

STUDY ON THE TRANSIENT AND STABILITY BEHAVIOUR OF A BOILING TWO-PHASE NATURAL CIRCULATION LOOP WITH Al_2O_3 NANOFLUIDS

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Abstract

The transient and stability behaviour of a two-phase natural circulation loop with water and 1 % by wt. Al_2O_3 nanofluid have been experimentally investigated in a natural circulation loop at different operating pressures and powers. The test results revealed that in single phase condition the natural circulation flow behaviour is similar with water and Al_2O_3 nanofluid, however, the buoyancy induced flow rates are found to be relatively higher with nanofluid than with water alone for corresponding operating conditions. In addition, with nanofluid, the boiling induced Type I flow instabilities are found to be significantly suppressed and boiling is induced at lower power than with water for the corresponding operating condition.

Introduction

Two-phase natural circulation loops have several applications in nuclear and process industries due to their simplicity and passive nature. Further, it eliminates the cost and maintenance of pumps inherent in forced circulation systems. However, one of the major problems associated with natural circulation systems is the occurrence of various types of flow instabilities [1]. Instabilities are known to occur depending on the system geometry and operating conditions. They can cause problems to system operation, control and may reduce the thermal margin available to the safe operation of the system. Hence over the years, a lot of research has been carried out to understand the nature and characteristics of various types of instabilities occurring in two-phase boiling systems [2-5].

Density-wave instability is the typical dynamic instability which may occur due to the multiple regenerative feedbacks between the flow rate, enthalpy, density, and pressure drop in the boiling system. The occurrence of the instability depends on the perturbed pressure drop in the two-phase and single-phase regions of the system and the propagation time delay of the void fraction or density in the system. Such an instability can occur at very low-power and at high-power conditions. This depends on the relative importance of the respective components of pressure drop such as gravity or frictional losses in the system. Fukuda and Kobori [6] have classified the density-wave instability as type I and type II for the low power and high-power instabilities, respectively. The mechanisms are well explained in [7].

Recently, nanofluids have gained lot of importance owing to their enhanced heat transfer characteristics as compared to base fluids. Lot of research has been carried out towards heat transfer studies of nanofluids. However, their role in natural circulation system is yet unexplored. In order to understand the effects of small sized nano particle suspensions on boiling two-phase natural

circulation, we have conducted experiments in a natural circulation loop with water and Al_2O_3 nano particles dispersed in water separately. The experiments were conducted over a wide range of power and pressures keeping the steam drum level constant. The experiments were repeated with water as that with Al_2O_3 nanofluid. The natural circulation characteristics with water and nanofluid were explored from flow initiation from rest to single-phase circulation, from boiling inception to two-phase circulation. The test results were compared between water and Al_2O_3 nanofluid.

2. The Experimental Facility

Figure 1 shows a schematic of the natural circulation loop. The facility 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. Sub-cooled 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 steam drum. In the steam drum, 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 steam drum through a pipe that joins the steam drum 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 paper by Gartia et al. [8].

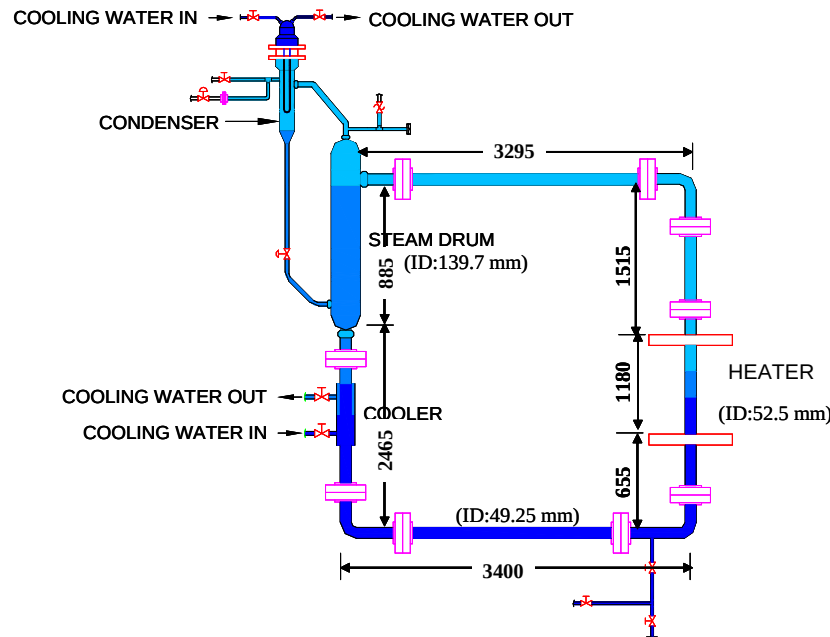


Figure 1. Schematic of experimental facility

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 transducer. The pressure drop measured across this pipe is an indication of the flow rate in the system. 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 interval was every one second.

Accuracy of measurements is as follows:

Temperature : + 0.75% of measured value in span (0-400 oC)

Pressure : + 0.35% of measured value in span (1-100 bar)

Differential pressure transducer: + 0.2 % of the measured value in span 0- 1550 mmWC

Water Level : + 0.2% of the measured value

The experimental conditions and ranges are shown in Table 1.

Table 1 Range of experimental parameters

Pressure	1 – 20 bar
Working fluid	Water/Alumina Nanofluid
Power	0 to 50 kW
Level	85 % of full SD level

2.1 Experimental Procedure

Before starting the experiments, the primary loop was filled with water under ambient conditions and all instruments were vented. The loop was pressurized to the required initial pressure by using nitrogen and 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. This is a power raising transient during which the temperature of liquid keeps on rising from atmospheric temperature to saturation temperature corresponding to the operating pressure because there is no heat sink available. 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. Thereafter, SD pressure is maintained by condensing the steam in the condenser. The steady state operation in two phase condition was made possible by invoking condenser which removes the heat supplied to the fluid in heated section.

Subsequently, an aqueous solution of nanofluid was prepared by adding 1 % (by weight) of Al_2O_3 nanoparticles of average particle size 40 - 80 nanometer and 99.7% purity to the water in the loop. The reason for using Al_2O_3 nanoparticles is the fact that the boiling characteristics of the base fluid water is most widely known and the thermal property of water- Al_2O_3 nanofluid for different particle concentration and the effect of temperature on it has already been studied [9]. The dispersion of the particle was first done by mixing the required volume of powder in a chemical measuring flask with distilled water and then using Ultrasonic vibration to disperse it. After making a proper mixture, the flask was kept again under ultrasonic vibration for about 4 hours, which is a sufficient time to ensure stable particle dispersion in water without agglomeration [9].

3. Results and Discussion

3.1 Natural circulation from rest state and before initiation of boiling

Figure 2 shows an example of the natural circulation behaviour of the loop with and without addition of nanofluid. The flow was initiated from rest condition with addition of power in steps of 2 kW keeping the steam drum pressure constant at 5 bar and the drum water level at 85 % of full level. During this whole process, there was no boiling as observed from the heater outlet temperature which was lower than the saturation temperature at corresponding pressure. The results indicate that the single-phase natural circulation behaviour is similar in both the cases. However, the natural circulation flow rate is found to be relatively larger with nanofluid than water especially at higher powers, indicated by increase in pressure drop in the horizontal leg of the loop.

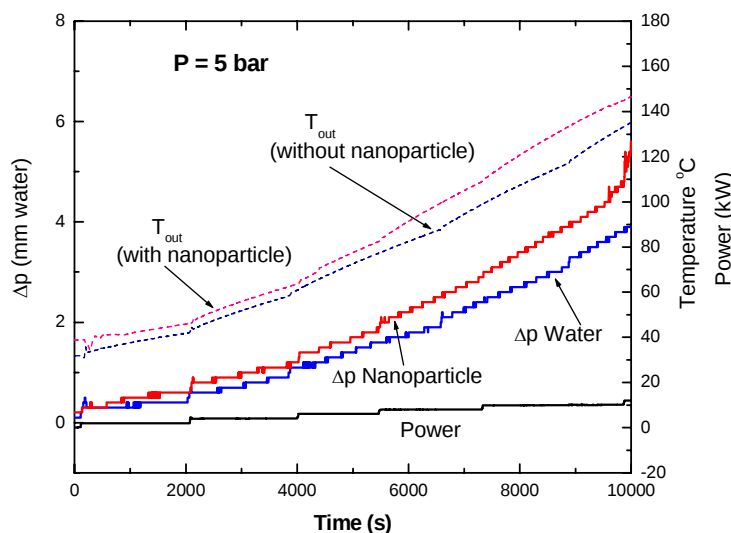


Figure 2. Natural circulation behaviour from rest condition at 5 bar

The buoyancy induced flow in a natural circulation loop can be increased either by reducing the viscous resistance forces or by increasing the driving buoyancy forces. The viscous resistance forces are function of fluid properties like viscosity and in turn due to friction factor. Therefore, if the friction factor is reduced due to addition of nanofluid then the flow may increase. For our set of experiments, we have used Al_2O_3 concentration of 1% by wt. in water, which corresponds to 0.32 % by volume. Bang and Chang [10] found a viscosity change of 1% for 0.6% volumetric fraction of Al_2O_3 -water nanofluid Kim et al. [11] and Murshed et al. [12] have concluded that the kinematic viscosity of nanofluid at room temperature differs negligibly from those of pure water at less than 1% vol. concentration. However, Pak and Cho [13] found a rise of ~10%, Lee and Jang [14] found a rise of ~5% and Wang et al. [15] found around 6% rise in viscosity with 0.6% volumetric fraction of Al_2O_3 -water nanofluid. Hence these measurements suggest that the change in viscosity for the low nanoparticles concentration (0.32 % by volume) is insignificantly small as compared to water. Besides experiments have revealed that the viscosity of nanofluid reduce significantly with rise in temperature. In fact recently Nguyen et al. [16] have experimentally measured the viscosity of Al_2O_3 nanofluid at varying temperature and found a substantially lower viscosity (~ 50% less) at higher temperature than at lower temperature. Recent experimental studies by Li and Xuan [17] and Xuan and Li [18] have shown that the friction factors of dilute nanofluid are almost equal to those of

water at the same Reynolds number and also do not get affected by the volume fraction of the nanoparticles. This was also confirmed by experiments of He et al. [19] where they concluded that the pressure drop of nanofluid (using TiO₂ nanoparticles) is very close to that of the base liquid for a given Reynolds number. This leaves us with the opinion that the increase in steady state flow is due to increase in driving buoyancy force. The relative increase in driving buoyancy force is due to large change in density and large temperature rise for same heat addition. Hence this gives larger temperature rise in the fluid. The next important physical parameter is the volumetric thermal expansion coefficient (β_T), which decides the magnitude of density change. Nayak et al [20] have experimentally determined the volumetric expansion coefficient of 1% Al₂O₃ and found that it is significantly greater than water alone (by ~17 %) at low temperatures where single phase natural circulation prevails.

Using the model of Vijayan et al [21], the steady state flow rate in the loop can be calculated by

$$W_{ss} = \left[\frac{2 g \rho_l^2 \beta_T H Q D^b A^{2-b}}{p \mu_l^b N_G} \right]^{\frac{1}{3-b}} \quad (1)$$

where W_{ss} is the steady state flow rate, g is the gravitational acceleration, ρ_l is the liquid density, H is the loop height, Q is the heater input power, D is the hydraulic diameter, A is the flow area, μ_l is the viscosity, C_p is the specific heat, p and b are the constants in the friction factor correlation of the form $f = p/Re^b$, Re is the Reynolds number ($DW/A\mu$) and N_G is the contribution of loop geometry to the friction number (effective loss coefficient for the entire loop)

which is defined as $N_G = \frac{L_t}{D_r} \sum_{i=1}^N \left(\frac{l_{eff}}{d^{1+b} a^{2-b}} \right)_i$; a, d, l being the non-dimensional area, diameter and

length respectively ($a_i = \frac{A_i}{A_r}$, $d_i = \frac{D_i}{D_r}$, $l_i = \frac{L_i}{L_t}$). Considering all these variations, the rise in steady

state mass flow rate is about 6 % which eventually increases the pressure drop by 10 %.

The heater outlet temperature of the fluid in case of water is always found to be lower than that with nanofluid although the flow is found to be lower in case of water as compared to nanofluids. This could be because of lower specific heat of nanofluid as compared to water [22]. Similar behaviour is also observed at higher pressures of 7 bar and 20 bar (Figs. 3 and 4).

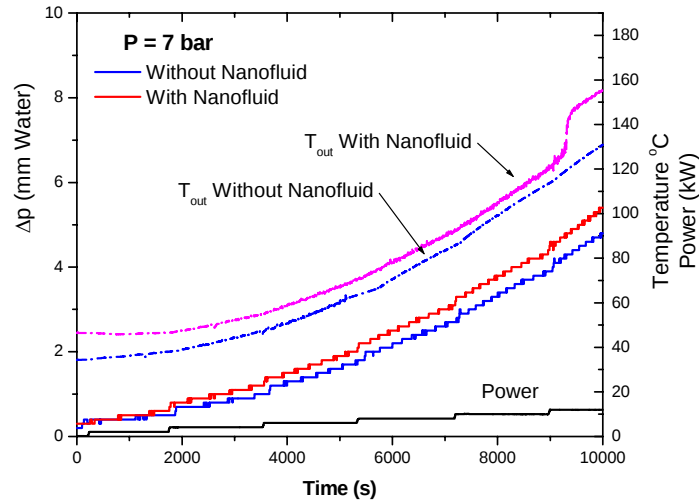


Figure 3. Natural circulation behaviour from rest condition at 7 bar

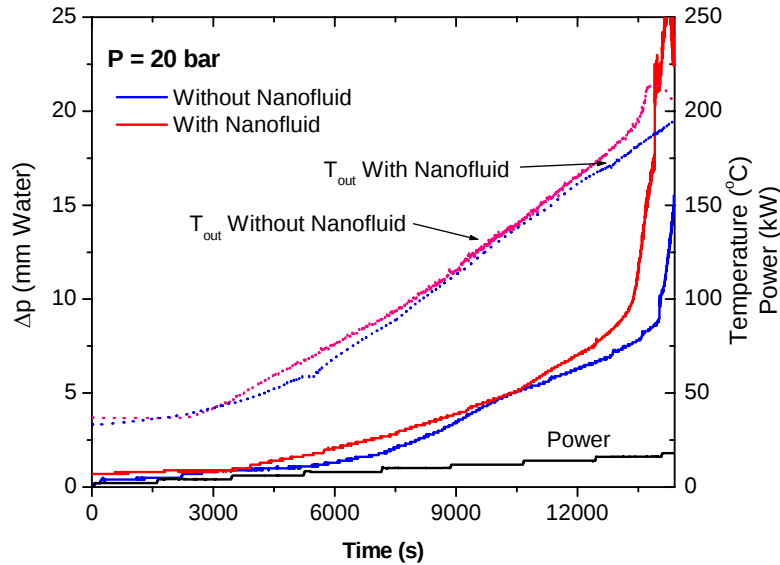


Figure 4. Natural circulation behaviour from rest condition at 20 bar

As said earlier, the single phase natural circulation characteristics depends on volumetric thermal expansion coefficient (β_T), specific heat (C_p) of the fluid and friction factor which indirectly depends on the fluid viscosity (μ_f). The Effect of the pressure has negligible effect on these properties for incompressible fluids. The Most important parameter which affects them is the fluid temperature. That's why the natural circulation flow rate was found to be almost the same at any pressure for corresponding power. (Figs 2-4)

3.2 Natural circulation with initiation of boiling and two-phase circulation

With further rise in power (continuation of results of Fig. 2), the buoyancy induced flow rate is found to rise suddenly with nanofluid after nearly 10000 s when the power was increased to 12 kW from 10 kW (Fig. 5). The steam drum pressure was kept at nearly 5 bar and its level was nearly 85

%. At this condition, the heater outlet temperature of nanofluid approaches closer to the saturation temperature. The sudden increase in flow is due to large rise in buoyancy force with initiation of boiling. However, the flow condition still remains single-phase at the above operating condition with water alone in the loop. In fact boiling is initiated in the loop with water alone at 14 kW heater power indicated by sudden increase in buoyancy induced flow rate as well as the heater outlet temperature reaching the saturation temperature.

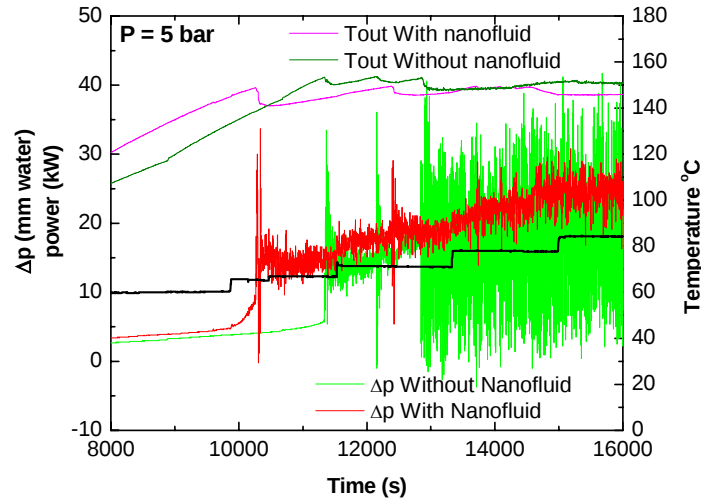


Figure 5. Natural circulation behaviour with initiation of boiling at 5 bar

The total energy input to cause boiling in both the cases have been shown in Table 2. It can be concluded from this table that nanofluid requires less energy to boil as compared to water, which increases with increase in pressure.

Table 2. Total energy input requirement to cause boiling

Pressure	Cumulative Power for boiling of water (kJ)	Cumulative Power for boiling of nanofluids (kJ)
5	72	68
7	81	75
20	141	129

The early initiation of boiling in case of nanofluid could be explained from the reduction in specific heat capacity of nanofluid as compared to water [10, 19]. Hence for the same heat addition rate, the rise in temperature in Al_2O_3 nanofluid is larger as compared to water. Besides, presence of nanoparticles may give rise to additional nucleation sites for bubble creation resulting in early initiation of boiling [23,24]

With initiation of boiling, violent oscillations in flow rate are observed with water alone as the fluid. These are classical Type I instabilities as defined in Introduction. Having a small concentration of Al_2O_3 nanofluid in water (1 % by wt.), the amplitudes of Type I instabilities are found to be strongly dampened. These phenomena are observed at higher pressures of 7 bar and 20 bar respectively (Figs 6 and 7).

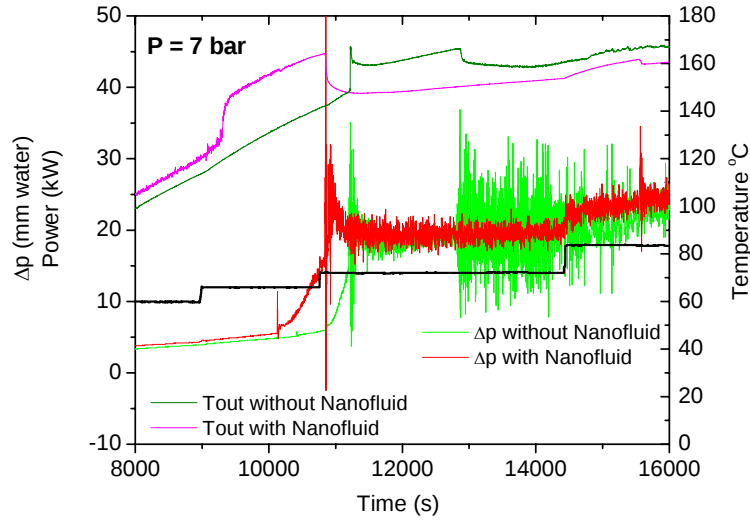


Figure 6. Natural circulation behaviour with initiation of boiling at 7 bar

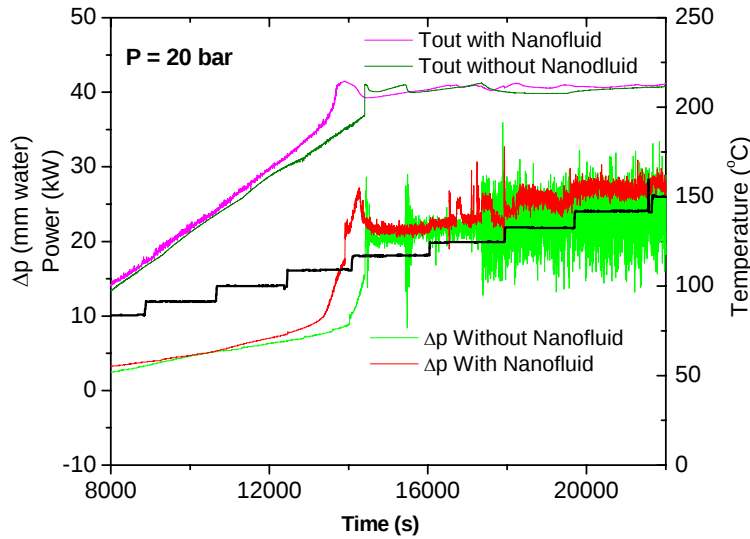


Figure 7. Natural circulation behaviour with initiation of boiling at 20 bar

A comparison of the effect of the pressure on flow instability characteristics can be seen in Figs 5-7. Unlike at high pressure (20 bar) large amplitude flow oscillations were observed at low pressures (5 & 7 bar) with initiation of boiling. An increase in pressure suppresses the boiling flow instabilities since at low quality condition; the void generated at high pressure is much less as compared to low pressure. As a result of which, any perturbation in quality will have small perturbation in void fraction or in driving buoyancy force at higher pressure as compared to that at low pressure. Since the perturbations are smaller at high pressure, this has a stabilizing effect.

Fig. 8 shows a comparison of Normalized Root Mean Square Deviations (RMSD) of oscillations between water and Alumina nanofluid observed during Type I instabilities at different pressures

keeping the steam drum level constant at 85 %. The results indicate that the flow instabilities are strongly dampened with nano particle suspension in water.

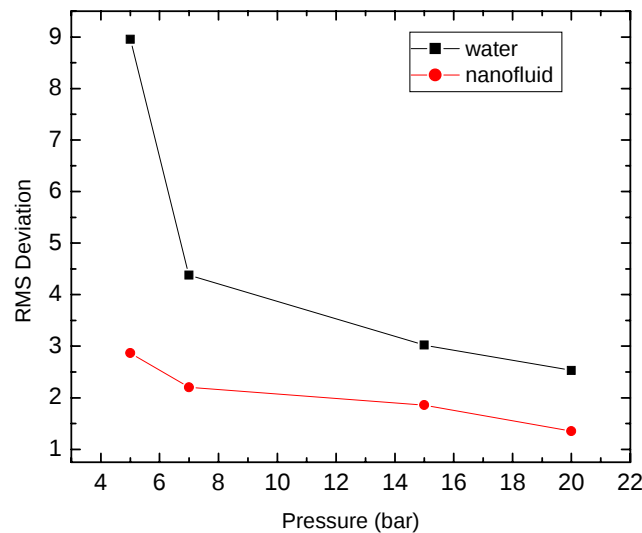


Figure 8. Comparison of RMS deviation of oscillations in unstable region between water and nanofluid

To understand the suppression of flow instabilities under boiling condition with the use of nano-sized particle suspensions in the base fluid, one needs to know the properties of nanofluid under boiling conditions, more specifically the variation of void fraction with quality and the two-phase pressure drop behaviour as compared to the base fluid. The significant variation of void fraction with quality under low quality condition is the primary cause for fluctuation of driving buoyancy force due to small fluctuation of quality responsible for occurrence of Type I instability. We postulate that the presence of nanoscale particles reduce the void fraction in the base fluid for a given quality, which thereby reduces the fluctuation of driving buoyancy force for small perturbation in quality suppressing the instability. The determination of void- quality relationship of nanofluid itself needs dedicated experiments.

3.3 Stable two-phase natural circulation

When the power is further increased, the boiling induced Type I flow instabilities observed with water as the fluid, get significantly suppressed as seen in Figs. 9 to 11. The amplitude of oscillations decrease with rise in power, the amount of reduction depends on the system operating pressure. Even with stable two-phase flow, there are small amplitude oscillations. Interestingly, the amplitude of these stable oscillations is much less with Alumina nano particles suspended in water than that with water alone. Even though, the flow characteristics are more or less similar with and without nanofluid, however the two-phase flow rates are found to larger with nanofluid than that with water alone indicated by larger measured pressure drop in the single-phase region.

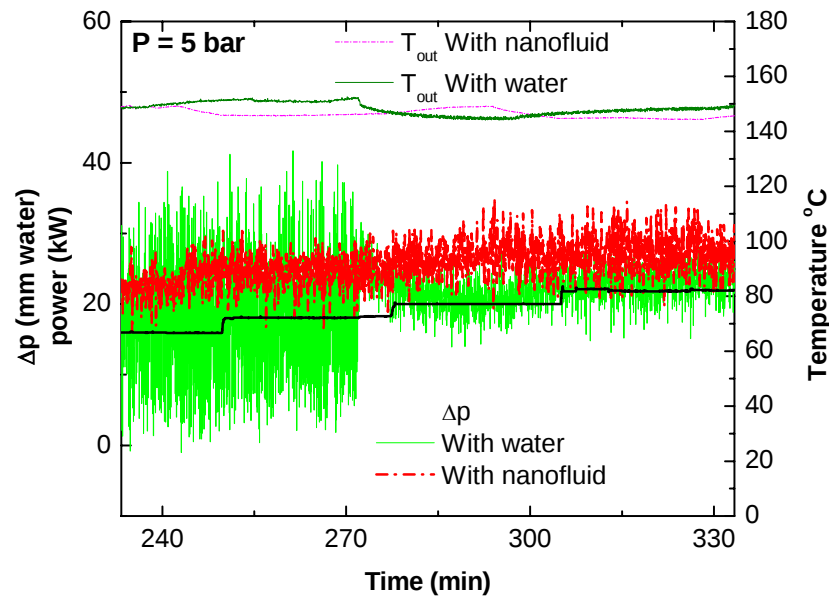


Figure 9. Natural circulation behaviour under two-phase condition at 5 bar

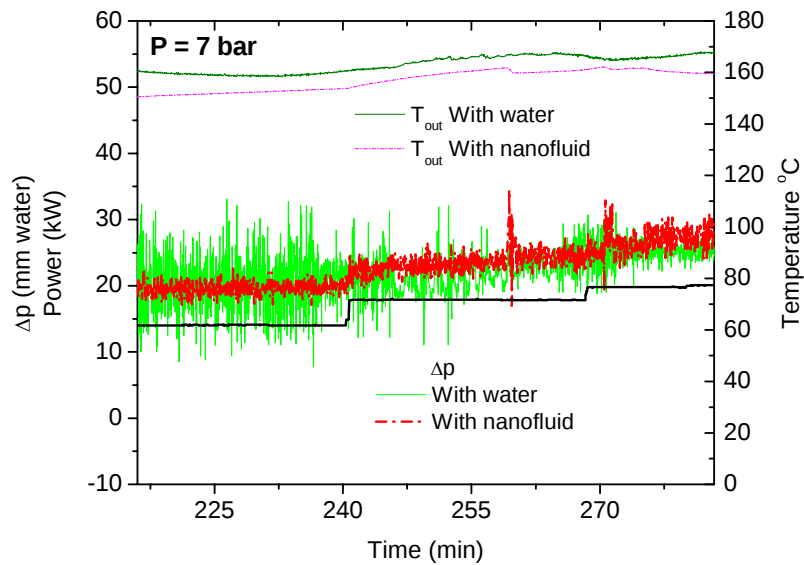


Figure 10. Natural circulation behaviour under two-phase condition at 7 bar

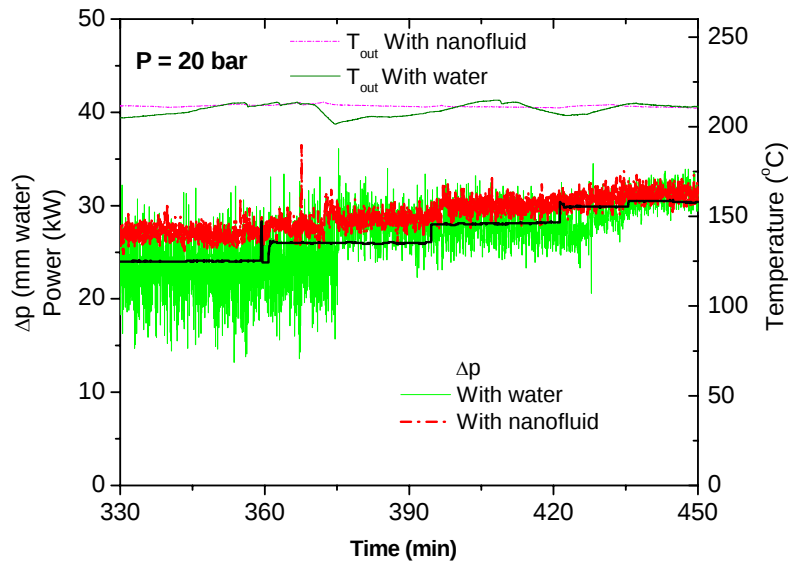


Figure 11. Natural circulation behaviour under two-phase condition at 20 bar

4. Concluding Remarks

A series of experiments were conducted in a boiling natural circulation loop at different operating pressures and power levels keeping the steam drum level constant with water and 1% by wt. concentration of Al_2O_3 nano particles dispersed in water. The particles were in the range of 40-80 nm. Experiments were conducted to study the natural circulation behaviour for wide range of operating condition, i.e. flow initiation from rest, single-phase circulation, boiling induced instability behaviour and stable two-phase circulation. Results indicated that natural circulation flow rate with Alumina nanofluid is relatively larger than that with water alone. Boiling is found to occur at lower power with Alumina nanofluid than that with water. The Type I instabilities are found to be significantly suppressed with Alumina nanofluid depending on the system pressure.

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