POLITECNICO
MILANO 1863

SCUOLA DI INGEGNERIA INDUSTRIALE
E DELL'INFORMAZIONE

Executive Summary of the Thesis

Investigation of flashing induced oscillations in vertical two-phase flows near saturation conditions

Laurea Magistrale in Energy Engineering - Ingegneria Energetica

Author: Karim Mohammed Abdalwaged Yassin

Advisor: Prof. Luigi Colombo

Co-advisor: Prof. Carlos Dorao

Academic year: 2022-2023

---

1. Introduction

Boiling Water Reactors (BWR) are basically a two-phase flow system where the fluid is heated up by the nuclear core and the steam is separated to run a turbine. The earliest review of two-phase flow instabilities was conducted by Boure et al. [2]: it showed that water-cooled reactors, among other systems, are subject to thermal-hydraulic instabilities triggered by small fluctuations in the flow. These instabilities can cause disastrous phenomena such as boiling crises, thermal fatigue, and mechanical failure.

Flashing-induced oscillations were first investigated by Wissler et al. (1956) [11]. They figured that to have oscillatory flow rate, the driving force in the rise must be greater than the frictional resistance to the flow. Jiang et al. [5] Provided the first detailed investigation on flashing related instabilities as well as a clear distinction between the two phenomena of flashing and geysering. While geysering is related to vapor generation, in the heating section, growth, detachment and condensation, the cause of vapor generation in flashing is the drop in hydrostatic head in the riser as the flow moves upward. Manera et al. [7] Performed stability analysis for a CIRCUS facility, a full-height scaled steam/water loop of a natural circulation cooled BWR, under low pressure and low heating power conditions at a constant inlet subcooling. It was concluded that flashing is the main source of instability during start-up. Natural circulation BWR (NCBWR) has been the topic of research for than three decades. It was proposed as a way to eliminate the use of recirculation pumps, hence avoiding pump trips that was thought to be one reason for instabilities in BWRs. In 1991, Aritomi [1] weighed the advantages and disadvantages of removing the recirculation pump, arguing that even though it might reduce the running and total cost, the reactor net power will be reduced with a poor control of the reactivity. Furthermore, it was found that the pump trip transient does not lead to an accident releasing radioactive materials into the environment. Further distinction between the forms of flashing was introduced by Wang et al. [9], they clarified that with manipulation of heat flux, at constant pressure, natural circulation system experience four kinds of waveforms namely, intermittent, double peak, sinusoidal, and periodic oscillations. The oscillations frequencies increase in the aforementioned order, with the irregular and period instabilities having the highest amplitude. The intermittent oscillations are characterized by an incubation time before the onset of flashing, while the incubation time is nonexistent in the sinusoidal waves. They found that the incubation time is inversely proportional to the heating power. At medium and higher heat flux the incubation time vanished and the oscillations become smoother.

Efforts have been made to understand the effect of geometrical and thermo-hydraulic factors on two phase flow instabilities. At fixed inlet subcooling, it has been discovered that the oscillation duration gets shorter as heating power and/or system pressure increase [4]. Increasing the pressure has a stabilizing effect by reducing the unstable flow region and the amplitude of oscillations Manera et el. and Yanan et al. [8] [12] respectively. During the cold start-up procedure, pressurizing the reactor above the critical pressure (750 kPa) eliminates the instability phenomena (Zhao et al. [12]). Wang et al. (2022) [10] showed that at low power, the flow is stable single-phase condition. But with the increase of heating power, relative amplitude of oscillations increases. However, with further increase of power, the amplitude is decreased. On the other hand, the Oscillation amplitudes always decrease with an increase in pressure . Increasing the chimney height have significant stabilization results, while decreasing the inlet flow resistance makes the operation more stable Yanan et al. [12]. However, Akshay Kumar et al. (2021) [6] proved analytically that flashing induced instability is not affected by the inlet and exit flow restrictions due to the strong coupling between the flow velocity and pressure drop in the system. Overall, Flashing-induced instability causes flow oscillations with a large amplitude which is harmful to the natural circulation system, and the phenomena needs to be avoided in operating conditions.

The objective of thesis is to identify the role of the driving forces (frictional vs. buoyance) on the wave characteristics (shape, amplitude and period) during the flash-induced oscillations under force convection. This will be done by investigating the effect of the pump bypass valve opem, the system pressure and the heating power.

2. Facility

The experimental facility Fig. 1 is a closed R134a loop. The working fluid is driven by a magnetically coupled digital gear pump located below the main tank. A conditioner (heat exchanger) is introduced before the pump in order to assure subcooled single-phase flow into the pump. The heated section inlet temperature is adjusted by passing the fluid through a pre-conditioner after leaving the pump. After the heater, the flow goes through the riser and back to the condenser. The system pressure is controlled by the saturation temperature of condensation. The temperatures of the pre-conditioner and the condenser are controlled by two chillers whose operating temperatures are regulated via interface software. The test section consists of a horizontal heating pipe followed by 5 m vertical U-tube. Inlet restriction (K_i) provides the required pressure drop at the inlet of the heater. The heating system Fig. 2a is divided into five distinct sections, allowing for independent specification of power to each section. To measure the wall temperature of the heated pipe, several external thermocouples are strategically distributed along the wall surface. Notably, thermocouples located at positions 6 (1117 mm from the inlet) and 10 (1917 mm from the inlet) encompass measurements on the top, bottom, and both sides of the wall, along with an internal thermocouple at the inflow. The two internal thermocouples measure the temperature of the flowing fluid.Two visualization glass points are present, one at the inlet of the heated pipe to make sure the flow enters as a single phase liquid, and the second is at the outlet to study the two phase flow patterns. Finally, a 5 m high U-tube to study the influence of gravity forces on the flow instabilities. The riser Fig. 2b is a 5 mm Quadra capillary hose made of thermoplastic material with polyester reinforcement and thermoplastic cover.

2.1. Measurements and accuracy

Table 1. provides a summary of the accuracy achieved in measuring various relevant parameters. The heat flux measurement involved calibrating the electrical heat applied to the pipe against the thermal heat transferred to the fluid under steady-state conditions. This calibration was performed for different temperatures and

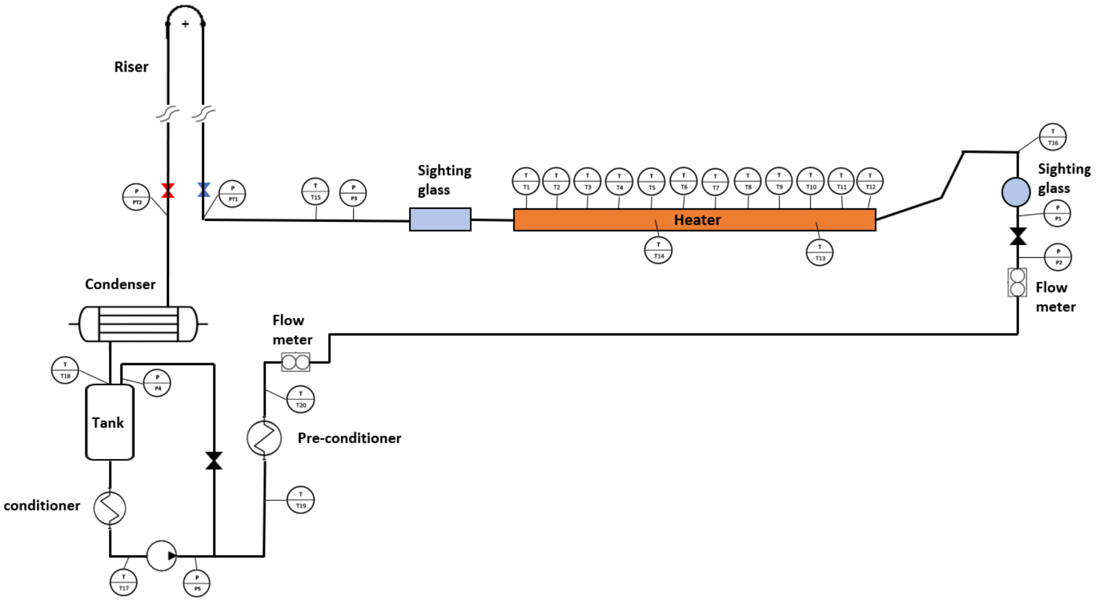


Figure 1: 2D schematic of the test facility

flow rates in the case of single-phase liquid flow, resulting in a final accuracy of 3%. The temperature and heat flux calibrations were part of PhD work of Chiapero [3].

Table 1: Measurements accuracy

Variable	Accuracy	Calibration
Mass flux G	0.2% of the reading	Supplier
Pressure drop ΔP	0.075% full-scale (fs = 50 kPa)	Supplier
Absolute drop P	0.04% full-scale (fs = 25 bar)	Supplier
Temperature T	0.1 K	Chiapero
Heat flux q''	3% of the reading	Chiapero

The vapor quality at the exit of the heated section can be determined by stating a heat balance along the pipe, as follows:

$$x(z) = \frac{\int_{z0}^{z} q"\pi D_i dz - GA_c cp_l T_{sub}}{GAH_{lv}} \qquad (1)$$

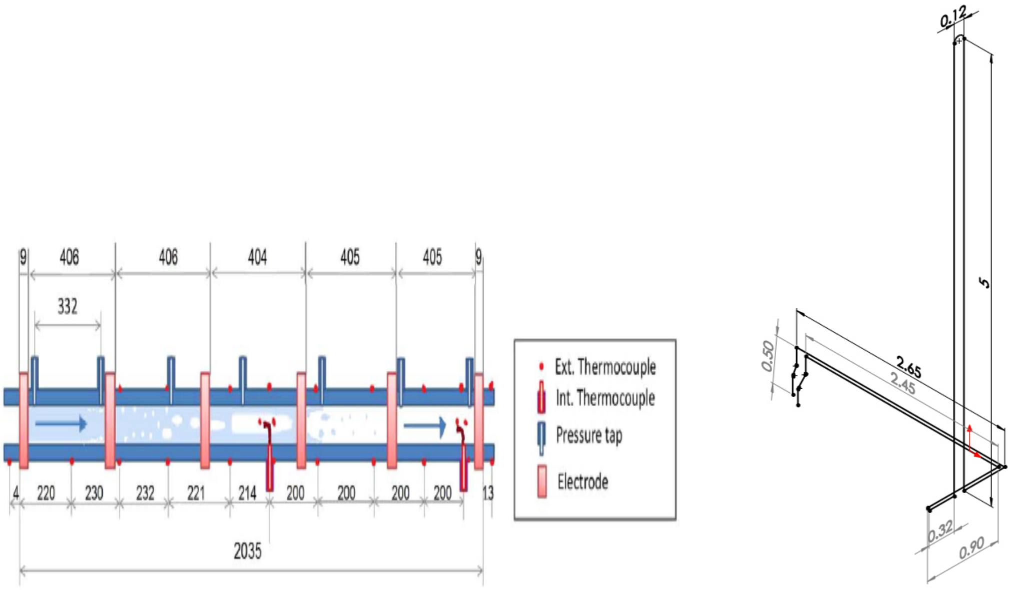
Let $x(z)$ represent the mixture quality at a specific point $z[m]$ along the heated section. The mass flux rate is denoted as $G[kg/m^2s]$, the liquid phase specific heat capacity as $cp_l[J/kgK]$, the enthalpy of vaporization as $H_{lv}[J/kg]$, the inlet subcooling as $T_{sub}[K]$, and A_c is the cross sectional area of the pipe.

Fig. 3 shows the propagation of error for the quality under operating conditions of P=7 kPa, and power=250 W, where the average mass flux is 213.11 kg/m^2s. It can be seen that the value of the error is independent of the inlet subcooling temperature, and quality can be written as $x = \overline{x} \pm 0.32$ The error is of the same order as the mean value, which is due to the simplifications used in the calculation of the quality of a two phase flow.

2.2. Experimental Procedure

The pump curve Fig. 4 was obtained by running the rig in steady state single phase liquid operation. The bypass valve was 1/2 turn open and the inlet restriction valve to the heater was gradually opened from almost zero to fully opened. The readings were recorded for at least 50 s for each open of the inlet valve. The same readings were repeated three times and the average values of mass flux and pressure drop were used to plot the pump curve. A polynomial function was fitted to the recorded values and the plot range was extended as shown.

The operational conditions were determined by four key parameters: the inlet absolute pressure (P_{in}), the inlet subcooling ($\Delta T_{sub,in}$), the heat flux (q"), and the pump bypass valve. The operating parameters were set to the desired study case and the system runs until steady state was achieved. The instantaneous readings were monitored via MATLAB. The parameters were adjusted so that the monitored ΔT_{sub} at the heated section exit was close to saturation. This case could be reached by either reducing the mass flux at a constant heating power or increasing the heat flux at a constant flow rate. After stabilization, we triggered the flashing instability by



(a) cross section of the heated section with the installed instrumentation.

(b) 3D sketch of the riser, dimensions in m.

Figure 2: Histogram of mass flux measurements for different acquisition times

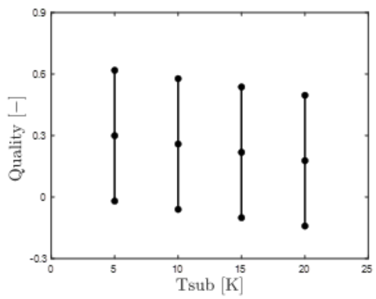


Figure 3: Error propagation of the vapor quality at the exit of the heater at P=7 kPa, and power=250 W

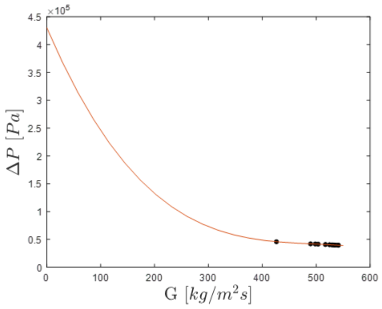


Figure 4: Pump characteristic curve for 1/2 turn bypass valve

applying a sudden change in one of the parameters (G, q_J) while keeping the remaining factors constant.

3. Results and discussion

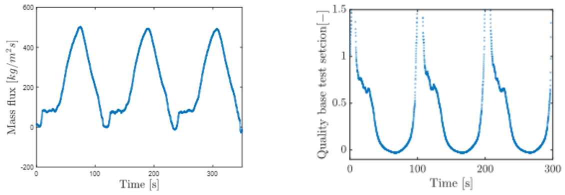
The objective of this experimental study is to examine the occurrence of flow instability and its correlation with various parameters in the forced circulation test facility. Following the procedures outlined above, the experiments were conducted. In this section the data obtained from the acquisition system are presented and discussed.

3.1. Oscillation types

At high heat flux and $7.5bar$ pressure, the oscillations were triggered by sudden drop in the mass flux, then the heating power was reduced in $50W$ steps at a time. In subplot b of each case the quality of the flow at the exit of the heating section was calculated according to Eqn.1.

3.1.1 Irregular intermittent oscillations

At low heat flux, the oscillations took an irregular repetitive shape. It is characterized by high amplitude and long time period. The cycle starts with close to zero flow rate which causes complete evaporation at the heater exit. As shown in Fig. 5b, the void fraction is much higher than 1 (super-heated vapor). As the Quality increases, the void propagation increases the flow gradually, But the condensation takes place in the horizontal piping connecting the heater to the adiabatic riser. As a consequence, the quality drops sharply until the flow becomes two-phase. During this time the mass flux is almost constant and this is called the incubation time. As the quality drops even further, the flow enters the riser as subcooled liquid and the flow temperature at some point is equal to the local saturation temperature and flashing is induced. The vapor bubbles grow due to drop in hydrostatic head, which pushes more flow outside the rise and causing sharp increase in the flow rate. Due to the increased flow rate, the heated section inlet temperature drops, which reduces the quality as seen in Fig. 5b. By the time the mass flux reaches maximum, the quality is minimum, which increases the subcooled liquid reserve in the riser, which -in turn- condenses the front wave of the propagating flashing and the flow rate starts dropping sharply. The inlet subcooling drops again because of the reduced mass flow rate and boiling is initiated, shown in Fig. 5b the quality start increasing until reaches maximum value which induces the next cycle of oscillation.

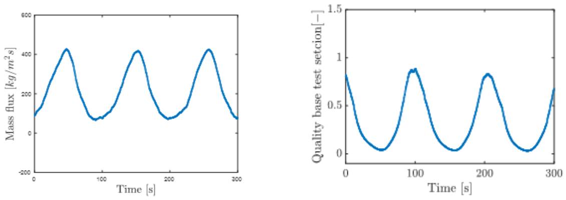


(a) Mass flux curve. (b) Quality.

Figure 5: Irregular intermittent oscillations

3.1.2 Pure sinusoidal oscillations

Under medium heat flux, the oscillation is sinusoidal and the incubation time is vanished. The instability is induced by boiling in the heater and enhanced by flashing in the riser. The flow leaves the heater always as two phase flow as seen in Fig. 6b, which means that continuous boiling is the main trigger of the oscillations. The flow is then condensed in the piping to the riser and flashing is induced, which gives the high jump in amplitude.

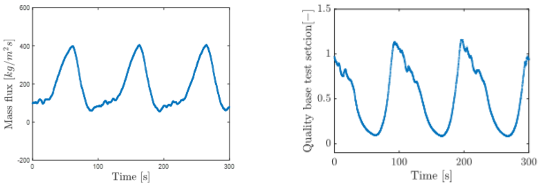


(a) Mass flux curve. (b) Quality.

Figure 6: Pure sinusoidal oscillations

3.1.3 Intermittent Oscillations

With further increase in the power, The incubation time increases and with it increases the time period of oscillations. At low flow rate, $T13$ increases above the corresponding saturation temperature, and the vapor quality becomes slightly higher than 1 (Fig. 7b). The temperature cools down in the adiabatic test section, and other components such as the condenser and horizontal piping, which causes a slight increase in the flow rate with small fluctuations due to eruptions from condensed bubbles (geysering). By the time the temperature approaches saturation and the quality gets close to zero, the flow enters the riser as subcooled liquid and the flashing is induced at some point in the riser which increases the flow to max Fig. 7a. Due to the high flow rate, the inlet temperature is reduced and the quality increases towards a maximum and the cycle is repeated.



(a) Mass flux curve. (b) Quality.

Figure 7: Intermittent oscillations

The wave shapes of forced circulation are similar to the ones mentioned in the work of Wang [9] for a natural circulation system. Based on the discussed types of flashing, the incubation time is affected by the structure of the riser i.e., longer horizontal piping and higher riser extends the incubation time when the flow leaves the heater with a quality close to or higher than 1. The geometry of the riser controls the size of subcooled liquid storage which suppresses the propagating wave of flashing. The instability is a combination of boiling, geysering and flashing, where flashing is more dominant at medium to lower heat fluxes.

3.2. Parameters effect

3.2.1 Pump curve slope

The bypass valve controls the slope of the pump curve. The more the valve is opened, the flatter is the slope. The slopes are superimposed in Fig. 8. Green line is 1/8 turn slope, red line is 1/2 turn and black line is the slope of 1 turn opened bypass valve. The effect of the valve open on the oscillation amplitude is obvious when the mass flux for 1/8 and 1 turns are compared, figures 9a and 9b respectively. The amplitude is almost doubled but the period does not seem to be affected. The increase in amplitude can be reasoned by the slopes as shown in Fig. 8: for the same change pressure drop $\Delta P_{Usection}$ the change of the flow rate will differ based on the corresponding slope i.e., the green line (1/8) turn will give a smaller change in the flow rate compared to the black line (1 turn). Figure Fig. 9 shows the effect of closing the pump bypass valve on the amplitude of oscillations. under the same operating conditions, the instability was triggered and the Mass flux oscillations were captured.

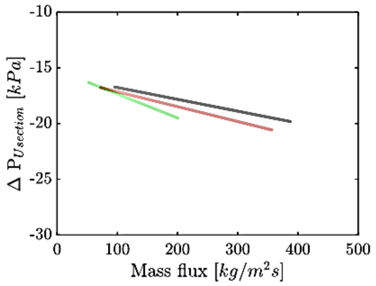
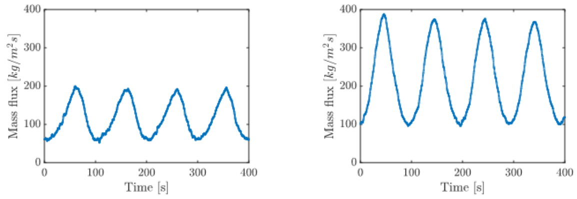


Figure 8: Superimposed slopes of the 3 bypass valve positions

3.2.2 Power

The heating power plays a big role in determining the shape, amplitude, and frequency of oscillations. From Fig. 11 the oscillations change with each step reduction in the power until the power is too small to evaporate the flow and single phase liquid is retained at 50W, Fig. 10. Fig. 11a shows the phase shift between $T13$ and T_{sub} as the power changes, it becomes clear that the shape of oscillation is sinusoidal only when the temperatures are synchronized otherwise the oscillations take an irregular shape and the incubation time increases. For power less than 250 W the waves take an irregular intermittent shape, for 250 W pure sinusoidal and for higher than 250 W it is intermittent. At 400 W the flashing is suppressed and the big peak amplitude is comparable with the amplitude of the fluctuations caused by geysering. The effect of power on amplitude is clarified in Fig. 12a where the amplitude is calculated as $G_{max} - G_{min}$. the amplitude keeps decreasing with the increase of power, which means that the increase of power suppresses the flashing and causes the reduction in the high amplitudes, similar to the results of natural circulation given by Wang [10]. This shows that flashing is more dominant and dangerous at low heat fluxes. The period corresponding to each Power is calculated as the time difference of two successive maximum values of mass flux $t_{G_{max1}} - t_{G_{max2}}$. As for the time period, Fig. 12b shows that the lowest period is for the pure sinusoidal oscillations at 250 W and the other two types of flashing have similar frequencies. This can be reasoned by the zero incubation time of sinusoidal oscillations, since the incubation time is the main reason behind the long periods for the other waves.



(a) Mass flux 1/8 turn. (b) Mass flux 1 turn.

Figure 9: Pump bypass valve effect on the oscillations

3.2.3 Pressure

Starting from system pressure about 6 kPa, the effect of the pressure on the flashing oscillations is observed. from Fig. 13a the oscillations are present, with a comparable amplitude, until the pressure is too high which suppresses the instabilities around 10 kPa and the single phase steady flow is restored. Increasing the pressure

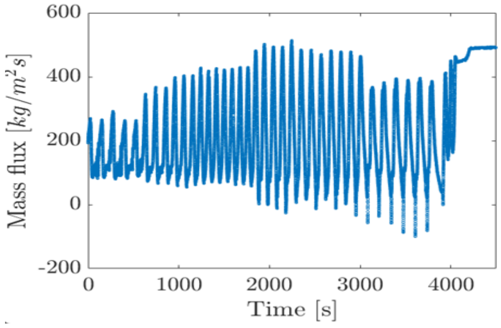
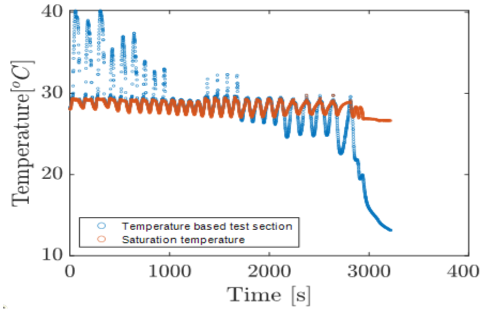


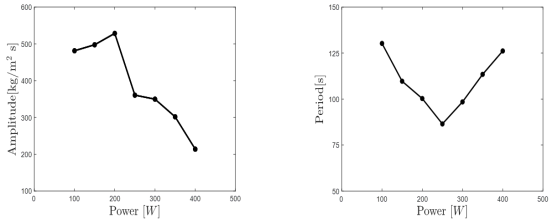
Figure 10: Mass flux oscillations.



(a) Temperature at the exit of the heater.

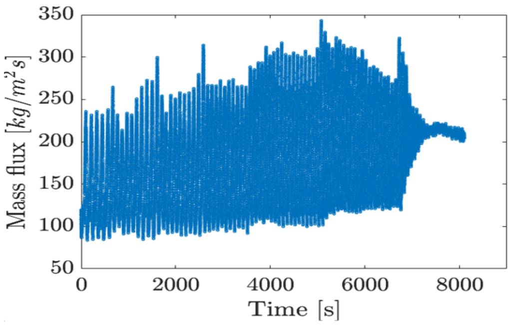
Figure 11: Heating power effect on the oscillations

means increasing the friction force which put resistance against the driving force. It results in a decrease in the density difference between the vapor phase and the liquid phase, as well as a decrease in the latent heat of vaporization. As a consequence, the fluid becomes more prone to vaporization, making it more challenging for the system to generate sufficient driving force under high-pressure conditions. As a result, the self-sustained oscillation is weakened or completely eliminated, and once the resisting force is dominant, the system becomes stable. Zhao [12] showed the effect of system pressure on natural circulation. He showed, on stability maps, that increasing the system pressure significantly suppresses the instability region in the natural circulation system, especially the intermittent oscillation region. In Fig. 14a, at low pressure the pressure drop of the two phase flow across the riser is high which increases the driving force due to higher density difference, hence why the oscillations are showing a higher amplitude. With further increase in the system pressure, the pump head is reduced and the mass flow rate is increased. The steep pump curve Fig. 4 explains the odd shape of the amplitude curve. It is opposite to the trend in case of natural circulation [10], which experienced a monotonic decrease with the increase of pressure. The incubation time is seen to be reduced with the increase in pressure which is reflected on the time period as shown in Fig. 14b.



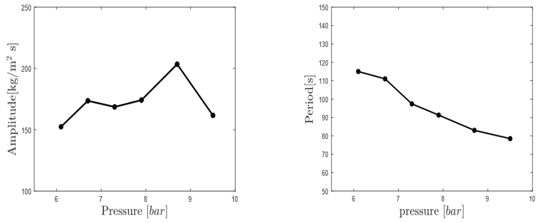
(a) Amplitude. (b) Time period.

Figure 12: Heating power effect on the wave characteristics



(a) Mass flux oscillations.

Figure 13: System pressure effect on the oscillations



(a) Amplitude. (b) Time period.

Figure 14: System pressure effect on the wave characteristics

4. Conclusions

In this thesis the contribution of the friction and buoyancy forces on the flashing instabilities under forced convection is identified. This experimental study is focused on analysing the wave characteristics under the effect of they pump bypass valve, the system pressure and the heating power. Based on the results, the following is concluded:

1. Three wave forms were observed, namely: irregular intermittent, sinusoidal, and intermittent oscillations. The oscillations were caused by a combination of boiling and flashing. The boiling triggers the oscillations but the onset and condensation of flashing cause the jump in amplitude.
2. Reducing the bypass valve open stabilizes the system, while increasing the heating power and system pressure suppresses the flashing phenomena in forced circulation system. The system is stable when the frictional forces are dominant, which happens at high pressure and/or low power (lower than 50 W).
3. Changing the power alters the oscillations shape, amplitude and frequency. The oscillations amplitude are the highest for low heat flux and low pressure conditions. pressurization at the start-up with a pressure higher than 10 *bar* can avoid the instability zone. The incubation time is reduced monotonically with increase in system pressure.

4.1. Future work

Future developments include installing measuring instruments of pressure and temperature along the riser to have better inspection of the flashing phenomenon. Furthermore, the impact of the heater inlet restriction valve on the parameters will be addressed.

References

[1] Masanori Aritomi, Jing Hsien Chiang, Tohru Nakahashi, Masumi Wataru, and Michitsugu Mori. Fundamental study on thermo-hydraulics during start-up in natural circulation boiling water reactors,(i) thermo-hydraulic instabilities. *Journal of Nuclear Science and Technology*, 29(7):631–641, 1992.

[2] JA Boure, AE Bergles, and L S_ Tong. Review of two-phase flow instability. *Nuclear engineering and design*, 25(2):165–192, 1973.

[3] Ezequiel Manavela Chiapero. Two-phase flow instabilities and flow mal-distribution in parallel channels. 2013.

[4] Kenji Fukuda and Tetsuo Kobori. Classification of two-phase flow instability by density wave oscillation model. *Journal of Nuclear science and Technology*, 16(2):95–108, 1979.

[5] SY Jiang, XX Wu, and YJ Zhang. Experimental study of two-phase flow oscillation in natural circulation. *Nuclear science and engineering*, 135(2):177–189, 2000.

[6] Akshay Kumar Khandelwal and Mamoru Ishii. Two-phase flow instability induced by flashing in natural circulation systems: An analytical approach. *International Journal of Heat and Mass Transfer*, 181:121890, 2021.

[7] A Manera, WJM De Kruijf, THJJ Van der Hagen, and RF Mudde. Experiments with the circus-facility on flashing-induced instabilities during startup of natural-circulation-cooled bwrs. In *Proceedings PHYSOR*, pages 7–11, 2000.

[8] Annalisa Manera and Tim HJJ van der Hagen. Stability of natural-circulation-cooled boiling water reactors during startup: experimental results. *Nuclear technology*, 143(1):77–88, 2003.

[9] Qiang Wang, Puzhen Gao, Xianbing Chen, Zhongyi Wang, and Ying Huang. An investigation on flashing-induced natural circulation instabilities based on relap5 code. *Annals of Nuclear Energy*, 121:210–222, 2018.

[10] Sipeng Wang, Yu-Chen Lin, Guanyi Wang, and Mamoru Ishii. Experimental investigation on flashing-induced flow instability in a natural circulation scaled-down test facility. *Annals of Nuclear Energy*, 171:109023, 2022.

[11] Eugene H Wissler, HS Isbin, and NR Amundson. Oscillatory behavior of a two-phase natural-circulation loop. *AIChE Journal*, 2(2):157–162, 1956.

[12] Yanan Zhao, Minjun Peng, Yifan Xu, and Genglei Xia. Simulation investigation on flashing-induced instabilities in a natural circulation system. *Annals of Nuclear Energy*, 144:107561, 2020.