EXPERIMENTS WITH THE CIRCUS FACILITY ON FLASHING-INDUCED INSTABILITIES DURING START-UP OF NATURAL-CIRCULATION-COOLED BWRS

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ABSTRACT

Stability measurements under low-pressure, low power-conditions have been performed on the CIRCUS facility, a full-height scaled steam/water loop of a natural-circulation-cooled BWR. In the start-up regime the flashing phenomenon has to be addressed as the main cause of instability. The first experiments show the occurrence of large flashing-induced non-linear oscillations. It is shown that a contra-intuitive increase of the heating power allows to overcome the flashing-instability region.

1. INTRODUCTION

In natural-circulation boiling water reactors (BWRs) two main different types of instabilities can occur, the so-called Type-I and Type-II instabilities [1]. Type-I instabilities are mainly due to the decrease in gravitational pressure head along the ascendant section of the system; they appear only if a long adiabatic section is present above the core, i.e. in natural-circulation-cooled BWRs, where a long riser built above the core is used to enhance the natural-circulation flow rate. Type-II instabilities are caused by the phase lags between the one- and two-phase frictional pressure losses in the core section and can therefore also occur in conventional BWRs, in which pumps are used to maintain the coolant circulation.

At low pressures, the Type-I instability region becomes more pronounced as a result of the so-called flashing phenomenon [2], i.e. boiling due to the decrease in hydrostatic head along the flow path of the coolant. The importance of this instability region at low pressures and low powers has been recognised only in the last years, because it is relevant for the design of innovative reactors types such as the ESBWR [3]. Indeed, instabilities at low pressures have been observed in experimental facilities [2], [4], [5], and flow resonances have been recorded during start-up experiments of the Dutch natural-circulation-cooled BWR Dodewaard [6]. The phenomena involved appear to be complex and have not been fully clarified; therefore more experimental data are needed for a better understanding of the relevant physical processes and to improve and validate thermalhydraulics codes in the low-pressure, low-power regimes.

2. THE CIRCUS FACILITY

The experimental test facility CIRCUS has been built at the Delft University of Technology to study two-phase flow dynamics during start-up conditions of innovative Boiling Water Reactors based on natural-circulation cooling. An important feature of the facility is that the main components are made of glass, allowing direct visualization of the flow and enabling a better understanding of the physical phenomena involved. A scheme of the facility (not to scale) is reported in Figure 1.

The facility is a full-height scaled steam/water loop of the Dodewaard reactor. The reactor core is simulated by 4 electrically heated fuel rods in coolant channels and by 4 separate bypass channels. The friction of each individual coolant or bypass channel can be regulated by means of an inlet valve block. The power of each fuel rod can also be varied separately. On the top of the core section, a long cylindrical glass tube is used to simulate the riser section. As mentioned previously, a long adiabatic section above the core is needed to enhance the natural-circulation flow rate. The two-phase mixture is condensed and cooled by means of a heat exchanger. A buffer vessel is used to damp temperature oscillations that can occur at the exit of the heat exchanger because of flow oscillations; a heater in the buffer vessel is used to control the temperature at the core inlet. Through the downcomer the water returns to the inlet of the core section. A valve allows regulation of the downcomer friction. The system pressure is regulated with a steam vessel, representing the steam-dome in a BWR, or alternatively with an expansion vessel in which a membrane is used to separate the water from the compressible air volume.

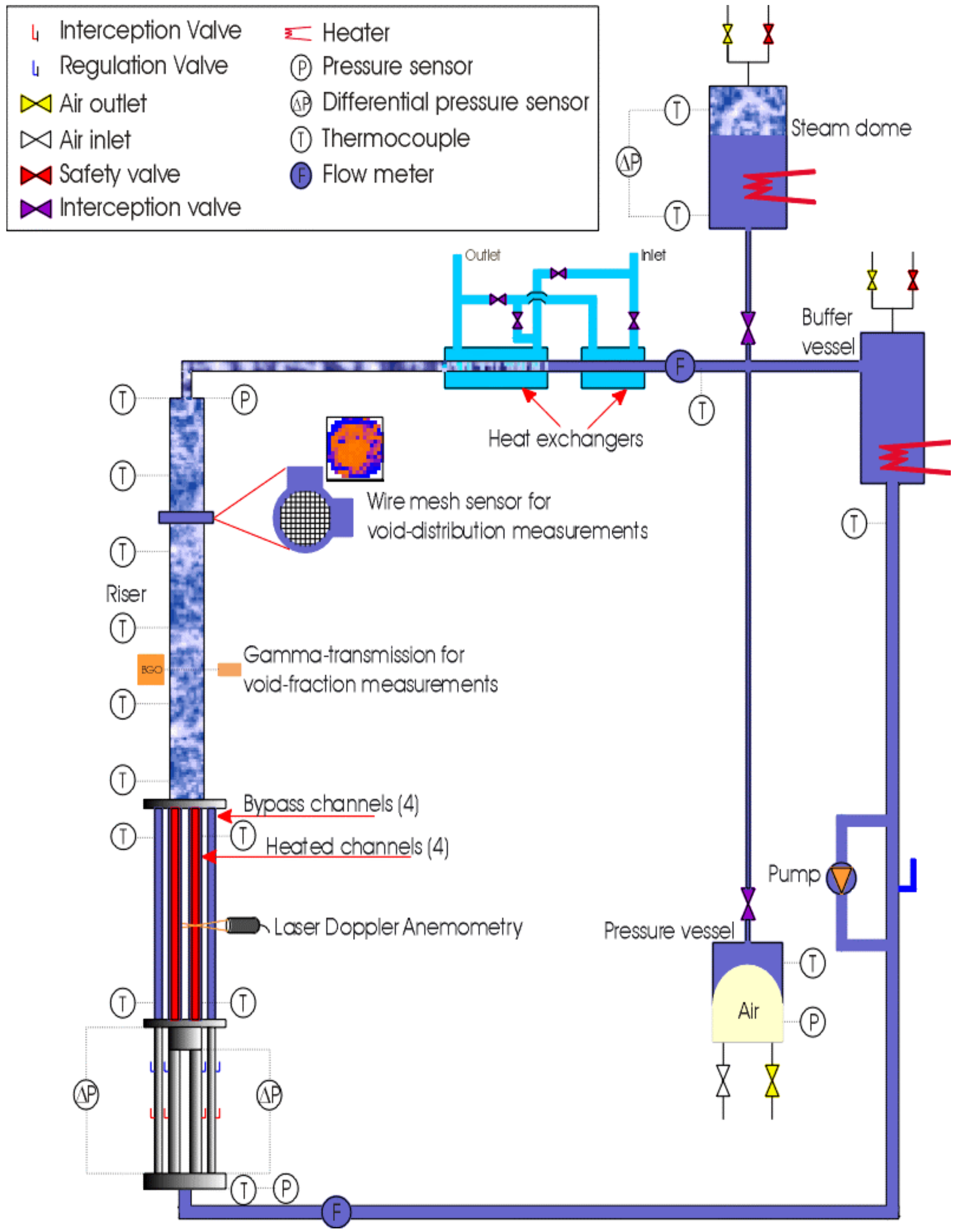


Figure 1: Scheme of the CIRCUS facility (not to scale). The main instrumentation is also shown.

The facility is equipped with thermocouples, flow meters, pressure sensors and with the following special instrumentation:

a) a laser-doppler-anemometry apparatus to measure local velocity fluctuations;
b) a gamma-transmission system to measure chordal void-fractions at different heights;
c) a wire-mesh sensor mounted at the top of the riser to measure the void-fraction distribution.

In Table 1 the main characteristics of the facility are given.

Table 1: Main characteristics of the CIRCUS facility.

Power range per rod	0-3 kW
Pressure range	1-5 bar
Fuel channel diameter	20.4 mm
Fuel rod diameter	12.5 mm
Bypass channel diameter	10 mm
Fuel channel length	1.95 m
Riser diameter	47 mm
Riser length	up to 3 m

3. DESCRIPTION OF STABILITY MAPS

In Figure 3 typical dimensionless stability maps obtainable with simple analytical models [7] are reported for a natural circulation thermalhydraulic system respectively at high and low pressure. The Zuber-subcooling plane [8] has been widely used in previous works to represent stability of such systems for which subcooling, power and flow rate are not independent. The Zuber number reported on the x-axis is directly proportional to the heating power and inversely proportional to the mass flow rate, while the subcooling number is proportional to the subcooling at core inlet.

The two different instability regions Type-I and Type-II are shown; the dashed line separates the one-phase from the two-phase flow operating points. The inaccessible region depicted in Figure 2.b represents operational points in which the temperature at the inlet of the core is higher than the saturation temperature at the riser exit. These points are inaccessible during normal reactor operation.

For a constant given subcooling, it is possible to cross four different regions (see arrow in Figure 2.a) by increasing the Zuber number. These regions are:

1. the stable one-phase region;
2. the unstable two-phase Type-I region;
3. the stable two-phase region;
4. the unstable two-phase Type-II region.

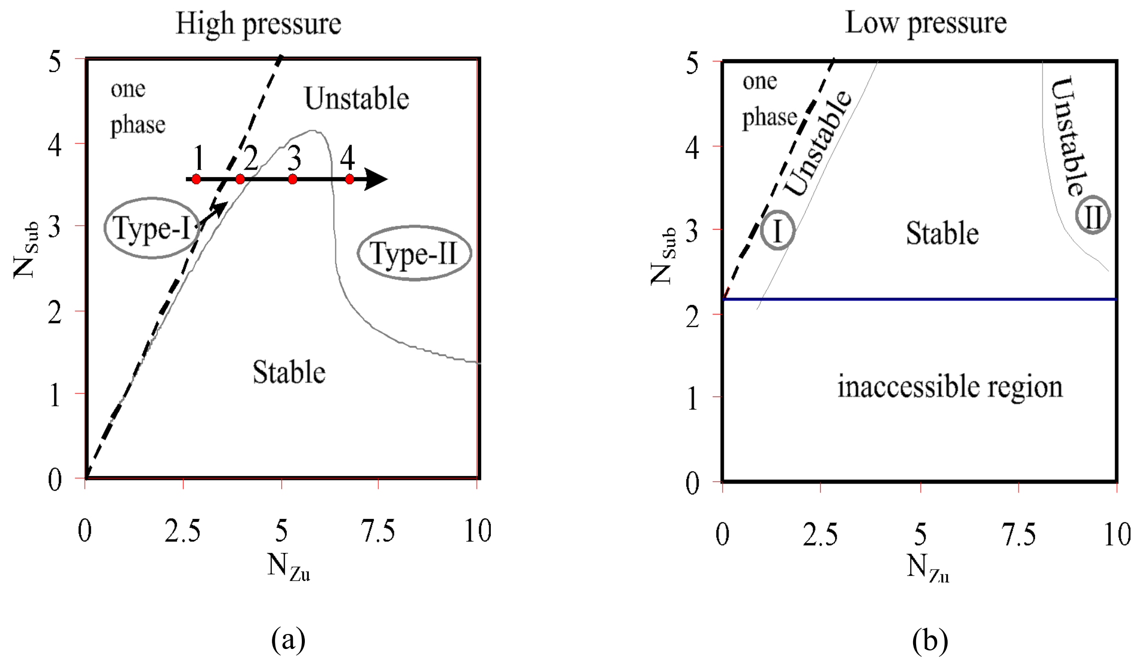


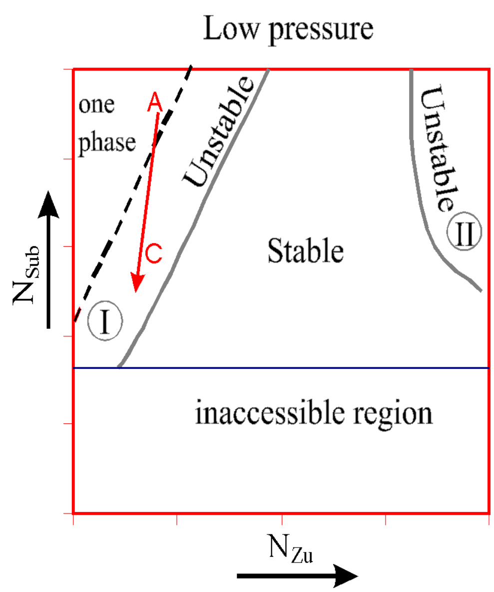
Figure 2: Dimensionless stability maps for a thermalhydraulic natural circulation system without (a) and with (b) flashing.

The Type-II instabilities can also occur in conventional BWRs, where pumps are used to maintain the coolant circulation (forced circulation). For this reason the transition from region 3 to 4 and the Type-II instability region have been studied extensively in the past, especially after the occurrence of large amplitude power oscillations in the conventional BWRs Caorso and LaSalle [9]. In this paper we will focus on experiments performed in region 2 (Type-I instabilities) at low pressures.

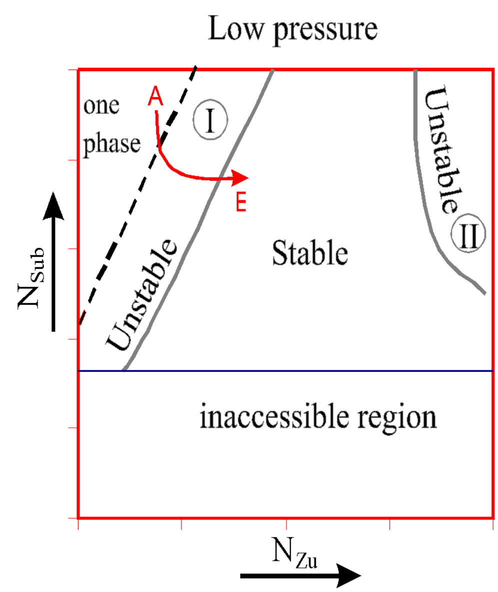
From Figure 2 it is evident that the Type-I instability region becomes larger at low pressure and has necessarily to be crossed to go from one-phase to two-phase natural-circulation flow. The enlargement of the unstable region is due to the flashing phenomenon. In fact, due to the considerable length of the adiabatic section above the core, the decrease in pressure head becomes significant. Since at low pressures the saturation temperature is strongly dependent on the pressure, also the saturation temperature decreases considerably along the riser section. This means that subcooled fluid leaving the core can reach saturation conditions at a certain height in the adiabatic section above the core, giving rise to a sudden void production (flashing). This void production leads to a rapid increase of the flow rate and thus to a decrease of the fluid temperature at the core exit. The flow will then decrease because the fluid no longer flashes in the riser. Subsequently, the fluid temperature in the core will again increase, giving rise to new void production in the riser section due to flashing. This process can become self-sustained and limit cycles occur.

4. SETS OF MEASUREMENTS PERFORMED

Two sets of measurement have been performed in the Type-I unstable region: the first series has been carried out at constant power and different inlet subcooling, the second series at constant inlet subcooling and different power levels. An indication of the path followed on the stability map during the two series of experiments is reported in Figure 3.a and Figure 3.b (red curve).



(a) Measurements at constant power and increasing inlet core temperature



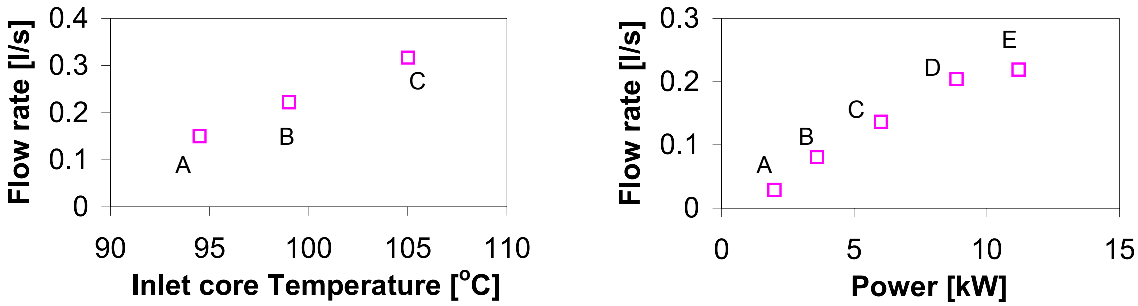
(b) Measurements at constant subcooling and increasing heating power

Figure 3: Indicative path (red) followed on the stability map in the first (a) and in the second (b) series of measurements, performed at constant power and at constant subcooling, respectively. In both cases the measurement started from the stable one-phase flow region.

In Figure 4 the flow rate is reported as a function of the controlled variable, respectively the inlet core temperature for the first set of measurements and the heating power for the second set. In both series of experiments the average flow rate increases from case to case.

In the first series of measurements the Zuber number decreases monotonously, since the mass flow rate increases and the power level is kept constant. The subcooling decreases because the experiments have been performed at increasing inlet core temperature.

In the second series of measurements the Zuber number increases monotonously despite the flow rate increase. This is because the relative increase in power is larger than the relative increase in flow rate. All operational points lie on a horizontal line since the experiments have been performed at constant inlet core temperature, with the exception of the first operational point in the stable one-phase flow region, that has been measured at a lower inlet core temperature (measurement A).



(a) (b)

Figure 4: Flow rate as a function of the controlled variable in the performed two series of measurements. The flow rate increases both for decreasing subcooling at constant power (a) and for increasing power at constant subcooling (b).

5. FROM STABLE ONE-PHASE TO UNSTABLE TWO-PHASE FLOW AT CONSTANT POWER

In the first set of experiments the Type-I region has been crossed starting from one-phase natural-circulation flow. The power has been kept constant, the operating condition has been changed by varying the core inlet temperature (see Figure 3.a). In Figure 5 the time traces of relevant signals corresponding to three operational points A, B and C are reported. Together with the inlet core flow rate, the temperature signals at the core inlet, riser inlet and riser outlet are shown. The difference between the temperatures at the inlet and at the outlet of the riser in stable one-phase conditions is partly due to heat losses along the riser section and partly due to absolute uncertainty in the temperature measurements (the exact absolute values of riser temperatures are not important for the work presented in this paper).

In case A shown in Figure 5 the natural-circulation flow is initially single-phase. The inlet core temperature has been gradually increased until the coolant starts flashing at the top of the riser. Flashing has an immediate effect on the flow rate, due to the abrupt decrease of the fluid density in the ascendant section of the loop (a first small peak in the flow is visible around 250 seconds). The flow changes originate temperature changes (peaks in the temperatures at the inlet and at the outlet of the riser following the peaks in the flow rate can be observed in Figure 5.A).

With increasing inlet temperature, a greater region of the riser section undergoes flashing and larger amplitude oscillations appear in the flow (see cases A, B and C in Figure 5).

Once flashing starts, periodic oscillations of constant amplitude can be observed, if the inlet core temperature is kept constant. Limit cycles can be seen in Figure 5.B and in Figure 5.C; note that the amplitude of the flow oscillation can be considerable (more than 300 % in case B and more than 400 % in case C shown in Figure 7).

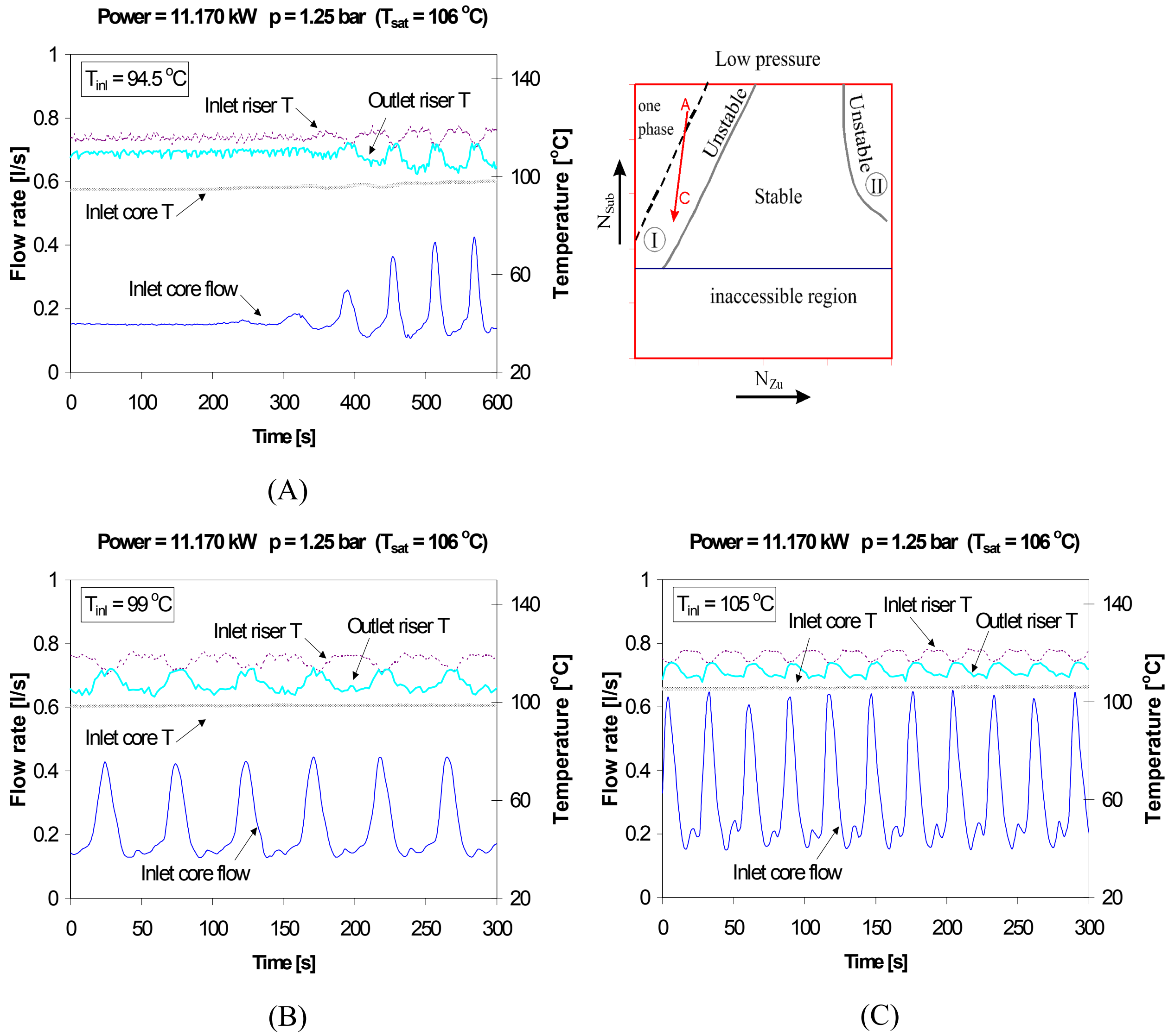


Figure 5: Time traces recorded at constant power and decreasing subcooling. At the top right the path followed on the stability map passing from case A to C is shown.

From Figure 5 it can be seen that inlet core flow rate and inlet riser temperature are approximately out-of-phase. During the abrupt flow increase, colder water suddenly enters the riser section. Thus, a maximum of the flow rate corresponds with a minimum of the inlet riser temperature. As a consequence of the flow increase, the coolant does no longer flash in the riser section, the flow decreases again and the flow temperature starts increasing. Flashing can then occur and a new peak in the flow rate is generated. The recorded time traces of flow rate and temperatures confirm our idea on the nature of flashing-induced instabilities.

In Figure 5 it can be observed for cases B and C that a small peak of the flow rate precedes the large peak. It seems plausible that this peak is a direct consequence of the (subcooled) boiling observed in the core section during the performed experiments. In fact, it was clear from visual inspection that bubbles were generated at the rods' surfaces and collapsed in the bulk of the fluid, giving a small contribution to the flow increase. This process was then followed by flashing in the riser, cause of the successive large peak in the flow.

In Figure 5.C the small flow peak due to (subcooled) boiling is more evident than in Figure 5.B, since in case C the inlet core temperature is higher and less bubbles collapse in the bulk of the fluid.

From the experiments shown, it is clear that the period of the oscillations becomes shorter with increasing inlet core temperature (from about 64 seconds in Figure 5.A to about 29 seconds in Figure 5.C). This result was expected since the period of the oscillations is inversely proportional to the velocity with which enthalpy perturbations travel in the system; the oscillation period is therefore inversely proportional to the flow rate, that increases from case A to case C (see Figure 4.a).

5. FROM STABLE ONE-PHASE TO STABLE TWO-PHASE FLOW AT CONSTANT SUBCOOLING

In the second set of experiments the Type-I instability region has been crossed at constant subcooling. Starting again from the one-phase region (Figure 6.A) without any flow and temperature oscillation, the zero-quality line that separates the one-phase from the two-phase flow operational conditions has been crossed increasing the power level of the core. At a power level of 3.6 kW flashing can be observed (Figure 6.B), leading again to flow and temperature oscillations. In contrast to the first series of measurement shown in Figure 5, strongly asymmetrical peaks appear this time in the flow rate. The period of the oscillation is quite large due to the very small flow rate. As expected, the oscillation amplitude increases as the power increases, since the operational condition moves deeper in the unstable region (Figure 6.C). The oscillation period keeps decreasing due to the continuous increase of the average flow rate.

A further increase of the power leads to a contra-intuitive decrease of the oscillation amplitude, while the average flow rate keeps increasing (Figure 6.D). This is because the operational point is moving from the unstable Type-I region to the boundary of the stable two-phase region (see arrow direction on the stability map at the top right of Figure 6).

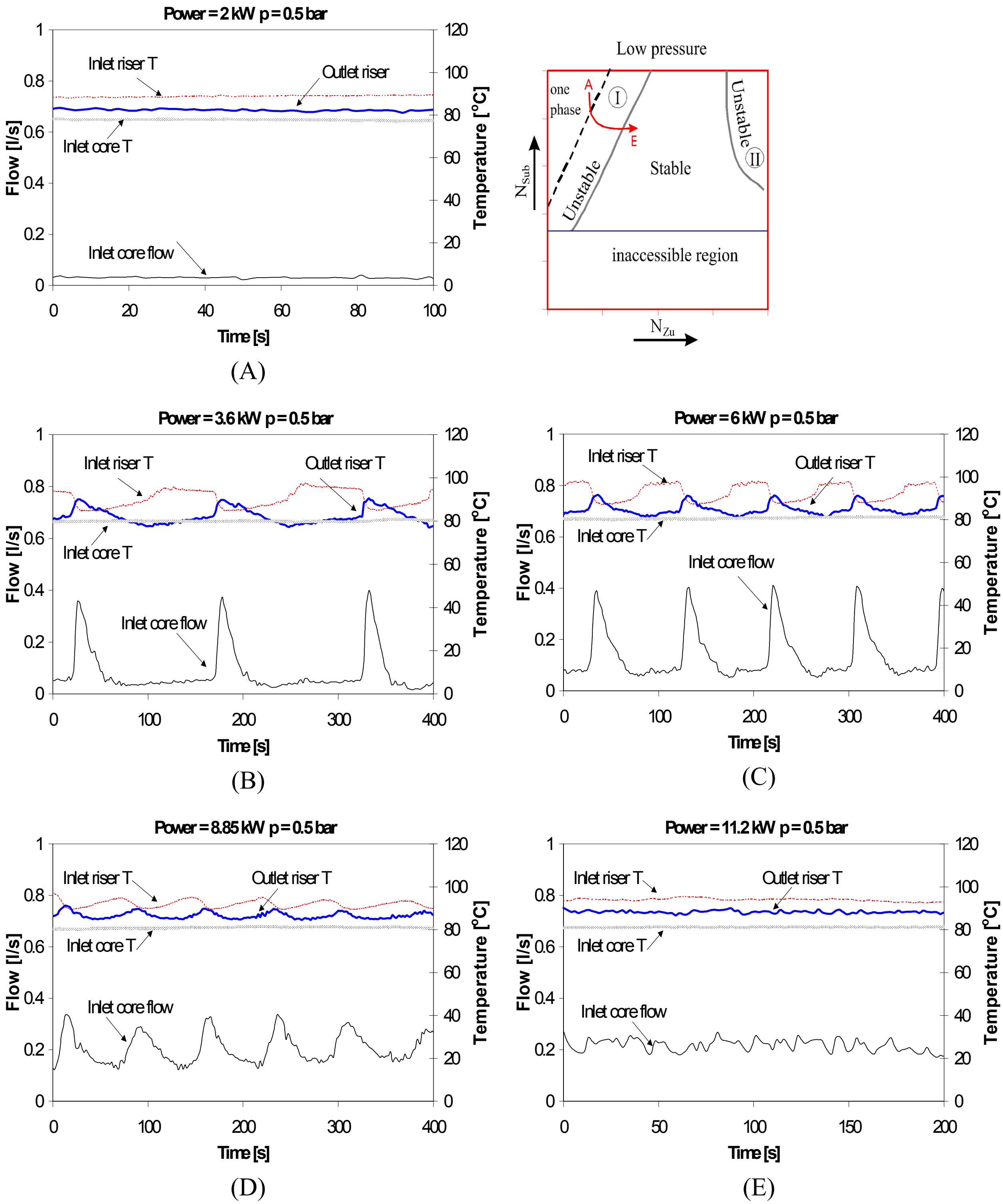


Figure 6: Time traces recorded at constant subcooling and increasing power level. At the top right the path followed on the stability map passing from case A to E is shown.

No large changes in the phenomenology have been observed compared to the previous set of measurements. Also in this second series of experiments on flashing-induced instabilities, (subcooled) boiling was observed. After each flow minimum (due to single-phase natural-circulation flow), bubbles are generated in the core as in the first set of measurements, but this time the bubbles generated do not condense in the riser due to the lower subcooling at the core exit. This continuous generation of bubbles gives rise to the plateau in the flow signal shown in Figure 6.B and in Figure 6.C. The plateau can also be seen in Figure 6.D, but it is no longer preceded by a minimum in the flow rate since in this case single-phase natural-circulation never occurs.

Increasing the power level again (Figure 6.E), a new stable condition is achieved, this time in the two-phase flow regime. The stable two-phase region has been entered. Steam is continuously generated and flows upward in the riser section. In contrast to figure 6.D, no large peaks due to flashing are observed.

CONCLUSIONS

The CIRCUS facility has been used to study natural-circulation-cooled BWRs dynamics at low powers and low pressures conditions. Flashing-induced instabilities have been observed, leading to self-sustained large-amplitude flow oscillations. It has also been shown that by increasing the power the system moves from the stable one-phase flow region, crosses the unstable two-phase flow region and moves into the stable two-phase flow region.

It can be concluded that a natural-circulation-cooled BWR can encounter instability problems during start-up. The reactor becomes stable again with power increase. This behavior is consistent with stability maps obtained by means of simplified analytical models.

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