

EXPERIMENTAL STUDY OF TWO-PHASE FLOW OSCILLATIONS IN A NATURAL CIRCULATION LOOP

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Abstract: *This work aims to investigate experimentally the oscillations during the operation of a natural circulation loop, designed to meet the single and two-phase flow similarity criteria to a typical Passive Residual Heat Removal (PRHR) system of an Advanced Pressurized Water Nuclear Reactor (APWR). The loop was one-tenth scale in height and operated at atmospheric pressure. It was comprised of a cylindrical vessel with descending tube, a core barrel housing electrically heated rods, and upper and lower plena interconnected to a seven-tube shell heat exchanger by hot and cold pipe legs. A data acquisition and control system was provided, including a power control and instrumentation, in order to permit variations of the power to the electrically heated rods, as well as to acquire flow rate, pressure and temperature data in a timely manner. The results obtained, especially in terms of temperature and flow rate oscillations, indicated that the loop was subject to a condition of cyclic two-phase flow instability. It was characterized by the periodic repetition of the same pattern of changing in the temperature, flow rate and other important flow characteristics, like the sequence of two-phase flow patterns during the instability period.*

Keywords: *natural circulation, natural circulation loop, two-phase flow, oscillation, geysering*

1. INTRODUCTION

Natural circulation systems are known to constitute inherently safe and reliable cooling devices for nuclear plants, for they rely only on the natural force of gravity to function properly. For this reason, the passive residual heat removal (PRHR) systems of advanced passive reactors, like the Westinghouse AP600 and AP1000 designs, are natural circulation loops.

Although safe and reliable, the natural circulation systems are very often subject to instabilities, or oscillations, which may take place in both single-phase and two-phase flow in natural circulation systems. The two-phase flow is more susceptible to instabilities than single-phase, as forced circulation systems exhibit instabilities only when in two-phase flow (Vijayan and Nayak, 2010). The two-phase flow instabilities must be well studied and understood because they can lead to excessive vibrations, sudden temperature or pressure changes and other problems in the loops, which can even affect the effectivity of the associated nuclear plant instrumentation and control (I&C) systems. In this way, several reviews regarding such theme have been carried out (Bouré *et al.* (1973); Kakac and Bon (2008); Bhattacharyya *et al.* (2012)).

A number of authors have already pointed out that some relevant factors propitiate the occurrence or not of the geysering oscillation in a natural circulation loop, especially the loop geometry, pressure, heating power, water inventory and subcooling.

As for the loop geometry, Murphy (1965) mentioned the relevance of the geometric ratio between the riser (hot leg in the nuclear field) length and diameter. A higher geometric ratio corresponds to a higher propensity to geysering, for a reason further discussed in this paper. Nevertheless, he only studied the geysering occurrence in the natural circulation within vertical columns, and not in a much more complex, complete natural circulation loop. In this case, the intricate geometry of the actual components of a loop scaled to a nuclear plant or its component (the PRHR system, for instance) may cause it to behave, especially when operating in two-phase mode, very differently from simpler, more often studied loops, like Murphy's vertical columns, or thermosyphons.

Using a thermosyphon, Kuncoro *et al.* (1995) showed that an increase in the loop operational pressure mitigates the geysering occurrence, as long as the saturation water temperature increases with that pressure. However, they did not evaluate the influence on geysering of a pressure that increases during the natural circulation in the loop.

Tong *et al.* (2014) showed that the effect of an increasing loop heating power is the reduction of the geysering period. They verified that the geysering phenomenon is more obvious under greater geometric ratio and larger heating power. They also studied how other factors, like the operational pressure, influence the geysering.

Lisowski *et al.* (2014) studied the influences of changes in the water inventory to the two-phase behavior of a complex natural circulation loop, rather than a thermosyphon or vertical column. They found that the water level plays an important role in the system stability, since it directly influences the hydrostatic pressures and, therefore, the local saturation temperatures. However, they did not comment on any influence of a pressure increase during the loop operation, as above mentioned. Nevertheless, they cited that a reduction in the water inventory favors the geysering, because it is accompanied

by a reduction in the natural circulation flow rate, thus propitiating the heat accumulation in the heated core.

As for the subcooling, Chen *et al.* (2015) verified the existence of a direct relationship, in which an increase in the subcooling corresponds to an increase in the geysering amplitude. But they did not provide a physical explanation for such relationship.

Chiang *et al.* (1993) carried out another study of a complex natural circulation loop, which comprises a test section with two long, parallel twin channels between inlet, lower and outlet, upper plena. They observed that the loop is subject to both geysering and the so-called natural circulation oscillation. The phenomena differ in the governing mechanism, which is the achievement of the local water saturation temperature, in the former case, and the oscillation of the hydrostatic head in the connection channel above the outlet plenum, in the latter case.

Wang *et al.* (1994) and Paniagua *et al.* (1999) also studied the occurrence of geysering in a complex natural circulation loop, of single channel in this case. The former study provided experimental data regarding the loop, whereas the latter performed a comparison between such data and the outputs got from a computer code developed for predicting the geysering instability, with decent results.

The objective of this study is to investigate the oscillations that occur in a natural circulation loop in the beginning of operation in two-phase mode. The experimental facility and instrumentation are described in the next section. In Section 3, the experimental results are presented and discussed. Conclusions are presented in the last section.

2. EXPERIMENTAL APPARATUS

The experimental study presented in this paper was carried out using the Nuclear Engineering Institute Natural Circulation Loop (named NCL in this paper), which was designed to meet the single and two-phase flow similarity criteria to a typical PRHR system of an Advanced Pressurized Water Nuclear Reactor (APWR). The loop was one-tenth scale in height to the PRHR system of the AP600 reactor and operated at atmospheric pressure (Botelho, 1993). The height between the lowest point of the heater and the highest point of the expansion tank was 2.283 m. The external diameters of the heater and heat exchanger were 0.19 m and 0.275 m, respectively. The main components of the NCL are depicted in Fig. 1, whereas the loop instrumentation is shown in Fig. 2.

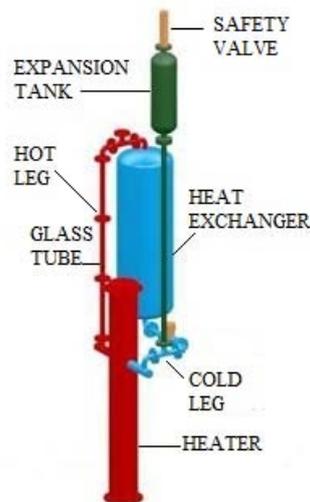


Figure 1: Main components of the NCL, out of scale.

The core barrel heater was in the low part of the loop and comprised 52 electrically heated rods equally spaced. The working fluid, which was distilled water, heated up as it rose up through the space between the rods. Each one of them was a cartridge resistance, whose external dimensions were a diameter of 0.009525 m and a length of 1.105 m, with 0.366 m of heated section, between the heights of 0.136 m and 0.502 m. Inside the heater, the electrically heated rods transferred thermal energy to the water in a controllable rate, up to the nominal value of 1100 W.

The shell and tube heat exchanger was in the upper part of the loop and comprised seven tubes, each one 0.6 m long. The primary, hot water flowed down inside the tubes, whereas the secondary, cooling water, coming from a water tank filled by the NCL building water supply, typically at an average temperature of 25°C, rose up inside the heat exchanger, between the tubes, according to the counter-current flow design. The secondary flow was controlled with a rotameter, in a range between 3 l/h and 12 l/h, thus allowing for subcooling changing.

The expansion tank was in the upmost part of the loop, thus pressurizing the NCL, and consisted of a cylindrical vessel with an external diameter of 0.21 m and a height of 0.395 m. A safety valve, whose opening pressure was 34.335 kPa, was mounted on top of the expansion tank, that is, in the highest NCL point, in order to keep the pressure under control. When the circuit was filled out with water prior to an experiment, the expansion tank was left with approximately half to two thirds of its volume of air in its top part, in order to accommodate the water dilatation as the loop heated up. A descending tube 1.2 m long connected the expansion tank to the loop, close to the heater, in the cold leg. The hot and

cold pipe legs had an internal diameter of 0.0234 m and connected the heat exchanger to the upper and lower plena of the heater, respectively. The hot leg was 1.034 m long and was made of two stainless steel sections and a glass tube between them, which allowed for the observation of the different two-phase flow patterns occurring in the loop. The NCL was thermally insulated with rock wool in an adequate fashion.

A data processing and control system was provided to the NCL, including a power control and instrumentation, in order to permit variations of the heating power, as well as to store power, flow rate, pressure and temperature data, with an acquisition frequency of 0.25 Hz, using a PXI industrial computer and the LabVIEW software. Table 1 presents the detailed position of the 12 type K thermocouples installed in the loop.

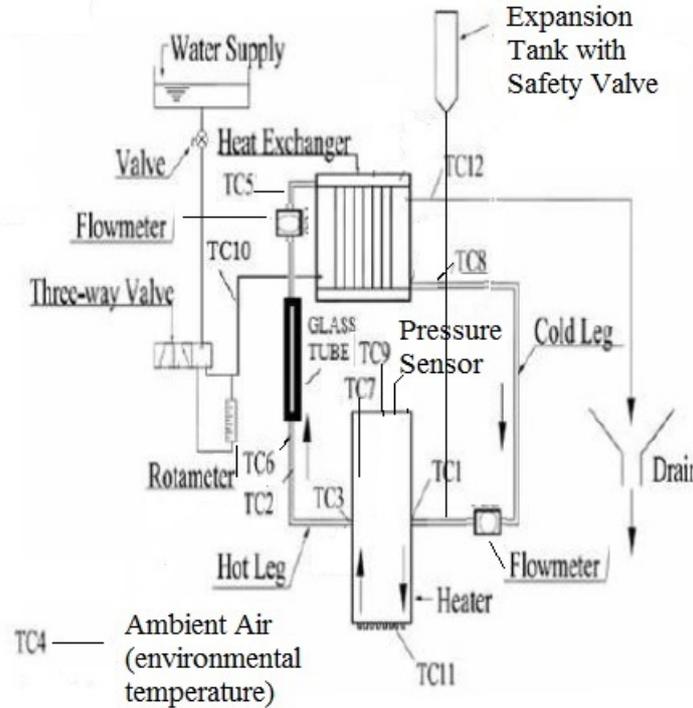


Figure 2: NCL instrumentation. The components marked with TC are thermocouples.

Shown in Fig. 2, the cold leg flowmeter was electromagnetic, whereas the hot leg one was based on the Doppler frequency principle, thus measuring flow velocity. The pressure sensor provided the gauge pressure below the heater upper cover. The heater power was controlled from a rack containing, among other electronic devices, an AC/DC transformer and a power multiplier. The glass tube allowed for the visualization of the different two-phase flow patterns with a color high-speed digital camera equipped with zoom lenses as well as other devices, like proper light projectors, an image acquisition program and a dedicated computer.

Table 1: NCL thermocouple position

| Thermocouple | Position | Thermocouple | Position |
|--------------|-------------------------------|--------------|--------------------------------------|
| TC1 | Heater downcomer | TC7 | Heater lateral upper plenum |
| TC2 | Hot leg lower part | TC8 | Heat exchanger exit, primary side |
| TC3 | Heater exit | TC9 | Heater upper cover |
| TC4 | Environmental air temperature | TC10 | Heat exchanger inlet, secondary side |
| TC5 | Hot leg upper part | TC11 | Heater inlet |
| TC6 | Hot leg middle part | TC12 | Heat exchanger inlet, secondary side |

3. EXPERIMENTAL RESULTS AND DISCUSSION

3.1 Experimental Results

The results presented in this section were obtained during typical operations of the NCL, at the nominal power of 1100 W and cooling rates of 3, 6, 9 and 12 l/h in the heat exchanger. The natural circulation experiments started with the single-phase flow and then, after about 20000 s, two-phase flow was observed, as shown in Fig. 3, obtained with the cooling rate of 6 l/h. It shows the temporal evolution of the highest loop temperature, at the heater exit, as well as the temperature in the hot leg middle part. It also shows the detailed evolution of those temperatures during the two-phase flow.

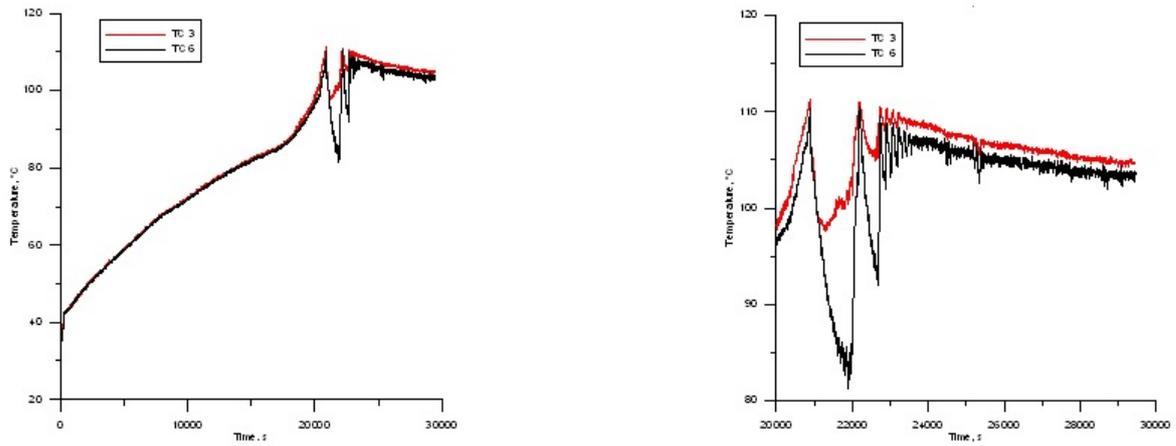


Figure 3: Evolution of the temperatures at the heater exit, TC3, and in the hot leg middle part, TC6, with the cooling rate of 6 l/h: a) during single and two-phase flow, on the left; and b) during two-phase flow only, on the right.

The two first temperature peaks can be attributed to the two occurrences of geysering in the NCL for the operation conditions defined above, characterized by the appearance of vapor eruptions, with the presence of the churn flow pattern. After the two vapor eruptions of the geysering phenomenon, non-violent vapor flow followed, in such a way that only the bubble and slug flow patterns were observed in the loop. This same sequence of two-phase flow patterns was observed for all cooling rates. Figure 4 shows snapshots taken from the flow patterns observed during the two geysering eruptions and during the rest of the experiment, with the cooling rate of 12 l/h.

The two-phase flow rate and velocity measurements are shown in Fig. 5, for cold and hot legs, respectively, with the cooling rate of 6 l/h. These data support the previous distinction between the two first, strong instabilities at times 20868 s and 22184 s, as the two geysering occurrences, and the other fluctuations of temperature, flow rate and velocity, which were less intense than the initial ones, associated to the vapor eruptions. This observation reinforces the supposition that, unlike the previous literature about geysering, the NCL has a distinctive feature, further explained, that governs the geysering occurrence or not. Such feature differs from the characteristics usually changed in order to explain the occurrence or not of that phenomenon, which are mainly the loop power, geometric ratio, pressure of operation and coolant water inventory. These factors keep constant during a typical experiment in the NCL and, even so, the geysering happens in the beginning of the two-phase flow and ceases to occur afterwards.

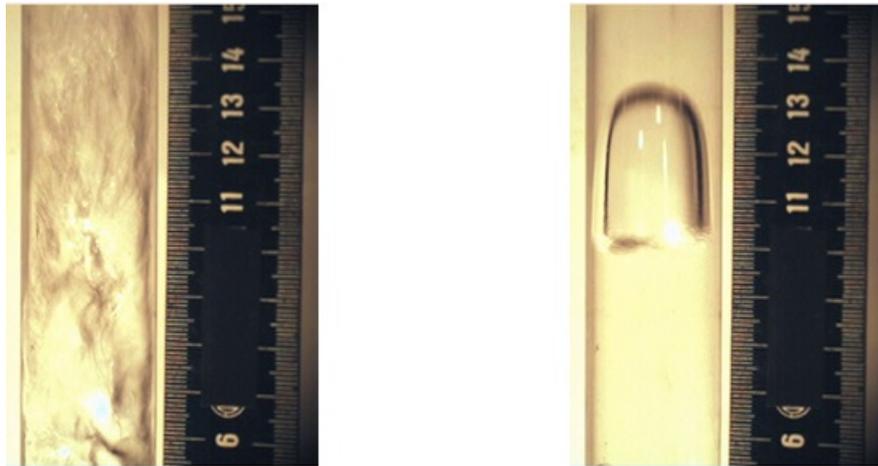


Figure 4: Snapshots of flow patterns with the cooling rate of 12 l/h: a) churn flow (geysering), on the left; and b) slug flow (after the eruptions stop), on the right. The ruler beside the glass tube is scaled in centimeters.

As for the gauge pressure below the heater upper cover, Fig. 6 shows its temporal evolution in the beginning of two-phase operation at the cooling rate of 3 l/h, together with the temperature in the heater exit, which was located close to the heater upper cover, less than 0.35 m below it. Again, the two first, outstanding and nearly simultaneous peaks of pressure and temperature corresponded to the two geysering occurrences in the NCL initial two-phase flow. Such magnitude of the geysering temperature and pressure peaks, when compared to the other respective variations, which was also observed with other cooling rates, like 9 l/h, as depicted in Fig. 7, allowed for the introduction of a geysering indicator for the specific NCL conditions, shown in the next section.

In Fig. 7, the equation below the separation line, which allowed the distinction between geysering and non-geysering

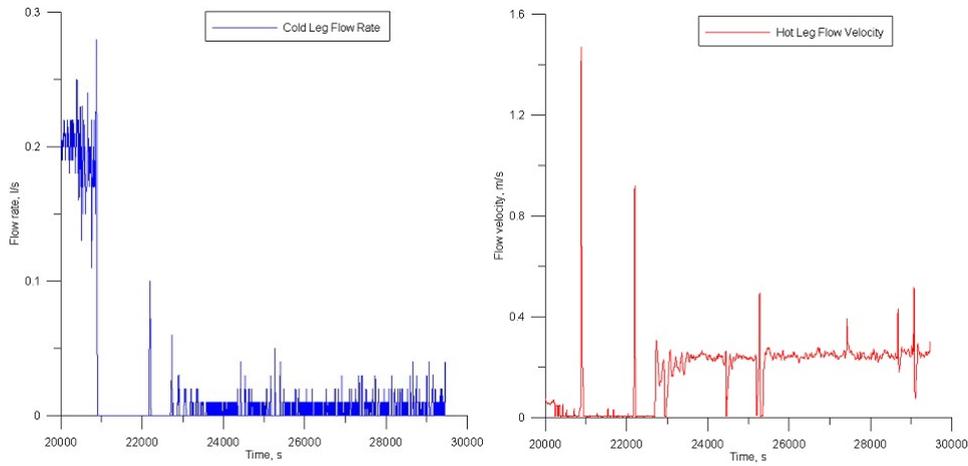


Figure 5: Measurements during the two-phase flow regime with the cooling rate of 6 l/h: a) flow rate in the cold leg, on the left; and b) flow velocity in the hot leg, on the right.

regions, located respectively in the upper, right and lower, left graph positions, provides the mathematical expression of that line. Such expression was based on an estimate, carried out with the NCL data available.

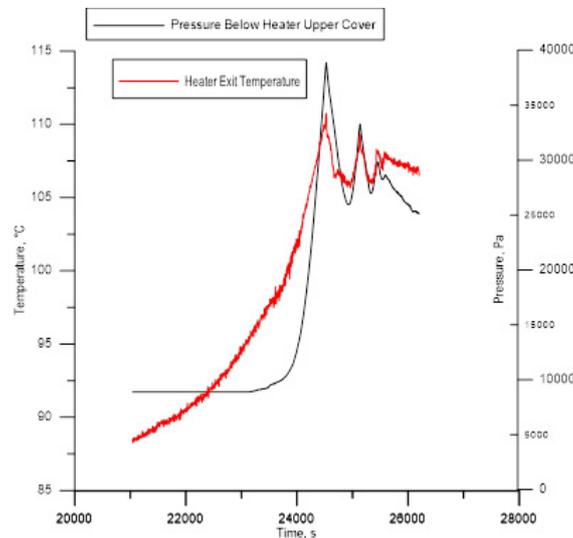


Figure 6: NCL temporal evolution, in the beginning of two-phase flow, of the gauge pressure below the heater upper cover and the heater exit temperature, with the cooling rate of 3 l/h.

3.2 Discussion

The first contributing factor for the geysering occurrence in the NCL was its high geometric ratio between the hot leg length and diameter. The ratio of 44.2, according to the criterion of Murphy (1965), classified the loop as subject to geysering. The influence of the geometric ratio on geysering can be explained by considering how it alters the flow rate in the natural circulation loop. A long and thin riser or hot leg has an associated high geometric ratio, and brings difficulty to the occurrence of natural circulation. Thus, a long and thin hot leg is more favorable to a stagnant flow condition in the loop, which will face, in this way, a heat accumulation in its low part, that is, the heater. The heat accumulation in the heater, on its turn, is the first step towards geysering in the NCL and in any natural circulation loop.

However, the key for understanding the geysering oscillations in the NCL is to realize that the loop possesses a unique variable pressure condition at the heater exit height, caused by the increase, during an experiment, of the pressure applied to the primary water by the expansion tank with its safety valve.

The explanation for the geysering occurrence of in the NCL is as follows. After the loop heated up and reached the two-phase flow, there was compressed air in the expansion tank, because of the dilatation of the water below it. Prior to the first geysering occurrence, the pressure in the safety valve was assumed to be just below its opening pressure of 34335 Pa, or 0.35 kgf/cm². The fact that the valve was heard opening just before a geysering occurrence in the NCL supported this assumption. It happened that the temperature of 111.3 °C at the heater exit, shown in Fig. 3, when the first geyser eruption occurred, was equivalent to the water saturation temperature at a pressure of 49038.43 Pa, which equaled the

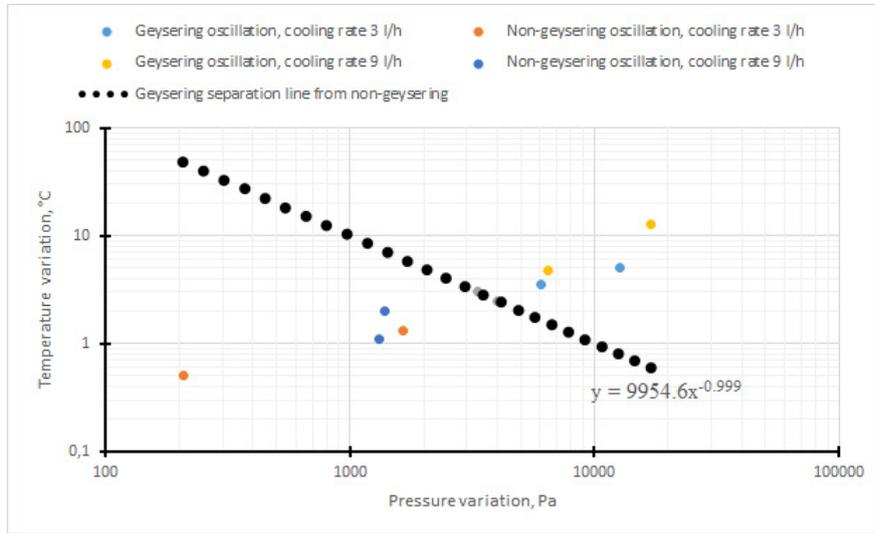


Figure 7: Variations of pressure and temperature during the NCL geysering and non-geysering oscillations, at the cooling rates of 3 and 9 l/h, and the respective separation line.

safety valve pressure plus a pressure of 1.5 m water column from the expansion tank added to its descending tube.

That is, the first geysering occurred when the temperature at the heater exit reached local saturation, under a special, pressurized condition, propitiated by the expansion tank plus its safety valve and descending tube, which pressurized the NCL. This situation, once confirmed as more experiments are being carried out, will represent a unique condition of this loop, the natural circulation under variable pressure (NCVP), not reported in the previous geysering literature.

An important evidence in favor of the occurrence of the NCVP in the NCL appears in Fig. 6. It shows that, prior to both geyser eruptions, there was a significant pressure increase below the heater upper cover, close to the heater exit. This implies that there was no bubble accumulation in the heater upper part (thus eliminating the possibility of the natural circulation oscillation occurrence in the NCL) and, most important, allows for the conclusion that the fluid was indeed subject to an increased pressure condition inside the heater before the geysering, as explained above.

When the boiling began inside the heater, the bubble formation reduced the hydrostatic pressure below the heater exit, thus decreasing the water saturation temperature, which propitiated the propagation of the eruption downward in the heater, in a kind of chain reaction, until the point when temperature was below saturation. Depending on the initial filling condition of the expansion tank with water versus air, the pressure in the safety valve might be slightly less than the opening pressure of 34335 Pa (0.35 kgf/cm²), then the valve would not open. Even so, the geysering occurred, but with a heater exit, local saturation temperature, a little less than 111.3°C.

Afterwards, the system exhibited only one or two more geyser occurrences. This happened because the air expanded during the first eruption, pushing colder water from the descending tube to fill part of the space left in the heater as the vapor erupted out (another part came from the cold leg). Such was the reason why a steep and relevant descent in the water temperature took place, both in the heater exit and in the hot leg, after the geysering occurrences. In this way, the air pressure in the expansion tank decreased. Consequently, the pressure increase caused the NCL geysering weakened, that is, both the pressure at the heater exit height and the corresponding local saturation temperature decreased, and the second eruption occurred at a lower temperature and with less intensity than the first one.

It is possible, observing that Fig. 7 is in log-log scale, to figure out an indicator of geysering, IG , and its corresponding normalized form, IG^* , according to Eq. (1) and (2), as follows.

$$IG = \Delta P \Delta T \quad (1)$$

$$IG^* = \frac{IG}{IG_{max}} \quad (2)$$

In Eq. (1), ΔP is the difference between the peak and the next local minimum pressure, during an oscillation, and ΔT , similarly, is the difference between maximum (peak) and next following minimum temperatures in an oscillation.

In Eq. (2), IG_{max} is the maximum value of the geysering indicator IG for a given experimental condition (3 or 9 l/h in Fig. 7). The values of the normalized geysering indicator IG^* , calculated from the data of Fig. 7, were at least one order of magnitude greater, in the case of the geysering oscillations, than in the case of the non-geysering oscillations. So, IG^* appeared to be an appropriate geysering indicator for the specific NCL condition, characterized by the NCVP.

As for the intensity or amplitude of the geyser eruptions, it requires a separate explanation, related to the loop two-phase subcooling condition during the oscillations, presented in Fig. 8. According to the explanation above, it was assumed that the temperature at the heater exit was approximately equal to the local saturation temperature.

In the occasion of the two geyser eruptions, at times 20868 and 22184 s, the loop subcooling was at a high level, and in the occasion of the first eruption, which was the most intense, it was maximum. Afterwards, when the eruptions

stopped, the subcooling decreased, reaching a value of approximately 23°C in the quasi-steady, final experimental state of the loop. In this way, a direct relationship between subcooling and geysering amplitude was present in the NCL. There is a previous reference to such relationship, by Chen *et al.* (2015), but without a physical explanation, like the following one.

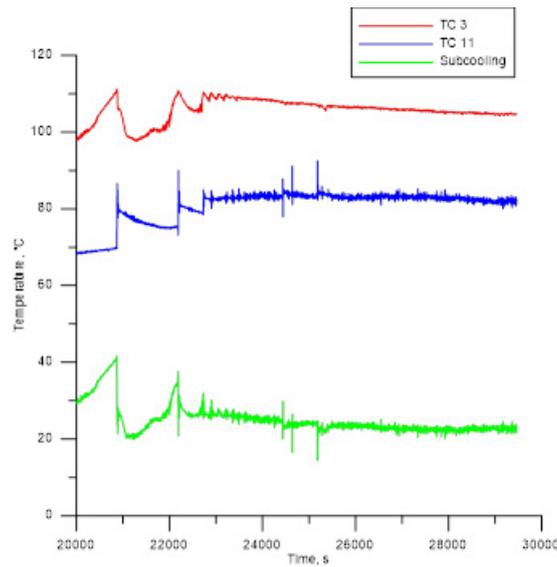


Figure 8: NCL temporal evolution of the subcooling, TC3 minus TC11, with the cooling rate of 6 l/h. The heater exit temperature, TC3, is assumed equal to the local saturation temperature. TC11 is the heater inlet temperature.

It is clear, from Fig. 8, that the responsible for the subcooling increase was the steep, abrupt increase in the heater exit, saturation temperature, during the heat accumulation period that preceded the eruptions – because of the pressure increase posed by the expansion tank pressure – and not the much less intense variations of the channel inlet temperature. Therefore, the subcooling was related to the amplitude of geysering, but as a side effect, and not as a causal factor. This explanation points out, again, to the crucial importance of the pressure variation in the NCL, that is, the NCVP.

Afterwards, having the geyser eruptions stopped, the loop lost its pressure increasing condition. The temperature at the heater exit gradually tended, in the long run, to decrease to an approximate value of 104.5°C , which corresponded to the local saturation temperature under the smaller, residual hydrostatic pressure from the expansion tank and its descending tube. The behavior of the loop in this final part of the experiment was much calmer than during the geyser oscillations. Only bubble and slug flow patterns were present, but not the churn flow. A parallel between thermal hydraulics and the geothermal science is appropriate here, in the sense that a hot spring without a pressure increase does not create a geyser, but a quiet warm pool instead.

4. CONCLUSIONS

The NCL was a natural circulation loop built in a 1:10 scale in height to the PRHR system of the Westinghouse AP600 nuclear reactor. It was observed that the loop oscillated in the beginning of operation in two-phase flow. The oscillation was characterized by a strong eruption of vapor, with the presence of the churn flow pattern. A long and calm period of one-phase flow, during which the heat accumulated inside the heater, preceded the eruption. After the eruption, a brief period of refilling occurred, with subcooled water coming from the heat exchanger plus the expansion tank and its descending tube. The refilling was responsible for a steep, abrupt temperature descent in the temporal evolution graph of the loop heater exit and hot leg middle part temperatures. These characteristics allowed for the preliminary classification of the loop instability as geysering, to be confirmed as more NCL operation data are gathered.

The beginning of the instability was triggered by the achievement of the local saturation temperature under the unique loop operation condition, to be confirmed, which was the natural circulation under variable pressure, NCVP. It was characterized by the occurrence, prior to a vapor eruption, of a relevant pressure increase in the heater, posed by the air pressure in the expansion tank, limited by the respective safety valve and added to the hydrostatic pressure of its descending tube water. This pressure increase provoked an increase in the local saturation temperature, with a great heat accumulation inside the heater.

A strong evidence in favor of the NCVP occurrence in the NCL was the relevant pressure increase below the heater upper cover, close to the heater exit, prior to the geyser eruptions. It means that there was no bubble accumulation in the heater upper part, as the water over there was pressurized, thus in accordance with the NCVP explanation.

Once achieved the higher saturation temperature in the overpressure condition, the vapor eruption started from the heater exit and propagated down the heater in a sort of chain reaction, because with the initial bubble formation, the hydrostatic pressure below the heater exit decreased, thus decreasing the local saturation temperature. In this way, more

vapor was generated downward in the heater, until the point where the saturation condition was no longer reached. After the first eruption, the heater was filled with subcooled water as above mentioned.

The geysering stopped to occur in the NCL after two or three occurrences because the air in the expansion tank expanded during each eruption, as the descending tube water below it occupied the empty space created in the heater by a geysering occurrence. Therefore, the air pressure decreased and the pressure increase in the heater exit vanished. The dimensionless indicator of geysering presented in this paper, IG^* , was able to distinguish the geysering and non-geysering NCL oscillations, by a difference of one order of magnitude or more.

In the long run, the temperature in the heater exit tended to the decreased local saturation value, due only to the hydrostatic pressure from the descending tube water column. Then, only the bubble and slug flow patterns were present in the loop, but not the churn flow, characteristic of the geysering eruptions.

The experiments performed in the NCL provided an insight to the complex two-phase flow behavior of the natural circulation loop, very different from that of simpler, more often studied loops, like thermosyphons and vertical columns. This happens because of the intricate geometry of the actual components included in a loop scaled to a nuclear plant or its component, the PRHR system for instance.

5. ACKNOWLEDGEMENTS

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