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An experimental investigation of single-phase natural circulation behavior in a rectangular loop with Al_2O_3 nanofluids

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ABSTRACT

In this paper, the natural circulation behavior in a rectangular loop was investigated experimentally with water and different concentration of Al_2O_3 nanofluids (0.3–2% by wt. and particle size 40–80 nm). It was demonstrated that, not only the flow instabilities are suppressed but also the natural circulation flow rates are enhanced with nanofluids. The enhancement in natural circulation flow rate and suppression of instabilities were found to be dependent on the concentration of nanoparticles in water.

1. Introduction

A natural circulation system operates on the basis of natural laws like gravity and buoyancy [1]. Although natural circulation is a benign gift of nature for applications to several heat removal systems due to the simplicity in design, elimination of hazards related to pumps, better flow distribution, cost reduction, etc. However, the potential threat of flow instabilities still eludes for its wide applications [2–4]. Although addition of local losses (orificing) may suppress instabilities [5], however, it is accompanied by significant flow reduction which is detrimental to the natural circulation heat removal capability.

The purpose of this research is concerned with the use of Al_2O_3 nanofluids to suppress the instabilities in a natural circulation loop induced by a heating–cooling system. Experiments were demonstrated by running the system to compare the pressure drop and natural circulation flow rate with water and that with nanofluids at different concentrations. Here, we have demonstrated experimentally, with nanofluids, not only the flow instabilities are suppressed but also the natural circulation flow rate is enhanced. The main focus of this research was to develop a technology to get rid of the flow instabilities generally associated with the natural circulation loop without degrading the natural circulation flow rate.

2. Experiment

2.1. Experimental facility

To substantiate the facts, we conducted experiments in a natural circulation loop with geometry as shown in Fig. 1. The test facility resembles rectangular in geometry with circular flow cross-section area. The geometry is relevant to that of solar water heaters and nuclear reactors. The pipes are made of glass with inner diameter of 26.9 mm. Important dimensions of the loop are shown in the figure (Fig. 1). The loop was heated with electric wire which was wound uniformly on the outer surface of the glass tube in the bottom horizontal leg. It was cooled at the top through a tube-in-tube type heat exchanger with tap water flowing through the annulus. An expansion tank was provided at the topmost elevation to accommodate the volumetric expansion of the fluid. It also ensures that the loop remains full of water. Thermocouples were installed at different positions in the loop to measure the instantaneous local temperature. The flow rate was measured using a pressure transducer installed in the horizontal leg of the loop. The instruments were connected to a data acquisition system which could scan all the channels in less than one second. The secondary side cooling water flow rate was measured with the help of a rotameter. The loop was insulated to minimize the heat losses to the ambient. The measurement accuracy was 0.4% (+1.1 °C) for thermocouples, +0.25% for flow rate and +0.5% of the span (0–1250 W) for power and pressure drop (−100 to +100 Pa). Experiments were conducted at different powers which are typical to that of a power raising and setback phenomena in any power generating system.

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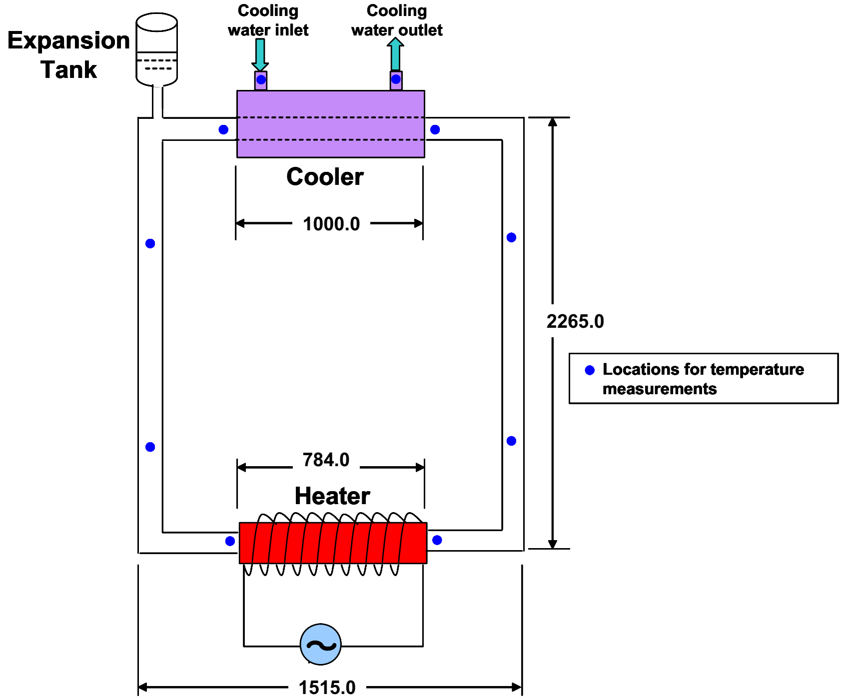

Fig. 1. Schematic of experimental facility.

2.2. Preparation of nanofluids

An aqueous solution of nanofluids was prepared by adding desired concentration (by weight) of Al_2O_3 (Alumina) nano powder of particle size 40–80 nm and 99.7% purity to the water in the loop. The reason for using Al_2O_3 nano powder is the fact that the thermo physical characteristics of the base fluid (water) is most widely known and the thermal property of water–Al_2O_3 nanofluids for different particle concentration has already been studied [6]. To prevent the particles from agglomerating and settling, the suspension was sonicated in an ultrasonic bath. 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 h, which is a sufficient time to ensure stable particle dispersion in water without agglomeration [7]. The settling velocity was calculated from a balance of buoyancy and viscous forces and using the Stokes law for the viscous resistance [8]. The settling velocity was found to be $\sim 1.043 \times 10^{-8}$ m/s for the mean particle size of 60 nm as used in this experiment. In fact, this velocity is negligibly small as compared to the momentum of the fluid due to natural convection. Further, from the measured pressure drop, the minimum flow velocity in natural circulation was calculated and found to be 1.71×10^{-2} m/s for the lowest power experiment. Since the momentum velocity of flow is significantly larger than the settling velocity of 1.043×10^{-8} m/s, it gave further evidence that there is no settling of nano powders during the natural circulation experiments. Hence, the question of settling of nano particles during the tests does not arise especially for the long duration steady state experiments.

3. Results and discussion

3.1. Steady state flow rate

The experiments were conducted first with water and then repeated for different concentration of Al_2O_3 nanofluids. The steady state natural circulation flow rate was measured at different power (50–350 W in steps of 50 W) keeping the secondary flow rate constant (1 lpm). Fig. 2 shows the measured pressure drop plotted at different power for water and different concentration of nanofluids. The rate of power rise and the initial conditions of the loop were the same in all the cases. The steady state flow rates are found to be higher with nanofluids (Fig. 2) as compared to that with water alone, indicated by the increased pressure drop in the loop (about 28–44%). The corresponding time averaged flow rates have been estimated and plotted as a function of operating power in Fig. 3 which shows that the flow rate is increased between 20% and 35% depending on the concentration of nanopowder and operating condition.

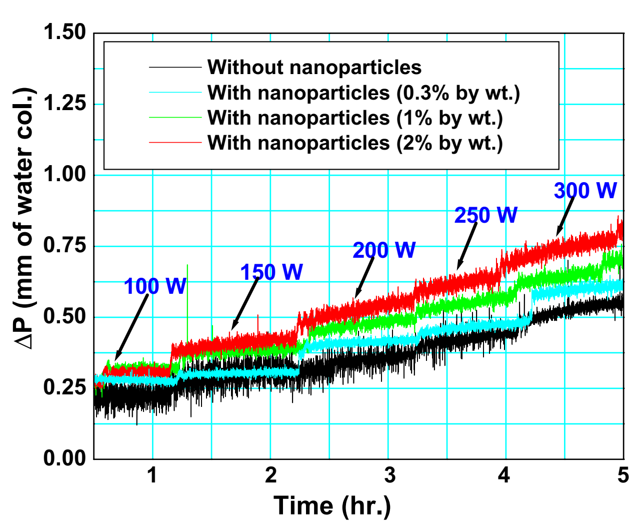

Fig. 2. Comparison of steady state flow rate with and without nanofluids.

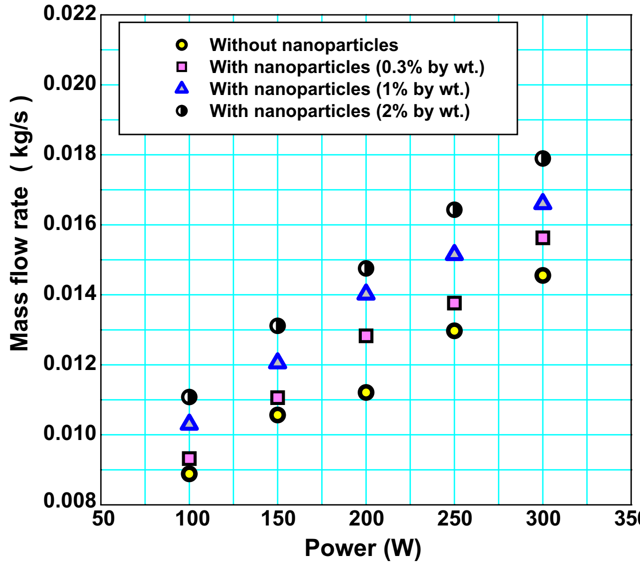

Fig. 3. Variation of steady state flow rate with different concentration of nanoparticles.

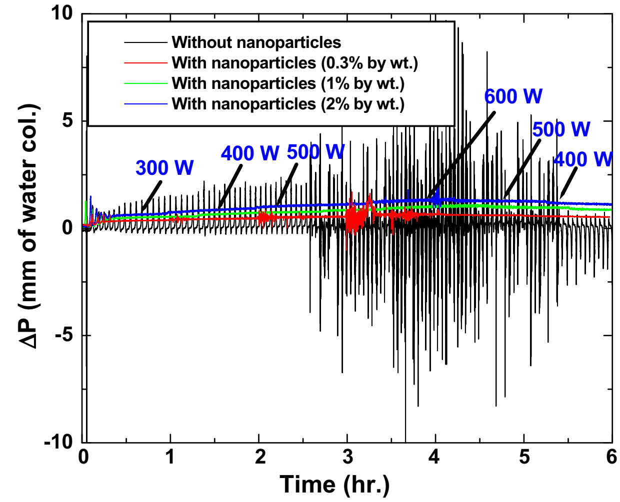

Fig. 5. Suppression of flow instability with nanofluids during power raising and set back process.

3.2. Stability characteristics

Experiments were conducted for various power transients wherein flow instabilities were observed when the loop was filled with water, that is, without addition of nanofluids. An example of the flow instability behavior of the natural circulation loop during a power raising and setback process is shown in Fig. 4. In this case, the fluid was heated from an initial power of 300 W in steps of 100 W, and the instabilities were observed even at 300 W. The amplitude of oscillations kept on increasing with rise in power. At 600 W, a power setback experiment was conducted to illustrate the instability behavior during a setback process. The power was reduced to 400 W from 600 W in steps of 100 W. The flow instabilities were found to be sustained and their characteristics are different for the corresponding powers.

A step power rise from 0 to 300 W is characterized by oscillatory regime with unidirectional pulsing. With rise in power it switches to bidirectional pulsing and a regime with chaotic switching between unidirectional and bi-directional pulsing (intermittency) with further rise in power. With power set back (400 W), the oscillatory regime again switched back to unidirectional pulsing. These oscillatory behaviors are shown in Fig. 4. The same experiment was repeated with different concentration of Al_2O_3 nanopowder (0.3–2%). The rate of power rise and the initial conditions of the loop were the same in all the cases. The most significant finding was that the flow instabilities are suppressed even with a low concentration of 0.3% by weight of Al_2O_3 nano powder (Fig. 5). It was found that the natural circulation flow rates are also increasing with increase in concentration of nanoparticles in addition to the suppression of instabilities as shown in Fig. 5.

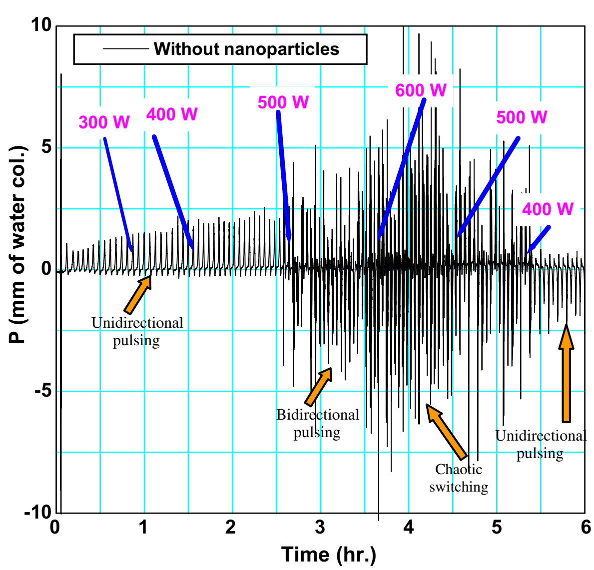

Fig. 4. A typical flow instability behavior in water during power raising and set back process.

3.3. Assessment of existing models to simulate natural circulation behavior with nanofluids

The steady state flow rate in a natural circulation loop can be calculated by equating the driving buoyancy force with the resisting frictional force. Vijayan et al. [9] have derived the expression for the steady state flow rate in a natural circulation loop as given by

$$W_{ss} = \left[\frac{2}{p} \frac{g \Delta\rho H Q D_r^b A_r^{2-b} \rho_l}{\Delta T \mu_r^b N_G C_p} \right]^{\frac{1}{3-b}} \quad (1)$$

where W_{ss} is the steady state flow rate, g is the gravitational acceleration, ρ_l is the liquid density, $\Delta\rho$ is the average density difference between the cold-leg and the hot-leg, H is the loop height, Q is the heater input power, D is the hydraulic diameter, A is the flow area, ΔT is the average temperature difference between the cold-leg and the hot-leg, μ_r is the reference 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 $a_i = \frac{A_i}{A_r}$, $d_i = \frac{D_i}{D_r}$, $l_i = \frac{L_i}{L_t}$.

From Eq. (1), it is evident that the main physical properties which affect the steady state flow in a natural circulation loop are the change in density ($\Delta\rho$) due to heat addition, viscosity (μ) and specific heat (C_p). These properties have been calculated using existing models [8,10] and plotted in Fig. 6a–c in the experimental range of volumetric fraction, $\varphi = 0.09 - 0.6$. It should be noted that the variation of these fluid properties due to addition of nano particles is negligibly small. Of course, Eq. (1) (described in the model of Vijayan et al. [9]) does not consider the effects due to axial conduction of the fluid. To illustrate that, we have also predicted the variation of thermal conductivity of fluid due to addition of Al_2O_3 nano powder in the above concentration range using the Hamilton–Crosser model [11,12]. It is evident from Fig. 6d that the thermal conductivity hardly increases to a maximum of 1.61% for the above concentration of nanoparticles. Hence, this slight enhancement of thermal conductivity due to addition of Al_2O_3 nanoparticles has little role to play on natural circulation behavior. In view of the above, the significant rise in the flow rate can not be explained using the existing models for prediction of fluid properties due to addition of nano particles, especially the physics in the thermal and hydrodynamic boundary layers.

The experimental data are also analyzed in the non-dimensional form. The generalized flow correlation for single-phase loops [13] is given by

$$Re_{ss} = C\left(Gr_m \frac{D}{L_{eff}}\right)^r \tag{2}$$

where the constant C and r depends on the constants of the friction factor correlation as shown below. The above correlation suggest that if we plot Re vs. $Gr_m D/L_{eff}$ on a log–log plot, the constant C and r can be obtained as the intercept and exponent. From the values of C and r, the p and b values applicable to the friction factor correlations can be obtained as $C = (2/p)^r$ and $r = (1/3 - b)$ where p and b are given by the friction factor correlation of the form $f = p/Re^b$. Depending on the value of the components p and b, the flow correlation is given as

$$Re_{ss} = 0.1768\left(\frac{Gr_m}{N_G}\right)^{0.5} \quad \text{laminar flow } (p = 64,\ b = 1) \tag{3}$$

$$Re_{ss} = 1.96\left(\frac{Gr_m}{N_G}\right)^{0.364} \quad \text{turbulent flow } (p = 0.316,\ b = 0.25;\ \text{Blasius correlation}) \tag{4}$$

Where $Gr_m = \frac{D_r^3 \rho_0^2 \beta_T g Q_h H}{A_r \mu^3 C_p}$, $N_G = \frac{L_t}{D_r} \sum_{i=1}^{N} \left(\frac{l_{eff}}{d^{1+b} a^{2-b}}\right)_i$, $L_{eff} = L_t + Le_t$ and

$$Re_{ss} = \frac{D_r W_{ss}}{A_r \mu} \tag{5}$$

Here, Le_t is the total equivalent length accounting for the sum of the individual local loss coefficients of the entire loop.

It should be noted that the validity of the above flow formulation (Eq. (3) and (4)) has already been well established for single-phase natural circulation loops demonstrated by its close agreement with a large number of experimental data obtained from around 25 different loops [13–15]. For the present loop, the experimental data with water alone are predicted well by the generalized flow correlation where as there is a large deviation for the

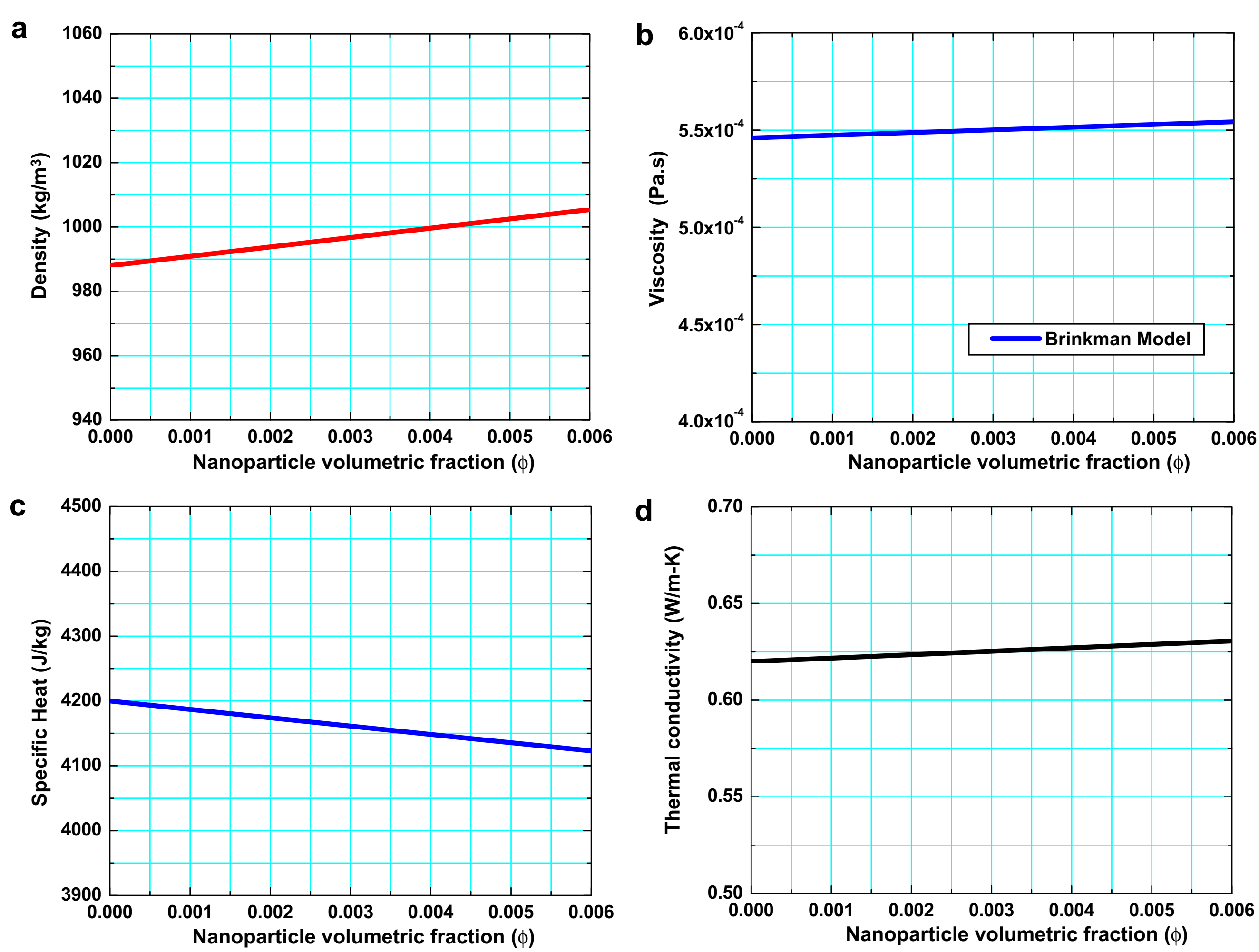

Fig. 6. (a) Variation of density. (b) Variation of viscosity. (c) Variation of specific heat. (d) Variation of thermal conductivity.

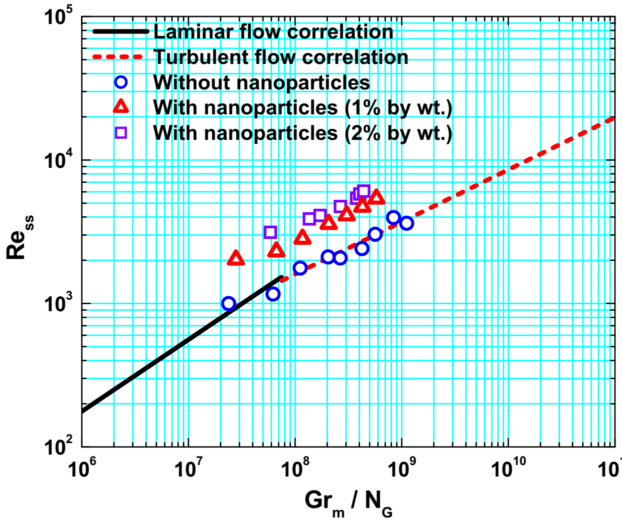

Fig. 7. Variation of steady state flow rate with different concentration of nanoparticles in non-dimensional plane.

experimental data obtained using nanofluids as shown in Fig. 7. This clearly points out the deficiency of existing property models for nanofluids.

3.4. Discussion on increase in flow rate

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 nanofluids then the flow may increase. In literature, there are a few reports on the viscosity of aqueous Al_2O_3 nanofluids vis-à-vis water. Bang and Chang [17] found a viscosity change of 1% for 0.6% volumetric fraction of Al_2O_3–water nanofluids. Similarly, Kim et al. [18], Murshed et al. [19] and Nguyen et al. [20] have concluded that the kinematic viscosity of nanofluids at room temperature differs negligibly from those of pure water at less than 1% vol. concentration. However, Lee and Jang [21] found a rise of ∼5% and Wang et al. [22] found ∼6% rise in viscosity with 0.6% volumetric fraction of Al_2O_3–water nanofluids. In view of the large variation in viscosity measurements especially at low nanoparticles concentration, it is very difficult to quantify the change in viscosity for dilute nanofluids vis-à-vis water. Besides experiments have revealed that the viscosity of nanofluids reduce significantly with rise in temperature. In fact recently Nguyen et al. [20] have experimentally measured the viscosity of Al_2O_3 nanofluids at varying temperature and found a substantially lower viscosity (∼50% less) at higher temperature than at lower temperature. In the absence of reliable experimental data the viscosity is calculated using existing model [23]. This predicts a small rise in viscosity for our experimental range of nanofluids concentration as shown earlier. Recent experimental studies by Xuan and Li [24] and Li and Xuan [25] have shown that the friction factors of dilute nanofluids 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. [26] where they concluded that the pressure drop of nanofluids (using TiO_2 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. It is well known that specific heat of nanofluids is less as compared to water [17,27]. Hence this gives larger temperature rise in the fluid. The next important physical parameter is the volumetric thermal expansion coefficient (β), which decides the magnitude of density change. To our knowledge, there are almost no test data on density and thermal expansion coefficient of nanofluids vis-à-vis water. Hence, in absence of that an analytical treatment to explain the increase in flow rate is given below.

Using the model of Vijayan et al. [9], the expression for the steady state flow rate in a natural circulation loop is given in Eq. (1) which can be further simplified to yield

$$W_{ss} = \left[\frac{2}{p}\,\frac{g\beta_T H Q D_r^b A_r^{2-b}\rho_l^2}{\mu_r^b N_G C_p}\right]^{\frac{1}{3-b}} \tag{6}$$

where β_T is the volumetric thermal expansion coefficient From equation (6), for the same geometry, the steady state flow rate is a function of the liquid density (ρ_l), volumetric thermal expansion coefficient (β_T), reference viscosity (μ_r) and the specific heat (C_p).

$$\text{i.e. } W_{ss} = f\left(\frac{\rho_l^2\beta_T}{\mu C_p}\right) \tag{7}$$

$$\text{or,}\quad \frac{(W_{ss})_{NANOFLUIDS}}{(W_{ss})_{WATER}} = \left[\frac{\left(\frac{(\rho_l)_{NF}}{(\rho_l)_W}\right)^2}{\frac{\mu_{NF}}{\mu_W}}\,\frac{\frac{(\beta_T)_{NF}}{(\beta_T)_W}}{\frac{(C_p)_{NF}}{(C_p)_W}}\right]^{\frac{1}{3-b}} \tag{8}$$

The volumetric thermal expansion coefficient is calculated using model given by Khanafer et al. [28]. It was found that $\lfloor (W_{ss})_{NANOFLUIDS}/(W_{ss})_{WATER} \rfloor \approx 1.03$ for 2% by wt. nanoparticles concentration (which corresponds to 0.6% by vol. concentration). Though the theory also predicts a rise in flow rate, still the actual rise in steady state flow rate at the lowest power is far more (∼22%). The difference in prediction and experiments is still larger at higher powers. This is due to the fact that the existing models for density, specific heat and thermal expansion coefficients are incapable to predict the actual variation of properties as seen by the large difference in the prediction and experimental results. Besides, the models do not care for the change in properties with variation of temperature. In view of this, it is recommended that more experiments need to be carried out to establish these properties especially with variation of temperatures.

3.5. Discussion on suppression of instabilities

With the lack of established data for physical property variation of nanofluids with temperature, it is definitely difficult to discuss the surprising characteristics of natural circulation with nanofluids. However, we have attempted to clarify the reason for suppression of flow instabilities with nanoparticles with the hypothesis of Welander [2].

According to this, following a thermal disturbance in the system, a hot pocket of fluid may emerge from the heated section slightly hotter than its normal steady state temperature. This hot pocket while ascending along the hot leg accelerates the flow because of larger buoyancy force thus created. When this hot pocket emerges out from the cooler, its identity is maintained because of the lower residence time due to larger velocity. Thus the hot pocket emerges from the cooler at a higher temperature than its normal steady state temperature. An opposite phenomena occurs if a cold pocket may emerge from the heater. As the cold pocket ascends along the hot leg and the hot pocket descends along the cold leg, the flow gets decelerated with the result that the hot pocket emerges hotter from the heater and the cold pocket emerges colder from the cooler with every passing cycle. This amplification process continues until the buoyancy force experiences a reversal in sign causing the flow to reverse. The above described amplification process then continues in the reverse direction, causing the flow to change its direction repeatedly from clockwise to anticlockwise and vice-versa.

Thus, the flow oscillations are mainly due to creation of hot and cold density pockets which get amplified with time in the system. We believe that the significantly increase in natural circulation flow rate due to addition of nanoparticles can dampen the small perturbing forces generated due to hot and cold pockets, which are responsible for sustaining the instabilities. In addition, the time lag among the regenerative feedback effects of flow rate, pressure drop and driving buoyancy force is reduced due to enhanced flow rate, which are the paramount factors for occurrence of flow instabilities. Of course, the enhancement of thermal diffusivity is not significant (hardly less than ~1.74%, calculated using the Murshed et al. model [16]); but this also aids in thermally diffusing the hot and cold pockets in addition to the significant momentum diffusion aided by the large flow rate.

4. Concluding remarks

In summary, the findings are novel and promising with regard to application of Al_2O_3 nanofluids in natural circulation systems, since the flow rates are improved and the flow instabilities are suppressed. The consequence of this finding is far-reaching. In a sense, the use of nanofluids will enable one to operate at an elevated power than usual, thereby increasing the efficiency of currently operating natural circulation systems due to enhanced buoyancy induced flow rate without to worry about the possibility of generally associated instabilities. This fact can also be exploited to build more efficient and reliable natural circulation systems based nuclear reactors, solar heaters etc. in future.

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