

NATURAL CIRCULATION FLOW BEHAVIOR AT REDUCED INVENTORY CONDITIONS

P.P. Kulkarni, A. K. Nayak*, P. K. Vijayan, D. Saha

Reactor Engineering Division
Bhabha Atomic Research Centre
Mumbai, India 400085

Abstract

The flow instability behaviour of a natural circulation loop was studied at reduced inventory conditions, which is important during a LOCA situation in a nuclear reactor with non-availability of circulating pumps. For this, experiments were conducted at low steam drum levels. Large amplitude U-tube type oscillations were observed at low power condition when the system was mostly under single-phase condition. With rise in power when boiling was initiated in the loop, low quality Type I density-wave instabilities were observed. The characteristics of Type I instabilities are found to be quite different from the oscillations observed under single-phase conditions.

Introduction

Boiling two-phase natural circulation loops have several applications in nuclear and process industries due to their simplicity, low maintenance and operational cost, etc. Many of the new generation reactors including that of the Indian Advanced Heavy Water Reactor (AHWR) also rely on natural circulation for removal of fission heat generated in the reactor core. Currently operating PHWRs and PWRs depend on natural circulation for removal of core decay heat following non-availability of circulating pumps. In these reactors, in addition to single-phase natural circulation, two-phase natural circulation can also occur if there is progressive decrease of system inventory following a LOCA situation. With decrease in system inventory, the pressure in the system also falls gradually and the decay power also reduces with time. Hence, it is of important to study the natural circulation behaviour in such systems at different reduced inventory conditions at different pressure and power levels.

One of the major characteristics of natural circulation is that it can be unstable depending on the system geometry and operating conditions. Flow instabilities are undesirable since they not only reduce the thermal margin but also make the system operation difficult. The characteristics of instabilities at different operating conditions can also be different. A literature review suggests several investigations have been carried out in the past to understand natural circulation instability behaviour in single and two-phase systems. Experimental investigations in two-phase natural circulation loops having single heated channel have been carried out by Jain et al.[1], Chexal et al. [2], Lee et al. [3], Jiang et al. [4] and Wu et al. [5]. They observed density wave instability in their experiments, which was found to be affected by channel exit restriction, inlet subcooling, pressure and channel inlet restriction. The effect of downcomer level was experimentally studied by Chexal et al. At low powers and low pressures, the natural circulation loops are susceptible to several types of instabilities as described in the literature by Boure et al. [6], Aritomi et al. [7], Kyung and Lee [8], Jiang et al. [4], and Nayak et al. [9]. Flashing, geysering and Type I density wave oscillations are typical examples. These instabilities may or may not occur in isolation.

In the present work, experiments have been carried out to understand flow instability behaviour of a single and two-phase natural circulation loop at reduced inventory conditions. The experiments were carried out over a wide range of power and pressure conditions and from single-phase to two-phase conditions. The instability characteristics under single-phase condition were found to be quite different from that with initiation of boiling.

1. Experimental set-up

A schematic of the experimental set-up is shown in Fig. 1. The experimental loop consists of a vertical tubular heater directly heated by electric current up to a maximum power of 80 kW. The inner diameter of heated section is 52.5 mm. Subcooled water enters the heater at the bottom and gets heated as it rises through the test section due to buoyancy. The steam water mixture coming out of the heater rises through the riser section and is passed on to a vertical separator. In the separator, the steam gets separated from the water by gravity. The steam then goes to the condenser where it gets condensed and the condensate falls back to the separator through a pipe that joins the separator at the bottom. The condenser is a 1-2 shell and tube type heat exchanger with steam condensing on the shell side and cooling water flowing in the tube side. The elevation of the primary loop is about 3.35 m and the length of the heated section (test section) is about 1.18 m. The horizontal length of the loop is 3.4 m. Further details of the experimental set up are given in the report by Kumar et al. [10].

The natural circulation flow rate in the loop is measured by calibrating the pressure drop across 2 m length of horizontal pipe (the flow in this stretch of pipe is single-phase) under forced flow with a differential pressure transmitter. The pressure drop measured across this pipe is used to calculate the flow rate using the pipe friction factor correlation developed using the data from the calibration runs as shown in Fig. 2. This method is adopted to minimize the pressure losses in the loop (with the possible insertion of orifice or venturimeter), which has significant influence on the natural circulation behavior. The loop pressure is measured with a strain gauge type pressure transducer having sensitivity of 2.0 mV/V. Temperature at various locations are measured with K-type (Chromel-Alumel), 1 mm OD mineral insulated thermocouples. All the data were recorded on-line using a fast data acquisition system. The sampling time was one second.

Accuracy of measurement are as follows:

Temperature: $\pm 0.75\%$ of span (0-400 °C)

Pressure : $\pm 0.35\%$ of span (100 bar)

Level : $\pm 0.2\%$

The experimental conditions and loop dimensions are shown in Table 1.

Table 1: Experimental conditions and geometry of the loop

Pressure	1 bar to 35 bar	
Working fluid	Water	
Power	0 to 70 kW	
Level	5 % to 85 % of full SD level	
Component	Pipe	I.D (in mm)

Test Section	50 NB Sch. 40	52.5
Loop	50 NB Sch. 80	49.25
Steam Drum	150 NB Sch. 120	139.7

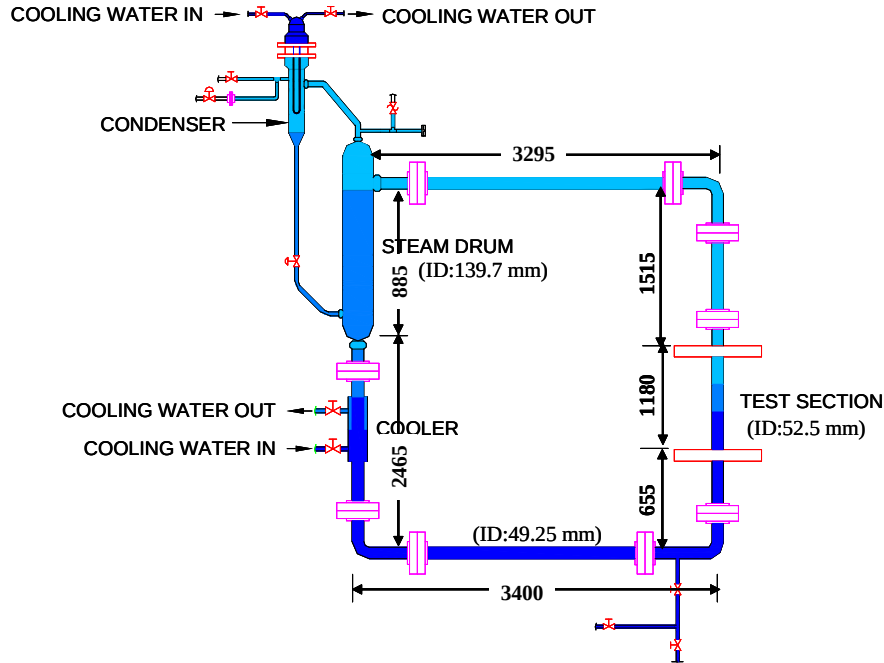


Figure 1 Schematic of high pressure natural circulation loop

2. Experimental procedure

The primary loop was filled with water under ambient conditions and all instruments were vented. The loop was pressurized to required initial pressure by using nitrogen and then the steam drum (SD) level was brought to required level by draining the inventory. Then experiments were carried out by supplying power to the test section. Power was raised in steps of 2 kW in every 30 minutes. To maintain the required pressure after power is raised, venting of nitrogen from SD was carried out. This was continued till temperature readings at the entry of the steam drum and at the condenser are equal and corresponds to the saturation temperature of prevailing SD pressure to ensure complete evacuation of nitrogen from the system. If the pressure still increases with the increase in power, pressure was stabilized by adjusting the condenser cooling water flow rate.

3. Results and discussions

The details of experiments carried out are as given in Table 2

Table 1: Experimental test matrix

SD Pressure	SD level
4 bar	85 %
4 bar	50 %
4 bar	10 %

10 bar	85 %
10 bar	50 %
10 bar	10 %

3.1 Natural circulation from rest state

Figure 2 shows an example of the natural circulation behaviour of the loop at 85 % steam drum level. The flow was initiated from rest condition with addition of power in steps of 2 kW. It can be seen that, with the addition of power, in absence of heat sink the fluid temperature keeps on increasing which increases the buoyancy force leading to continuous increase of mass flow rate.

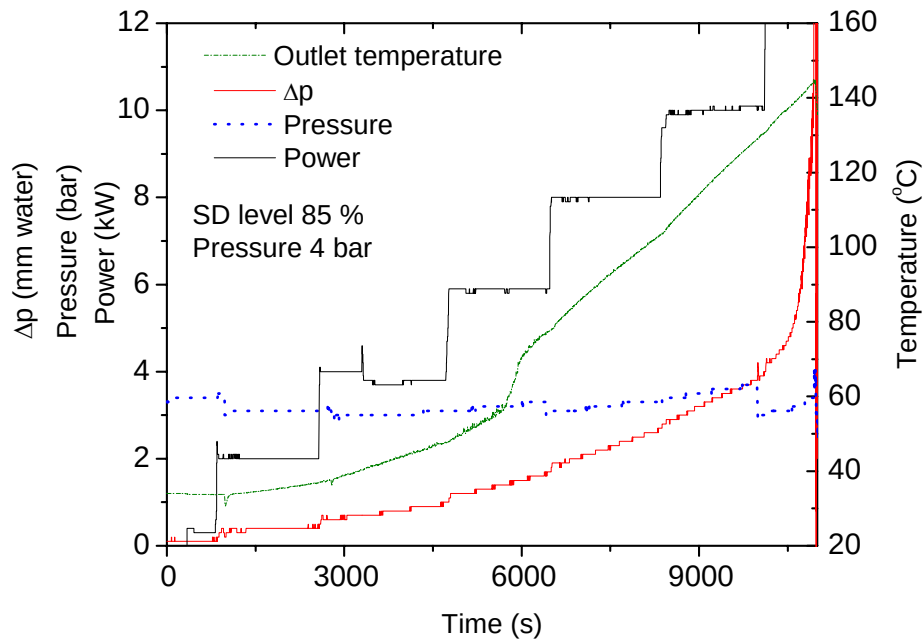


Figure 2. Natural circulation from rest state at 85 % SD level

Figure 3 and 4 show the natural circulation behaviour at reduced inventory i.e 50 % and 10 % SD level. Here we can see that, in single phase natural circulation region, highly oscillating flow is observed. Because of low steam drum level, a U-tube manometer type situation arises in the natural circulation system. When the power supply is turned on, then local boiling starts and liquid tries to move up due to the buoyancy force available between downcomer and riser. But, due to higher frictional force in the riser section as compare to small buoyancy force developed at low power, liquid is not able to form a complete loop. Hence it will start oscillating. The oscillation amplitude increases with increase in power. Also, as shown in figs 3 and 4 it is observed that, the amplitude at low power region (3000 s – 9000 s) is higher for lower steam drum level (10 %) than at relatively higher steam drum level (50 %). Whereas the amplitude of oscillation is more or less similar for both in the region just before boiling (9000 s to 12000 s).

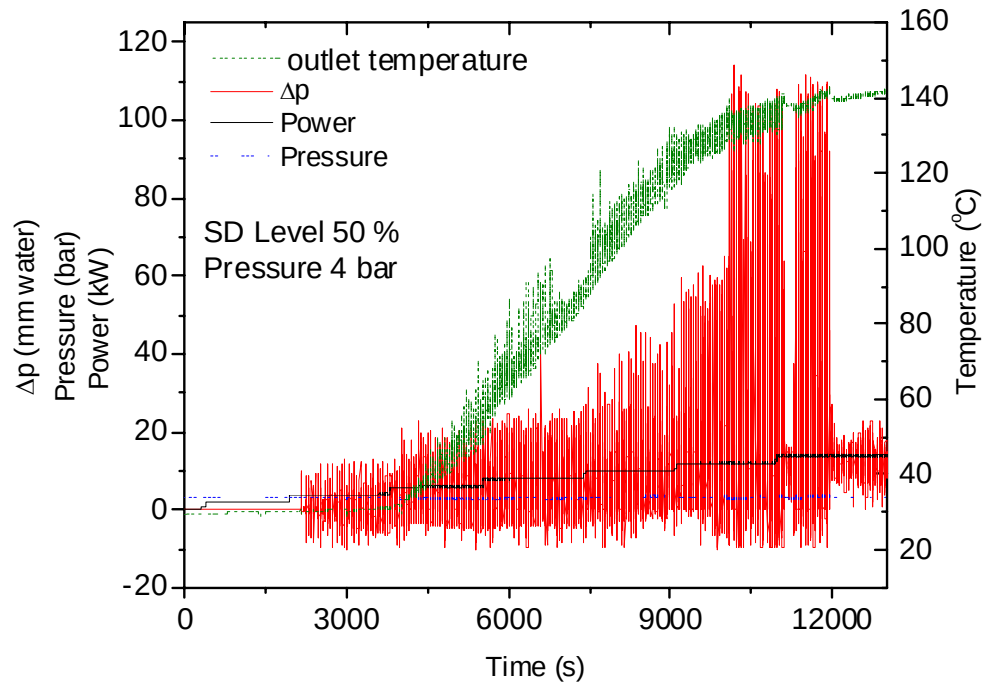


Figure 3 Natural circulation from rest state at 50 % SD level

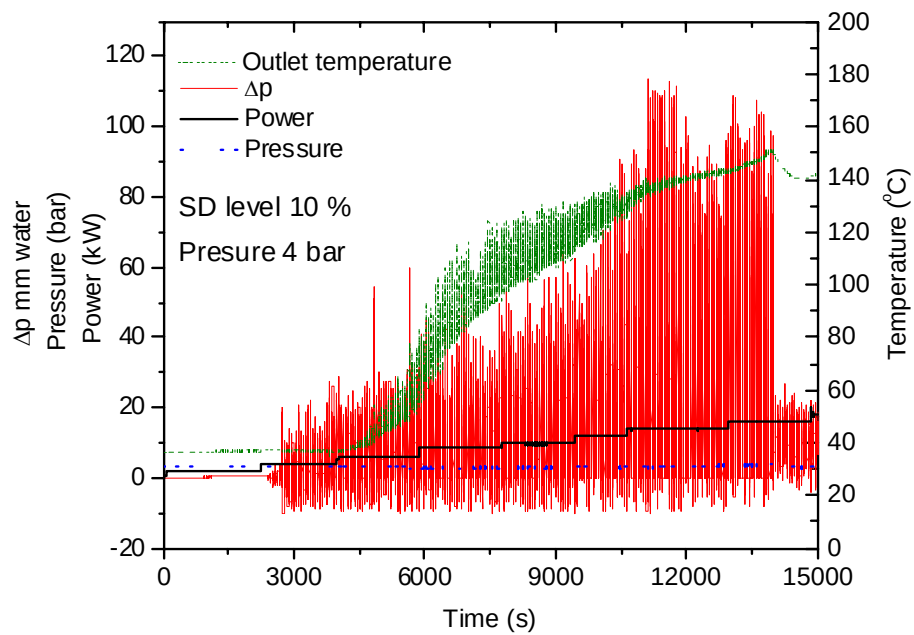


Figure 4 Natural circulation from rest state at 5 % SD level

3.2 Natural circulation behaviour during inception of boiling

Figures 5-7 show the natural circulation characteristics during inception of boiling for 85 %, 50 % and 10 % SD levels. It can be seen in Fig 5 that, after inception of boiling, at 85 % level oscillations are observed which are characteristics of type – I instability. On the contrary, after boiling is established, the oscillations in 50 % and 10 % level are diminished and a stable flow is formed. This is because, once boiling is induced, the vapor can reach the steam drum through the riser, get condensed in the condenser and again the condensate is returned to the steam drum establishing a complete loop.

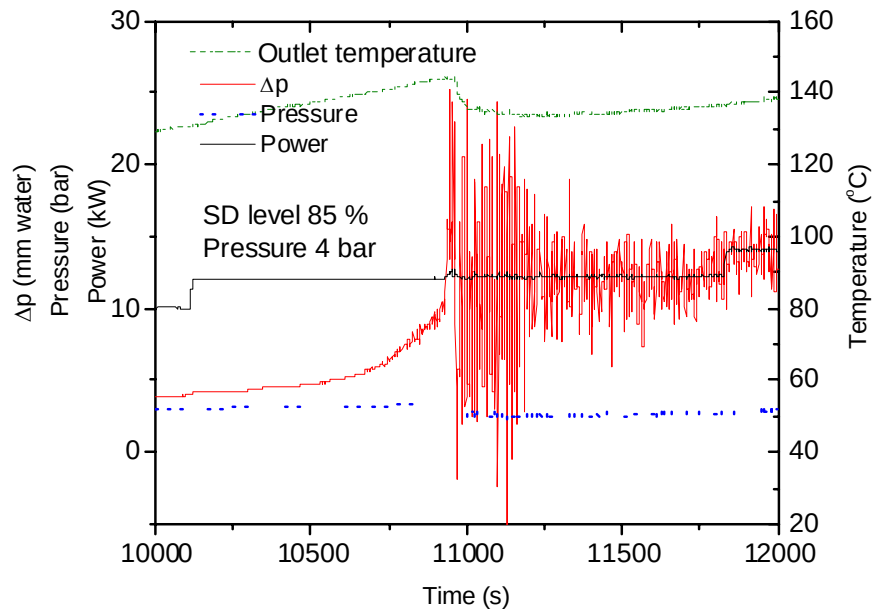


Figure 5 Natural circulation behaviour at inception of boiling at 85 % SD level

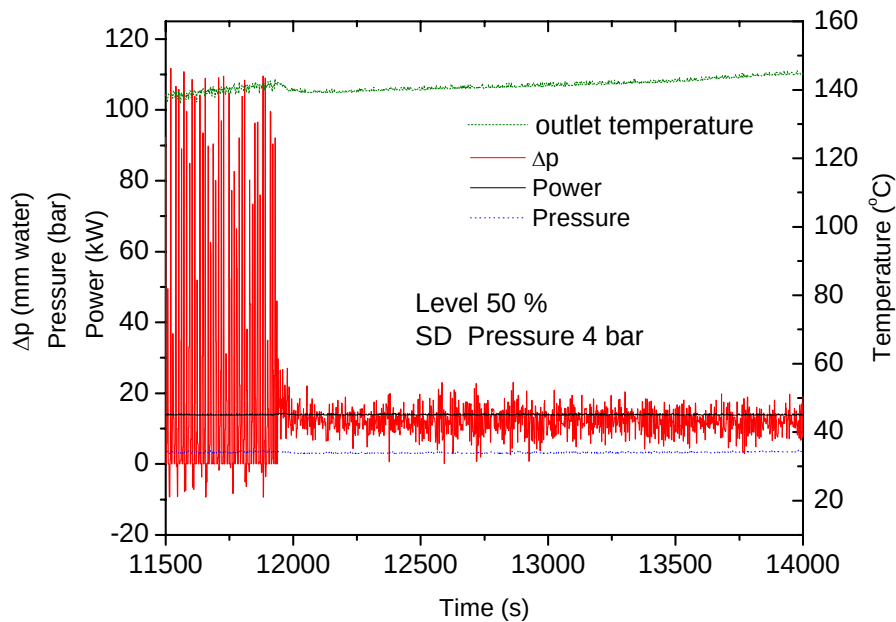


Figure 6 Natural circulation behaviour at inception of boiling at 50 % SD level

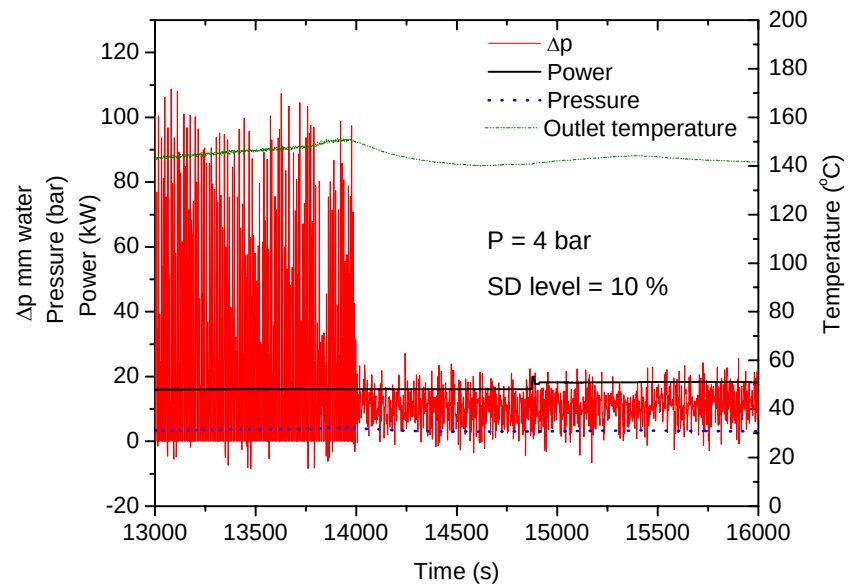


Figure 7 Natural circulation behaviour at inception of boiling at 5 % SD level

Once the stable two phase flow is formed, natural circulation behaviour at all the steam drum levels is observed to be similar.

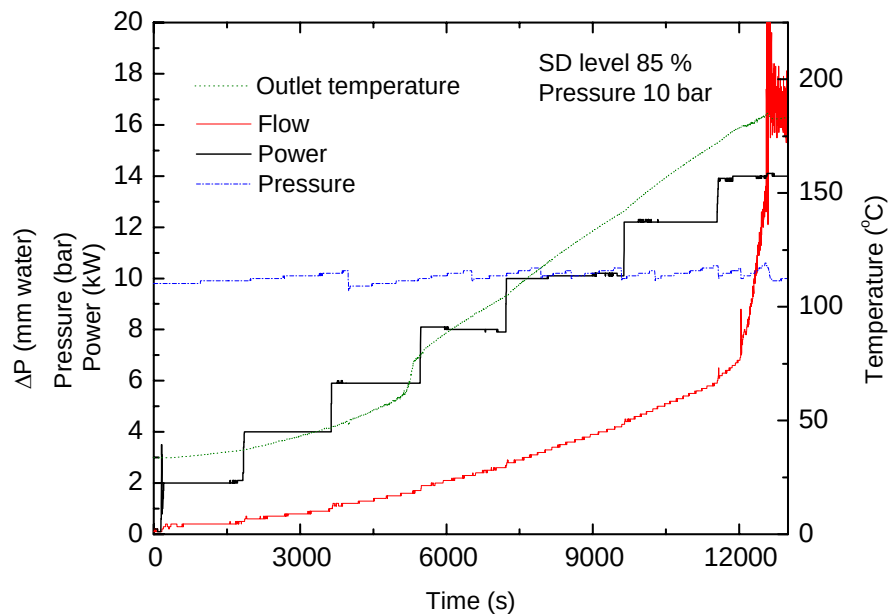


Figure 8 Natural circulation behaviour from rest at 10 bar and 85 % SD level

3.3 Effect of increased SD pressure

Similar experiments were carried out at 10 bar SD pressure. As seen in Fig. 8, there is very little difference in single phase natural characteristics in 85% SD level case. Only, because of increased pressure, boiling occurs at higher power input. However, the flow rate corresponding to input power is same in both the cases.

For 50 % and 10 % cases, the natural circulation behaviour is similar i.e. oscillations are observed till boiling is occurred but, the amplitude of oscillations is substantially reduced.

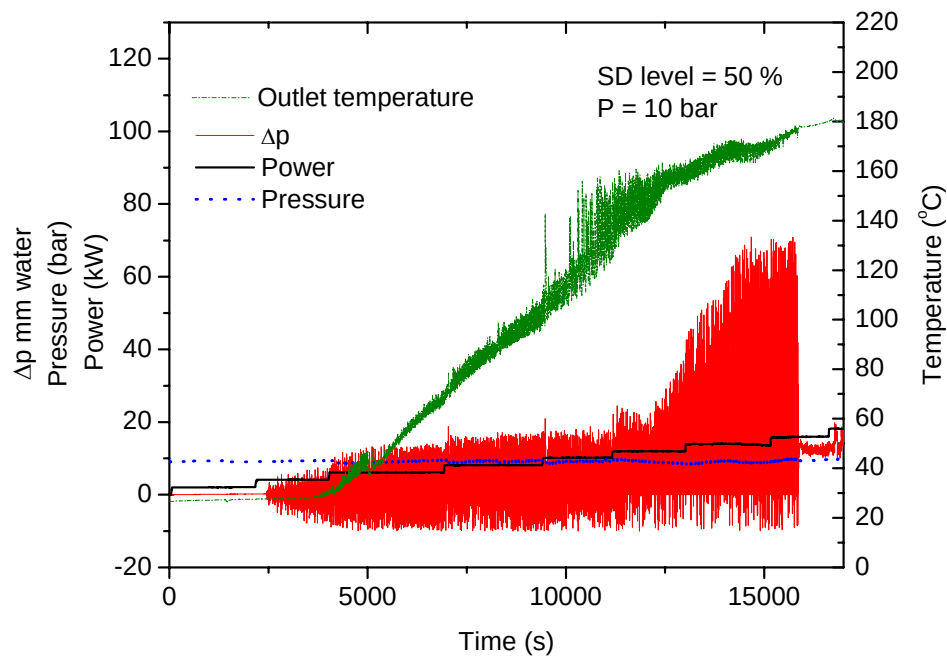


Figure 9 Natural circulation behaviour from rest at 10 bar and 50 % SD level

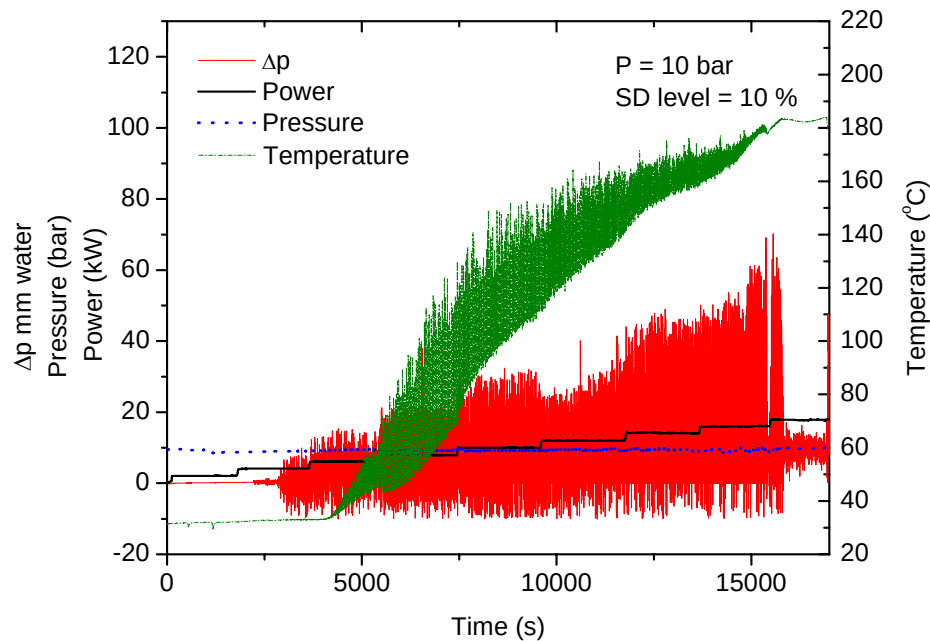


Figure 10 Natural circulation behaviour from rest at 10 bar and 5 % SD level

In the two phase region, at high pressure, the behaviour is found to be similar as that of low pressure except for the reduced amplitude.

4. Conclusions

The stability behavior of a closed natural circulation loop was studied experimentally. Experiments were conducted at low steam drum levels. It was found that the at reduced steam drum level, natural circulation system with low steam drum level is more unstable than with high steam drum level the exhibiting large amplitude oscillatory behaviour. The amplitude of oscillation is more for system with low steam drum level. However, as boiling in induced, system with low steam drum attains stability and the system with high steam drum level shows type-I oscillations. At high pressure, the amplitude of oscillations is reduced substantially.

5. References

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