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ORIGINAL

Pool boiling heat transfer characteristics of ZrO_2–water nanofluids from a flat surface in a pool

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Abstract Nucleate pool boiling of ZrO_2 based aqueous nanofluid has been studied. Though enhancement in nucleate boiling heat transfer has been observed at low volume fraction of solid dispersion, the rate of heat transfer falls with the increase in solid concentration and eventually becomes inferior even to pure water. While surfactants increase the rate of heat transfer, addition of surfactant to the nanofluid shows a drastic deterioration in nucleate boiling heat transfer. Further, the boiling of nanofluid renders the heating surface smoother. Repeated runs of experiments with the same surface give a continuous decrease in the rate of boiling heat transfer.

1 Introduction

Boiling is a common yet a very efficient mode of heat transfer where liquid phase transforms into vapour phase over a hot surface extracting a large amount of thermal energy with a small temperature difference. Application of boiling covers a very wide range. In recent times the application of boiling is increasingly suggested for systems which are characterized by ultra high heat flux in a very compact volume. This has prompted the researchers to try different augmentation techniques [1] for enhancing the rate of boiling heat transfer further, particularly during the nucleate boiling regime. Use of additives like surfactants [2] or solid particles in boiling liquids is a common practice. Nanofluids which constitute dispersion of nanometric solids in a liquid shows dramatic increments in thermal conductivity [3, 4] and possess enough prospect for enhancement in heat transfer during convection [5, 6]. This has encouraged the researchers to investigate the application of nanofluids for augmentation of boiling heat transfer.

However, the heat transfer behavior of nanofluid in pool boiling is not completely understood till date. Further, the observation made so far in this regard present some controversies. The rate of boiling heat transfer was observed to deteriorate in Al_2O_3–Water nanofluid by Das et al. [7, 8]. The authors have postulated that sedimentation of nanoparticles render the heater surface smoother and reduce the number of active nucleation sites. As a result there is a fall in heat transfer rate during boiling. On the contrary, Bang and Chang [9] observed an increase in the surface roughness of heater due to boiling of nanofluids. In other set of studies [10, 11] a phenomenal increase in critical heat flux (CHF) was recorded without any significant change in the rate of heat transfer in nucleate boiling regime. Tu et al. [12] reported increase in both heat transfer coefficient and in CHF. Contradictory results have also been reported regarding the bubble generation pattern in the boiling of nanofluids. You et al. [10] observed an increase in bubble size and decrease in the frequency of bubble departure. On the other hand, Tu et al. [12] observed a decreased in bubble size with no significant change in bubble frequency.

Addition of small amount (ppm level) of surfactant increases the rate of heat transfer in nucleate boiling regime substantially [2]. In general, surfactants enhance the nucleate boiling by decreasing the bubble departure diameter and increasing its frequency. However, so far, no

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study has been made to investigate the combined effect of surfactant and nano particle addition on the boiling behavior. Such a study is very relevant as surfactants are often added to nanofluids for stabilization of the particles.

The motivation of the present study is manifold. The majority of boiling studies have been made using Al_2O_3 based nanofluids, with the exception of a few studies [10, 11] with silica based nanofluids. To understand the general behavior of this new fluid medium it is important to investigate the boiling of other nanofluids also. In the present study a new nanofluid-ZrO_2 dispersed aqueous system has been chosen. The effect of surfactant when used as a stabilizer in nanofluid on boiling heat transfers has also been investigated.

2 Nanofluid preparation and experimental set up

Nanofluid samples were prepared by dispersing 0.005, 0.01, 0.02, 0.5, 0.07 and 0.15 vol% of nanocrystalline ZrO_2 powder in the deionized water. An ultrasonic vibrator and magnetic stirrer were used for nearly 3–4 h to ensure proper mixing of the nanoparticles into the base fluid. Prior to dispersing powder in liquid, the particles were characterized by X-ray diffraction (XRD) for phase identification (Fig. 1a). Selected samples were examined under Transmission Electron Microscope (TEM) to study the size, dispersion, and morphology of nanoparticles in the base fluid. Figure 1b shows that the nanoparticles are indeed near spherical in shape having 20–25 nm diameters and have a tendency of agglomeration and non uniform dispersion before ultrasonic vibration and magnetic stirring. The latter tendency possibly arises due to electrostatic attractive forces among the particles and hydrophobic nature of particles. For a better dispersion, 1.0 vol% of tetramethyl ammonium hydroxide ($(CH_3)_4NOH$, TMAH) were added to some samples of nanofluid as surfactant. After appropriate stirring a proper dispersion of particles and better stability against the sedimentation was observed.

The set up for the pool boiling experiment (Fig. 2) consist of a heating section and a liquid pool assembly. These two are separated by a 5 mm thick bakelite plate. A plane copper plate of 60.5 mm diameter extended through the bakelite plate in the liquid water/nanofluid pool is used as boiling surface. The pool is confined inside a borosilicate flanged glass tube of 150 mm diameter and 300 mm height. Copper test plate is heated from below by a cylindrical copper heater assembly (50.8 mm diameter and 110 mm length). Four equally spaced cartridge heaters (10 mm diameter and 100 mm length), each of 250 W are inserted in the copper cylinder for homogeneous heating. To minimize the radial heat loss fiber type blanket insulation (Supercera) of 100 mm thickness is provided around the copper cylinder. Ceramic insulation of 50 mm thickness is used to minimize the downward axial heat loss. The entire heater assembly is placed inside a brass casing. Teflon bush is furnished radially around the extended test

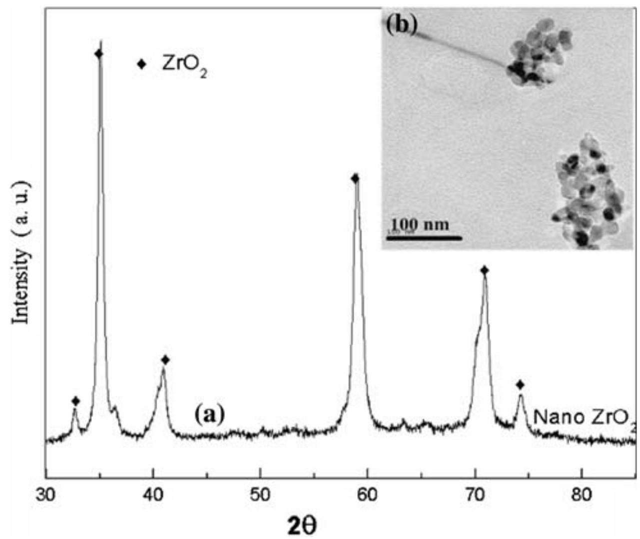
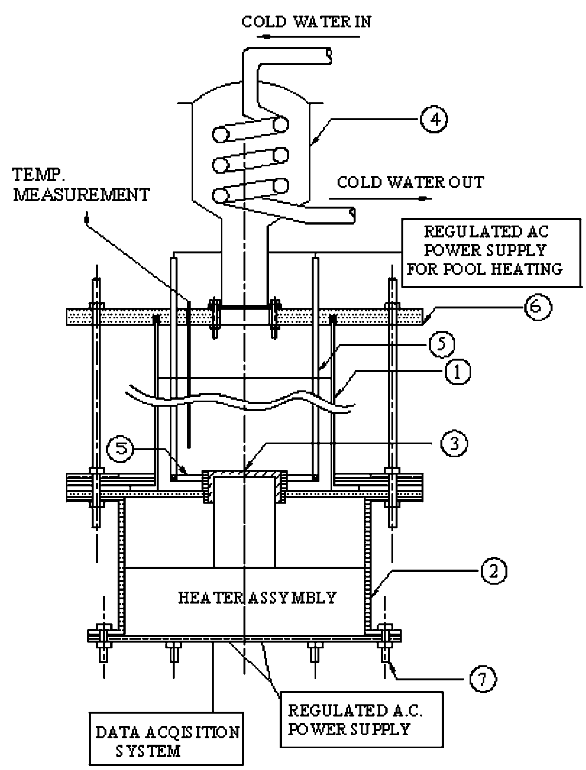


Fig. 1 **a** XRD patterns of nano-crystalline ZrO_2 powders. **b** TEM photograph of 25–30 nm nano-crystalline ZrO_2 dispersed nanofluid



1. Borosilicate glass 2. Heater assembly 3. Test plate 4. Reflux condenser 5. Auxiliary heater 6. Top cover 7. Leveling screw

Fig. 2 Experimental facility for investigation of boiling heat transfer plate to restrict the nucleation from the vertical surfaces. Vapors created from the test plate is condensed in a gravity type condenser that receives the vapor and after condensation returns the condensate to the pool. For maintaining the temperature of the liquid pool, a secondary heater coil of 300 W is provided. Power supply to the primary and secondary heaters is varied by controlling separate variacs. To measure the temperature of the test plate a copper constantan (T type) sheathed thermocouple of 0.5 mm diameter is used. It is placed just below (1.5 mm) the top surface of the test plate to get an accurate temperature reading of the boiling surface. Bulk fluid temperature is also measured by an insulated copper constantan thermocouple placed just above the test surface. Power input to the heaters and voltage signals from the thermocouples are analyzed and stored using an Agilent 34970A data logger (20 channels, maximum speed 200 Hz) and a computer. The heat flux was determined by measuring the voltage and current input to the heating assembly. To prevent the leakage from the copper–teflon contact line and bakelite–teflon contact line high temperature resistant paste (Aremco 517) is used which can withstand up to 1,200°C.

To study the boiling heat transfer it is very important to characterize the surface accurately. The surface roughness of the heater is measured using a profilometer having a diameter tip of 5 μm and a sensitivity of 0.05 μm. Typical measured values of roughness (Ra) of a new test surface lies in the range from 0.5 to 0.7 μm.

Before studying the boiling heat transfer from the nanofluids the set up was tested using deionized water under pool boiling condition. The boiling curve compares reasonably well with Rohsenow correlation [13]. A detail discussion regarding this is available elsewhere [14].

3 Results and discussion

Figure 3 depicts the boiling curves for pure water and nanofluid having different vol% of particle concentration in nucleate boiling regime. The maximum value of surface heat flux for all the boiling experiments was restricted to around 1,500 kW/m^2 to avoid the over heating and failure of the heater assembly. It may be noted that this value is close to the critical heat flux of pure water as given by Zuber correlation [15]. It is interesting to note that at the lowest concentration of nanoparticle (0.005 vol%) the coefficient of boiling heat transfer in the nucleate boiling region is substantially higher compared to that observed in pure water. However, there is a steady decrease in the heat transfer coefficient with the increase in ZrO_2 nanoparticle concentration further. At a concentration of 0.15 vol% of ZrO_2 the boiling curve falls much below that recorded for pure water. The decrease in the heat transfer coefficient with the increase in particle concentration was also observed by Das et al. [7] and Bang and Chang [9]. However, You et al. [10] did not observed any effect of particle concentration on the coefficient of nucleate boiling heat transfer while Wen and Ding [6] observed the rate of heat transfer to enhance with the increasing particle concentration. This clearly points out that other parameters of both the nanofluid and the boiling surface are also important and a complex interplay between all these factors ultimately decides the rate of heat transfer.

Several researchers have reported an increase in CHF for nanofluids. The present investigation reveals a very interesting picture in this regard. Boiling curve for nanofluids having concentration of ZrO_2 more than 0.07 vol% have slopes higher than the curve (Fig. 3) recorded for pure water. Though experiments were conducted up to a maximum value of surface heat flux of 1,500 kW/m^2 (due to limitation of the test facility) the higher slope of the boiling curve indicated a possible higher value of CHF compared to that in pure water. However, this needs verification through further experimentation.

It may be noted that both You et al. [10] and Vassallo et al. [11] reported increase in CHF for nanofluids. Though You et al. [10] varied the concentration of the solid particles no clear trend of the effect of the solid concentration has emerged from their study. On the other hand, a constant solid concentration was not strictly maintained during the experiments conducted by Vassallo et al. [11]. They have observed different values of CHF in different test runs but could not explain this difference from the basic physics. This clearly indicates the need for a systematic study of CHF from nanofluids covering a wide range of particle concentration.

It is a common practice to use different surfactants and stabilizers in the synthesis of nanofluid [3, 4]. In an

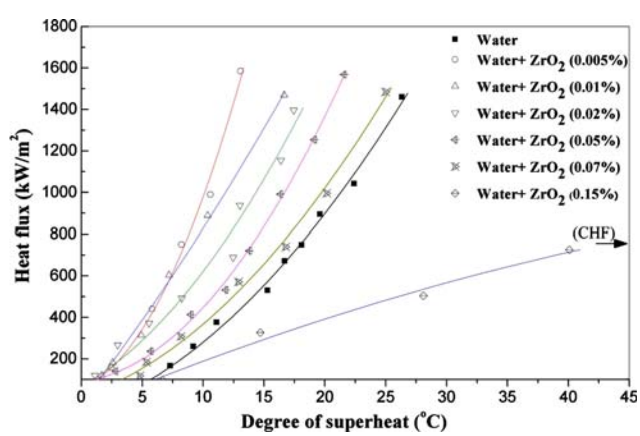


Fig. 3 Boiling curves of pure water and nanofluid without addition of surfactant

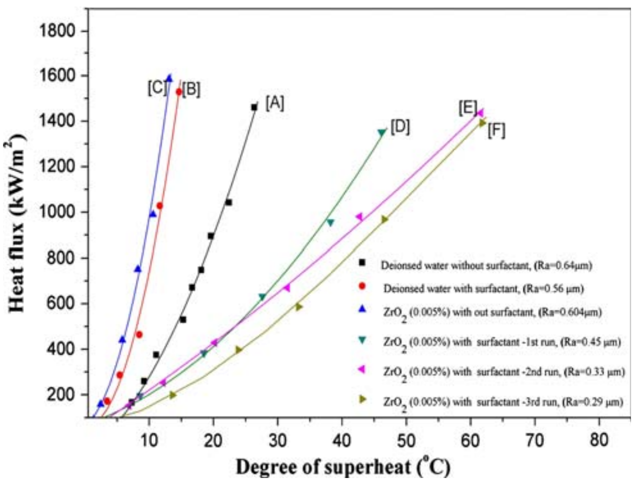


Fig. 4 Boiling curves of pure water and nanofluid with addition of surfactant

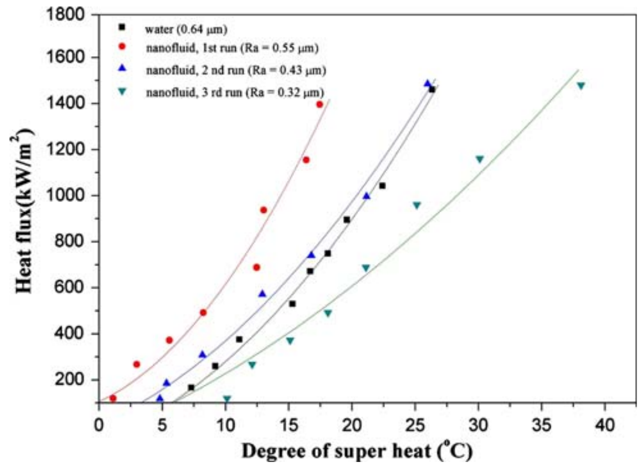


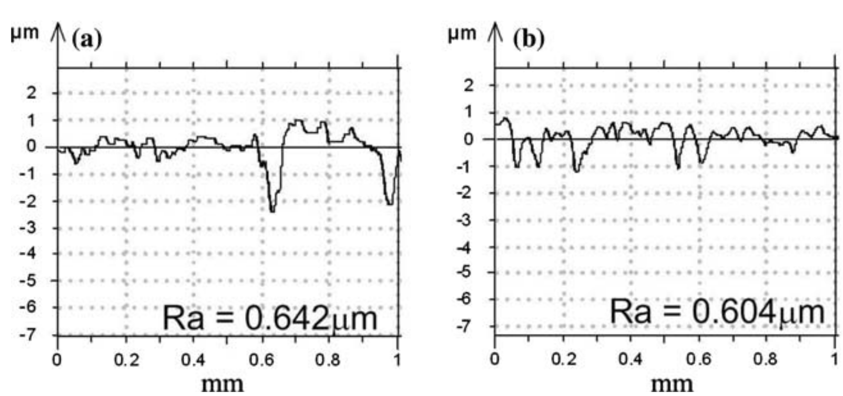
Fig. 6 Boiling heat transfer behavior of 0.02 vol% ZrO_2 nanoparticles dispersed water based nanofluid (multiple run without cleaning surface)

aqueous system, addition of surfactant enhances the rate of boiling heat transfer [2]. Wasekar and Manglik [16] reported that nucleate boiling heat transfer performance of water increases with the addition of ionic surfactant due to early incipient of nucleation and decrease in the size of bubble at the time of departure. They have also mentioned that after some limiting value of surfactant addition in plane water the trend gets reversed. However no systematic study has so far been made to investigate the effect of surfactant in boiling of nanofluids.

In the present work boiling curves for deionized water (A), deionized water and 1.0% of surfactant by volume (B), ZrO_2 (0.005 vol%) based nanofluid without surfactant (C) and ZrO_2 (0.005 vol%) based nanofluid with surfactant have been obtained. A comparison between these curves is shown in Fig. 4. Nanofluid with 0.005 vol% solids have been considered as it provided a high value of heat transfer augmentation. Curve B and C depicts substantial increase in boiling heat transfer compared to curve A, indicating a low volume percentage of ZrO_2 dispersion or addition of surfactant improves the heat transfer characteristics. Surprisingly, a mixture of ZrO_2 and surfactant reduces the boiling heat transfer to a very large extent. This unique observation indicates that a rigorous study is needed to investigate the change of properties of the fluid medium due to simultaneous addition of nanoparticles and surfactants and the effects of such changed properties on boiling.

Das et al. [7, 8] observed degradation of boiling heat transfer in a nanofluid. They further observed a decrease in roughness of boiling surface due to interaction with nano particle and attributed the fall in heat transfer coefficient to the increased smoothness of the heater. In the present investigation, we have also observed a similar trend of fall in the boiling heat transfer with the increase of nano particle concentration. Figure 5 shows the typical surface profile of the test plate after the experiments with deionized water and 0.005% dispersed ZrO_2 nanofluid. It can be seen from the figure that the surface behaves smoother due to deposition while nano particles are added with the water. To verify the proposition of Das et al. [7, 8] we have planned a separate set of the experiments where repeated boiling runs were conducted on the same boiling surface using fresh nanofluid sample of same concentration. After each test run the boiling surface was washed by water and its surface roughness was measured before fitting in the test

Fig. 5 Surface roughness profile of test plate after experiment with **a** deionized water and **b** ZrO_2 (0.005 vol%) dispersed water based nanofluid



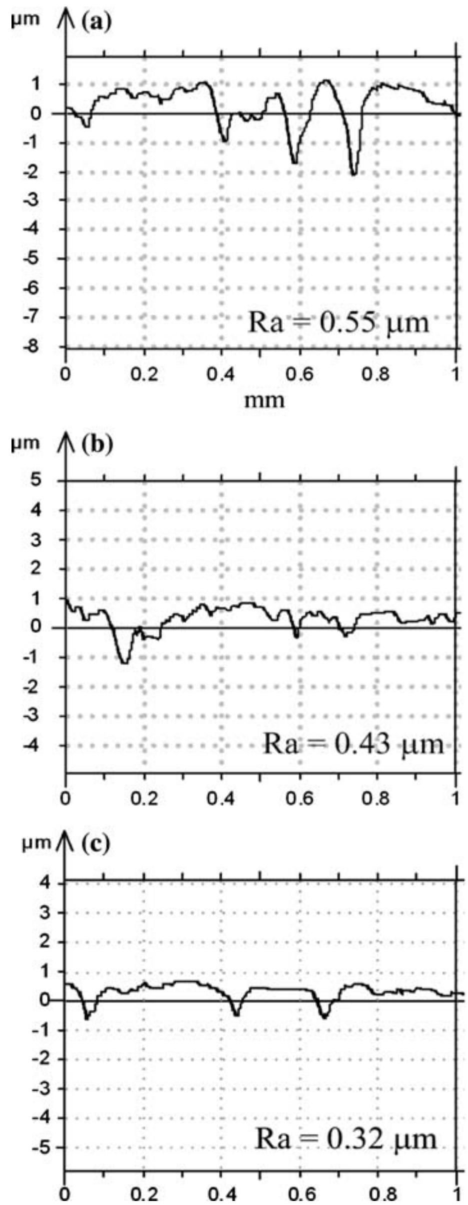


Fig. 7 Surface roughness profile of test plate after experiment of ZrO_2 (0.02 vol%) dispersed water based nanofluid (multiple run without cleaning surface), **a** 1st run, **b** 2nd run and **c** 3rd run

rig for the next run. Figure 6 depicts the results for a nanofluid concentration of 0.02 vol% without any surfactant. Figure 7 shows the surface roughness profile of plate after each run. It has been observed that with the repetition of experiment both surface roughness and the coefficient of boiling heat transfer decreases. Similar studies have also been made using nanofluids having 1.0 vol% of surfactant and identical trends of a decrease in heat transfer was observed as can been seen from curves D, E and F in Fig. 4. A probable cause of such degradation in boiling heat transfer could be a decrease in the number of nucleation site due to prolonged boiling of nanofluid as also anticipated by Das et al. [8].

4 Conclusion

Nucleate boiling heat transfer of ZrO_2 based aqueous nanofluids with different combinations has been investigated covering a wide range of surface superheat. Boiling curve has also been constructed for nanofluids having surfactant as a stabilizer. Finally, repeated test runs have been taken using the same the boiling surface to investigate the effect of surface roughness. Some of observed results are unique in nature and are not in conformity with those reported earlier. In general, the contradicting results are observed during the boiling of nanofluids can be complex nature of boiling heat transfer. During boiling several parallel mechanism of heat transfer namely phase change, natural convection due to surface tension, micro convection due to bubble departure, Marangoni convection due to surface tension gradient along the bubble surface are present. The presence of solid particles in nanofluid not only changes the thermal conductivity substantially but can also alter the surface tension of the fluid and the surface properties of heater. The effect of nano particle can depends on number of parameter like composition, shape, size, concentration agglomeration etc. Therefore, it is two early to predict generalize the heat transfer behavior of nanofluids. A large number of systematic experiments under controlled conditions are needed to ascertain the effect of each parameters of the nanofluid on boiling heat transfer.

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