Nanofluids: A Novel Promising Flow Stabilizer in Natural Circulation Systems

Arun Kumar Nayak, Manas Ranjan Gartia, and P. K. Vijayan
Reactor Engineering Div., Bhabha Atomic Research Centre, Trombay, Mumbai 400085, India

DOI 10.1002/aic.11659
Published online November 24, 2008 in Wiley InterScience (www.interscience.wiley.com).

Keywords: nanofluids, natural circulation, instability

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. In this note, we have demonstrated experimentally, with nanofluids, not only the flow instabilities are suppressed but also the natural circulation flow rate is enhanced.

The purpose of this research note is concerned with the use of metal oxide nanofluids to suppress the instabilities and enhance the flow rate in a natural circulation loop induced by a heating-cooling system. These findings were demonstrated experimentally by comparing the steady state flow rates and instability of natural circulation between water and that with three different nanofluids (Al_2O_3, CuO, and TiO_2) having different particle sizes and concentrations. The main focus of this research was to develop a technology to eliminate the flow instabilities generally associated with the natural circulation loop without degrading the natural circulation flow rate.

To substantiate the facts, we conducted experiments in a natural circulation loop with geometry as shown in Figure 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 around 26 mm. Important dimensions of the loop are shown in Figure 1. The loop was heated with electric wire which was wrapped around 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 differential 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. Experiments were conducted for different power transients which are typical to that of a power raising and setback phenomena in any power generating system.

Natural Circulation Behavior with Water Alone

Experiments were conducted for various power transients wherein flow instabilities were observed when the loop was filled with water, i.e., without addition of nanoparticles. An example of the flow instability behavior of the natural circulation loop during a power raising and setback process is shown in Figure 2. In this case, the fluid was heated from an initial power of 300 W in steps of 100 W and the secondary side cooling water flow rate was kept constant at 1 l per minute. In this case, 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.

Correspondence concerning this article should be addressed to A. K. Nayak at arunths@barc.gov.in.

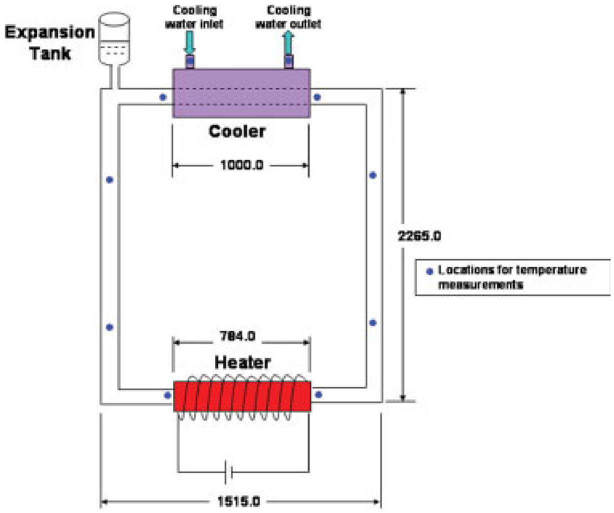

Figure 1. Schematic of experimental facility.

[Color figure can be viewed in the online issue, which is available at www.interscience.wiley.com.]

Natural Circulation Behavior with Al_2O_3 Nanofluids

Subsequently, an aqueous solution of nanofluids was prepared by adding desired concentration (by weight) of Al_2O_3 (Alumina) nanoparticles of 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 thermophysical 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 particle size distribution was characterized with a TEM (transmission electron microscope). It was found that all the particles are within the specified ranges. The dispersion of the particles 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 particles in the suspended state were further characterized with dynamic light scattering technique and the particles were found to be in the nanostate. 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 with the momentum of the fluid due to natural convection. Hence, the question of settling of nanoparticles during the tests does not arise especially for the long duration experiments.

Flow Stability Characteristics with Al_2O_3 Nanofluids

The experiments were repeated with different concentration of Al_2O_3 nanoparticles (0.5% to 2%). The rate of power rise and the initial conditions of the loop were the same in all the cases as that with water. The most significant finding was that the flow instabilities are suppressed even with a low concentration of 0.5% by weight of Al_2O_3 nanoparticles (Figure 3).

Similar results were also observed for other power transients when the power was increased from 150 to 600 W in steps of 150 W (Figure 4) and also when the power was increased from 400 to 600 W in steps of 100 W and reduced to 500 W (Figure 5). In all the cases, the flow was found to be stable with addition of Al_2O_3 nanoparticles. In the former case, the flow was found to be stable up to 450 W and became unstable at 600 W with repeated flow reversals when water alone was the working fluid. However, with the addi-

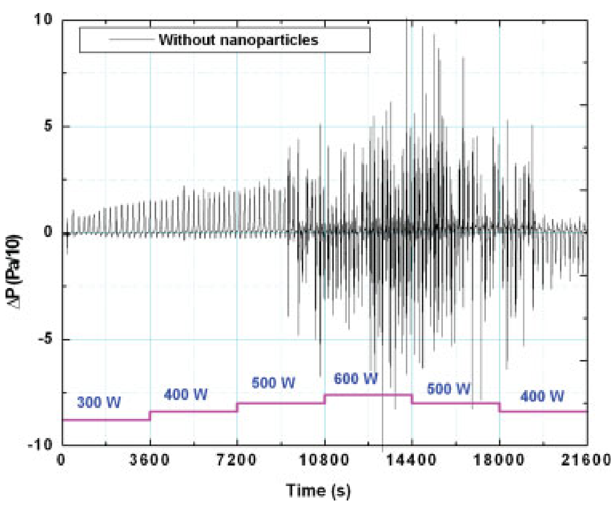

Figure 2. A typical flow instability behavior in water during power raising and set back process.

[Color figure can be viewed in the online issue, which is available at www.interscience.wiley.com.]

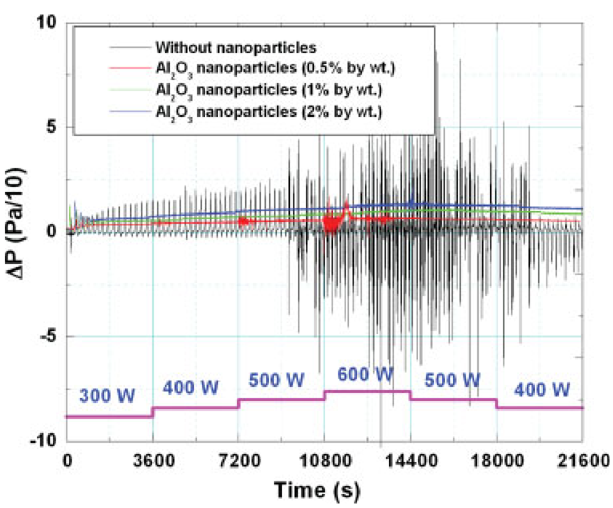

Figure 3. Suppression of flow instability with nanofluids during power raising and set back process.

[Color figure can be viewed in the online issue, which is available at www.interscience.wiley.com.]

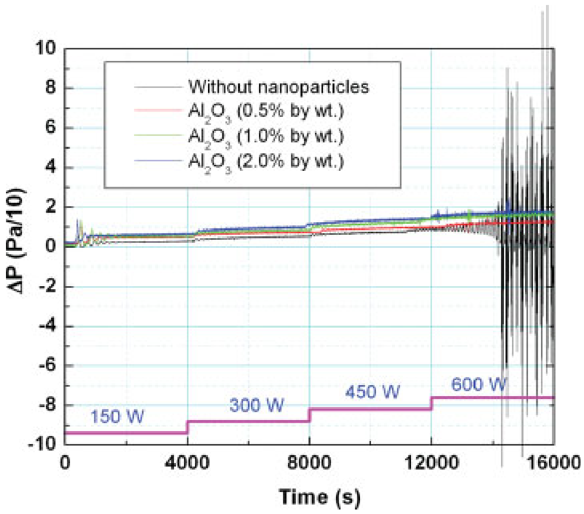

Figure 4. Flow instability behavior with Al_2O_3 nanofluids during power raising from 150 W to 600 W.

[Color figure can be viewed in the online issue, which is available at www.interscience.wiley.com.]

tion of Al_2O_3 nanoparticles, the flow became completely stable. In the latter case (Figure 5), the flow was unstable even at 400 W when water alone was the working fluid. The instability characteristics with water were similar as that observed in Figure 2. With addition of Al_2O_3 nanoparticles, the flow was found to be stable for this power transient.

Steady State Flow Characteristics with Al_2O_3 Nanofluids

The steady state experiments were conducted at different powers with water alone and then repeated with different concentration of Al_2O_3 nanofluids. The power was increased in small steps of 50 W from an initial low power of 100 W while maintaining the secondary side cooling water flow rate of 1 l per minute. The steady state flow rates are always found to be higher with Al_2O_3 nanofluids (Figure 6) as compared with that with water alone, indicated by the increased pressure drop in the loop (about 28% to 44%). The corresponding time averaged flow rates have been estimated and plotted as a function of operating power in Figure 7 which shows that the flow rate is increased between 20 to 35 % depending on the concentration of nanoparticles and operating conditions.

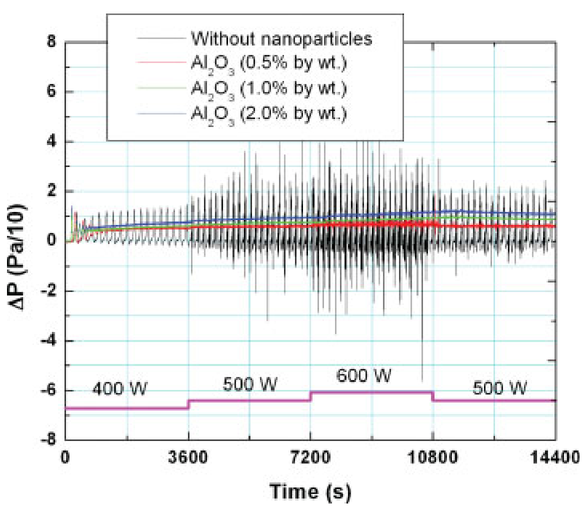

Figure 5. Flow instability behavior with Al_2O_3 nanofluids during power raising and set back process with an initial power of 400 W.

[Color figure can be viewed in the online issue, which is available at www.interscience.wiley.com.]

Discussion

From the measured data, the difference in the driving force between water and nanofluids in the natural circulation loop can be characterized by comparing their temperature distribution at different heating powers. Figure 8 shows the measured variation of averaged temperature difference between hot leg and cold leg of the natural circulation loop with and without addition of nanoparticles. As evident from the figure, there is less than 1°C variation in ΔT (temperature difference between the hot-leg and cold-leg) with and without nanoparticles which govern the driving buoyancy force. This is even negligible at higher power. But the increase in natural circulation mass flow rate with nanofluids has been demonstrated in Figure 6, which is significantly large especially at higher powers.

To understand the physics behind the flow rise due to addition of nanoparticles, the physical property of the Al_2O_3 nanofluids have been calculated for the Al_2O_3 concentration of 0.5% to 2% by weight in water, which corresponds to 0.15% to 0.6% by volume. 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

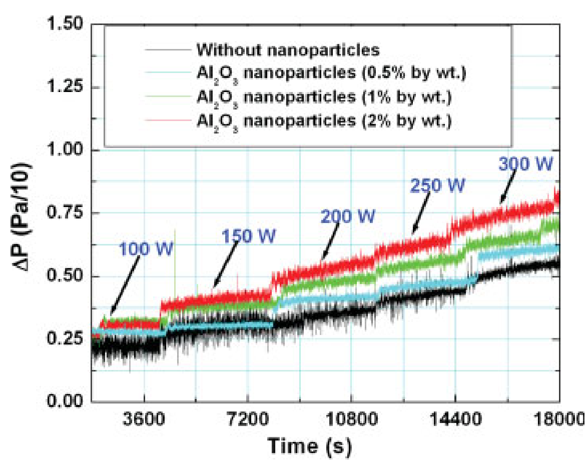

Figure 6. Comparison of steady state flow rate with and without nanofluids.

[Color figure can be viewed in the online issue, which is available at www.interscience.wiley.com.]

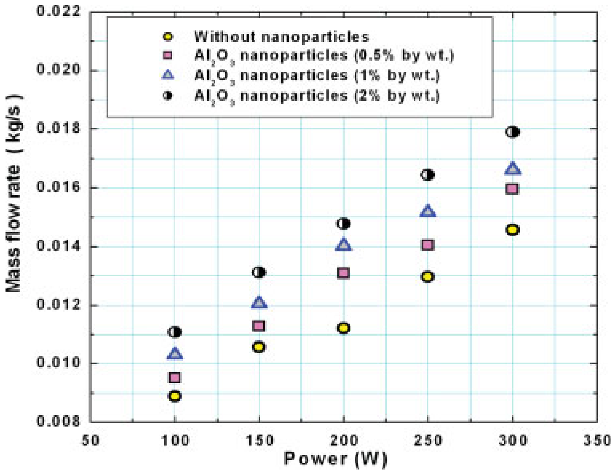

Figure 7. Variation of steady state flow rate with different concentration of nanoparticles.

[Color figure can be viewed in the online issue, which is available at www.interscience.wiley.com.]

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

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 $f = p/\mathrm{Re}^b$, 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 $N_G = \frac{L_t}{D_r}\sum_{i=1}^{N}\left(l_{\mathrm{eff}}/[d^{1+b}a^{2-b}]\right)_i$; a,d,l being the nondimensional 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 density (ρ), viscosity (μ), and specific heat (C_p). These properties have been calculated using existing models[8,10] and plotted in Figures.9a–c in the experimental range of volumetric fraction, $\phi = 0.15-0.6\%$. It should be noted that the variation of these fluid properties due to addition of nanoparticles 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 nanoparticles in the above concentration range using the Hamilton-Crosser model.[11–12] It is evident from Figure 9d 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 nanometallic oxide particles has little role to play on natural circulation behavior. Hence the significant rise in the flow rate cannot be explained using the existing models for prediction of fluid properties due to addition of nanoparticles, especially the physics in the thermal and hydrodynamic boundary layers.

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. As 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 nanoparticles during the natural circulation experiments.

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]

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 significant 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[13]); 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.

Natural Circulation Behavior with Different Nanoparticles

To understand the influence of material type and its size on the natural circulation characteristics, we conducted experiments with two other metallic oxide nanoparticles hav-

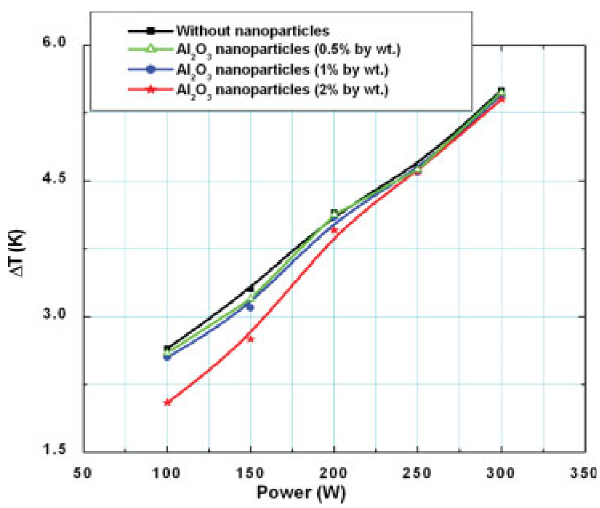

Figure 8. Comparison of time averaged temperature difference between hot-leg and cold-leg with and without nanoparticles for stable flow conditions.

[Color figure can be viewed in the online issue, which is available at www.interscience.wiley.com.]

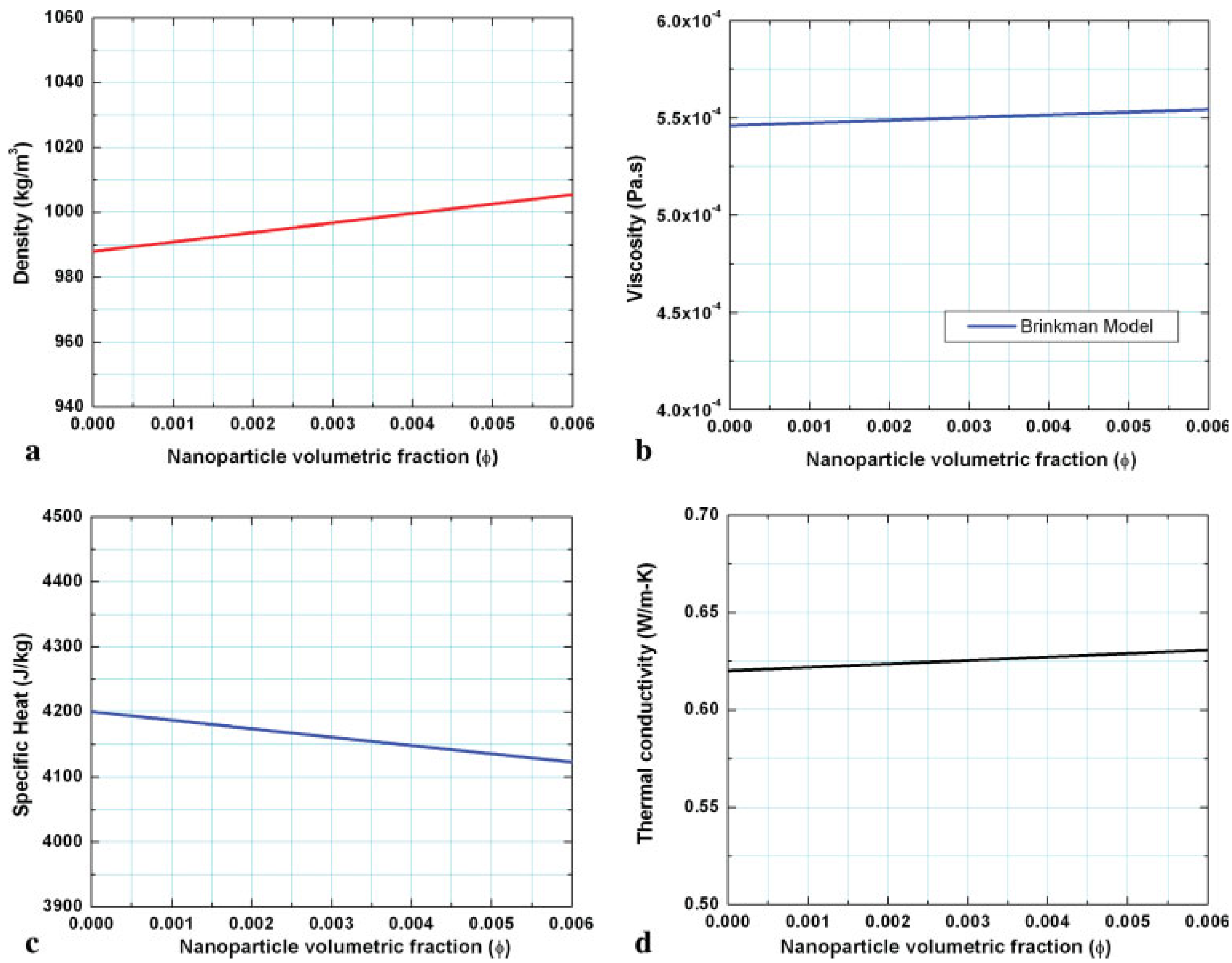

Figure 9. (a) Variation of density, (b) variation of viscosity, (c) variation of specific heat, (d) variation of thermal conductivity.

[Color figure can be viewed in the online issue, which is available at www.interscience.wiley.com.]

ing different sizes. One was CuO having particle size of 20–50 nm and purity of 99.2% and the other was TiO_2 having particle size of 10–25 nm and purity of 99%. Stable nanofluids of these materials were prepared by sonication using the procedure as discussed earlier. The concentration of nanofluids was 0.5% by weight in all the cases. Experiments were repeated with these nanofluids in addition to Al_2O_3 for this concentration for the same power transients discussed earlier.

Figure 10 shows a comparison of flow instability behavior of loop with water and with different nanofluids. In this case, the fluid was heated from an initial power of 300 W to 600 W and subsequently reduced to 500 W in steps of 100 W. The secondary side cooling water flow rate was kept constant at 1 l per minute throughout the experiments. Interestingly, the flow was found to be stable with all the metallic oxide nanofluids for such a small concentration of 0.5% by weight. Similar behavior was also observed for another power transient as shown in Figure 11.

Steady state natural circulation characteristics of the system with different nanofluids and water are presented in Figure 12a for an equal concentration (0.5% by wt) of nanofluids. The corresponding time averaged values are shown in

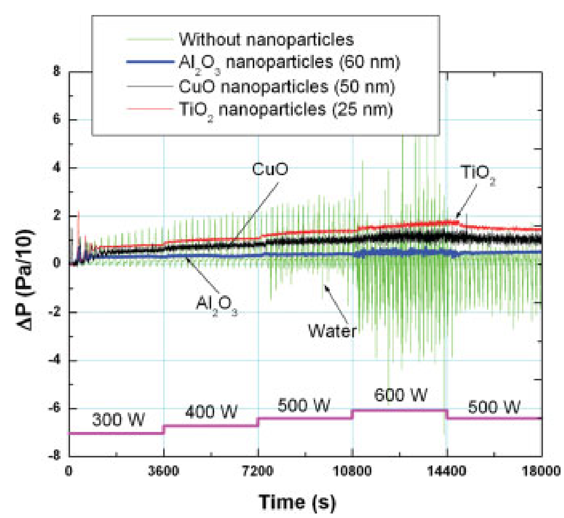

Figure 10. Suppression of flow instability with different metallic oxide nanofluids during power raising and set back process.

[Color figure can be viewed in the online issue, which is available at www.interscience.wiley.com.]

Figure 12b. Mostly, the natural circulation flow rate was found to be higher with nanofluids as compared with that with water. The increase in flow rate was found to be dependent on the type of nanoparticles, i.e., material and its size. Although at low powers TiO_2 nanofluids was found to have large buoyancy induced flow rate as compared with CuO, Al_2O_3, and water; however, at high power (>250 W), CuO nanofluids were found to have significantly large buoyancy induced flow rates. Moreover, it is very clear that TiO_2 and Al_2O_3 nanofluids are promising over the entire power range of operations as the flow rate increases consistently even at such a low concentration. On the other hand, CuO even though produces very large flow rate as compared with water and other metallic oxide nanofluids at high powers; however, at very low powers, the enhancement of flow rate is not realized.

Concluding Remarks

In this article, we have demonstrated through a series of experiments, the application of nanofluids in natural circulation loops as widely used in process and nuclear industries, to suppress the flow instabilities and enhance the buoyancy induced flow rate. These tests consistently showed that the suppression of instabilities for wide variety of power transients with three different metallic oxide nanofluids (Al_2O_3, CuO, TiO_2) for varying concentration and particle sizes. The enhancement in buoyancy induced flow rate was found to increase with the concentration of nanoparticles. The natural circulation flow rate with CuO nanofluids was found to be the highest at high power, whereas the flow rate with TiO_2 was higher at low power as demonstrated in our experiments. Overall, TiO_2 and Al_2O_3 nanofluids are found to be promising over the entire power range of operations since the flow rate increases consistently with power as compared with water even at such a low concentration 0.5% by weight.

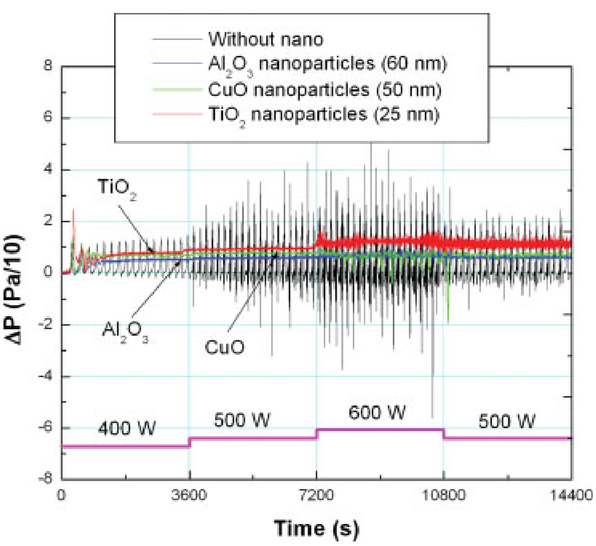

Figure 11. Flow instability behavior with different nanofluids during power raising and set back process with an initial power of 400 W.

[Color figure can be viewed in the online issue, which is available at www.interscience.wiley.com.]

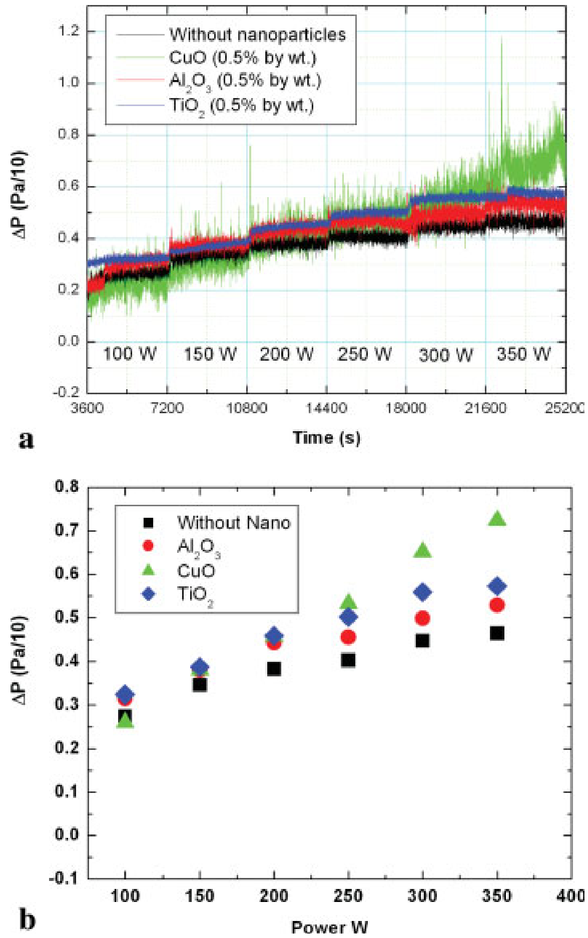

Figure 12. (a) Variation of flow behavior with different nanoparticles (0.5% by wt). (b) Variation of steady state flow rate with different nanoparticles (0.5% by wt).

[Color figure can be viewed in the online issue, which is available at www.interscience.wiley.com.]

Literature Cited

1. Greif R. Natural circulation loops. *J Heat Transfer*. 1988;110:1243–1258.
2. Welander P. On the oscillatory instability of a differentially heated loop. *J Fluid Mech*. 1967;29:17–30.
3. Nishihara T. *Oscillatory Instability of a Single-Phase Natural Circulation Loop*. Kyoto, Japan: NURETH-8, 1997.
4. Vijayan PK. Experimental observations on the general trends of the steady state and stability behaviour of single-phase natural circulation loops. *Nuclear Eng Design*. 2002;215:139–152.
5. Misale M, Frogheri M. Stabilization of a single-phase natural circulation loop by pressure drops. *Exp Thermal Fluid Sci*. 2001;25:277–282.
6. Das SK, Putra N, Thiesen P, Roetzel W. Temperature dependence of thermal conductivity enhancement for nanofluids. *J Heat Transfer Trans ASME*. 2003;125:567–574.
7. Das SK, Putra N, Roetzel W. Pool boiling characteristics of Nanofluids. *Int J Heat Mass Transfer*. 2003;46:851–862.

8. Buongiorno J. Convective transport in nanofluids. *ASME J Heat Transfer*. 2006;128:240–250.
9. Vijayan PK, Nayak AK, Pilkhwal DS, Saha D, Venkat Raj V. Effect of loop diameter on the stability of single-phase natural circulation in rectangular loops. *In the Proceedings of the 5th International Topical Meeting on Reactor Thermal Hydraulics (NURETH-5)*, Salt Lake City, USA, September 21–24, 1992;1:261–267.
10. Xuan Y, Roetzel W. Conceptions for heat correlation of nanofluids. *Int J Heat Mass Transfer*. 2000;43:3701–3707.
11. Hamilton RL, Crosser OK. Thermal conductivity of hetrogeneous two component systems. *I & EC Fundam*. 1962;1:187–191.
12. Lee S, Choi US, Li S, Eastman JA. Measuring thermal conductivity of fluids containing oxide nanoparticles. *ASME J Heat Transfer*. 1999;121:280–289.
13. Murshed SMS, Leong KC, Yang C. Determination of the effective thermal diffusivity of nanofluids by the double hot-wire technique. *J Phys D: Appl Phys*. 2006;39:5316–5322.

Manuscript received Aug. 23, 2007, and revision received Aug. 1, 2008.