward flow is typically 3 to 4 times of the reversed flow.

3. Due to large magnitude flow oscillations and flow reversal, significant heated wall temperature oscillations were present in conjunction with other hydrodynamic oscillations. For the current system the largest wall temperature variations occur at the point near the boiling boundary. The temperature variation could be as high as 60℃, which could cause significant cyclic thermal stress on the heating element and could be a concern for the design of a heating element such as a fuel element.

4. The average loop mass flow rate increases with increase in heated power and inlet fluid temperature.

5. The first fundamental oscillation (large magnitude oscillation) frequency increases with increase in heated power and with decrease in inlet fluid subcooling. This implies that the period of this large magnitude oscillation may be correlated with the time period required for boiling of subcooled liquid flowing into a heated region.

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