International Journal of Thermal Sciences 48 (2009) 2215–2220

Contents lists available at ScienceDirect

International Journal of Thermal Sciences

journal homepage: www.elsevier.com/locate/ijts

Boiling heat transfer on a high temperature silver sphere in nanofluid

H. Lotfi, M.B. Shafii*

Department of Mechanical Engineering, Sharif University of Technology, Tehran, Iran

ARTICLE INFO

Article history:
Received 10 November 2008
Received in revised form
5 April 2009
Accepted 8 April 2009
Available online 26 May 2009

Keywords:
Boiling
Nanofluid
Heat transfer

ABSTRACT

To investigate boiling heat transfer characteristics of nanofluids, transient quenching experiments of a high temperature silver sphere in water-based nanofluids with Ag and TiO_2 nanoparticles were performed. A silver sphere with a diameter of 10 mm and an initial temperature of 700 °C was quenched in these nanofluids at a temperature of 90 °C. The results showed a considerable reduction in the quenching ability of nanofluids compared to that of pure water. The presence of nanoparticles in water caused the film boiling mode to vanish at lower temperatures depending on the mixture concentration. Calculated heat transfer rates in nanofluids were lower than those in pure water. In the quenching experiments with an unwashed heated sphere, the film boiling mode did not appear and the hot sphere quenched more rapidly through nucleate boiling. In this case the sphere surface was covered by a thin layer of nanoparticles. It was evident that nanoparticle deposition on the sphere surface prevented vapor film from forming around it and resulted in quick quenching of the hot sphere.

1. Introduction

Ultrahigh-performance heat transfer is one of the most vital needs of many industrial technologies. Recent technological advances in manufacturing have led to the miniaturization of many components in numerous applications. Downsizing many electronic devices, such as microprocessors, requires more innovative techniques of heat dissipation. Many engineering systems such as power stations include problems related to boiling. In this regard, associated phase change heat transfer has been used extensively to acquire good heat transfer performance. Accordingly, various techniques for the enhancement of boiling heat transfer have been proposed and studied.

Recent advances in nanotechnology have allowed for the development of a new category of fluids termed nanofluids. Such fluids are liquid suspensions containing particles of nanometer dimensions. The idea is to suspend ultra fine solid particles in a fluid in order to change the thermal properties of the fluid [1–4]. Nanofluids have been found to be capable of providing considerable heat transfer enhancement compared to conventional fluids such as water, ethylene glycol and engine oil. Several investigations reported the thermal conductivity enhancement of nanofluids with low nanoparticle concentration (1–5 vol.%) to be more than 20% [5–8]. Eastman et al. [9] reported an outstanding increase in thermal conductivity of 40% with only 0.3 vol.% of nanoparticles of copper having an average size of less than 10 nm. Xuan and Li [10] summarized the main factors that could enhance heat transfer as follows: (a) the nanoparticles increased surface area; (b) increased interaction and collisions among the particles and fluid; and (c) increased mixing fluctuation and turbulence of the fluid.

Owing to these attributes, it is expected that the heat transfer performance of water, the most widely used coolant, can be improved. However, the real worth of such fluids can only be tested under convective conditions [11–13]. Xuan and Li [14] measured the convective heat transfer coefficient of water–Cu nanofluids, and found substantial heat transfer enhancement. For a given Reynolds number, the heat transfer coefficient of nanofluids containing 2 vol.% Cu nanoparticles was shown to be approximately 60% higher than that of pure water.

While using nanofluids for convective cooling, one must be aware of its boiling characteristics. This is because even if the nanofluid is unattractive with respect to two phase applications, during convective heat transfer with high heat fluxes, the boiling limit may be reached. It is important that the behavior of the nanofluid under such conditions is accurately known to avoid unwanted effects such as local hot spot which can cause significant deterioration of reliability of the components to be cooled. In this regard, studies and understanding of the boiling heat transfer characteristics of nanofluids are very much in an infant stage. Furthermore, to our knowledge, there are only few previous studies involved in describing "film boiling" heat transfer performance of nanofluids.

Das et al. [15] performed pool boiling experiments with a 20 mm cylindrical cartridge heater in a nanofluid in which alumina nanoparticles with an average size of 38 nm were suspended in pure

---

* Corresponding author. Tel.: +98 21 66165675; fax: +98 21 3912677.
E-mail address: behshad@sharif.ir (M.B. Shafii).

1290-0729/$ – see front matter © 2009 Elsevier Masson SAS. All rights reserved.
doi:10.1016/j.ijthermalsci.2009.04.009

Nomenclature

A (m^2)	sphere area
Bi	Biot number
c (j/kg C)	silver heat capacity
m (kg)	sphere mass
q'' (w/m^2)	Total heat flux from sphere
$q''_{\mathrm{w,cond}}$ (w/m^2)	heat flux due to conduction through the vapor film
$q''_{\mathrm{w,rad}}$ (w/m^2)	radiation from the wall into the bulk liquid
q''_{vap} (w/m^2)	heat loss due to vapor generation at the interface
$q''_{\mathrm{i,cond}}$ (w/m^2)	heat flux from the liquid interface into the liquid due to conduction
$q''_{\mathrm{i,adv}}$ (w/m^2)	heat flux from the liquid interface into the liquid due to advection
T (C)	sphere temperature
T_{sat} (C)	liquid Saturated temperature
T_∞ (C)	liquid temperature
t (s)	time
Greek	
θ (C)	wall superheat ($T-T_{\mathrm{sat}}$)

water. They investigated the nucleate boiling characteristics in terms of volume concentration of up to 4% and observed that the nucleate boiling heat transfer deteriorated due to the deposition of nanoparticles on the heated surface. Vassallo et al. [16] performed pool boiling experiments with a 0.4 mm diameter NiCr wire in 15 and 50 nm silica nanofluids. They reported that the maximum heat flux before wire failure occurred was remarkably up to about 3 times higher than that of in pure water. However, no significant heat transfer enhancement was observed in the nucleate boiling regime. Park et al. [17] performed some experiments to investigate film boiling heat transfer in nanofluids during the quenching process of a high temperature stainless steel sphere in alumina nanofluids. They reported that film boiling heat fluxes in nanofluids were lower than those in pure water. As can be seen, the current understanding of the boiling process in nanofluids is in a primitive stage and more theoretical and experimental works are needed to evaluate the boiling heat transfer characteristics of nanofluids.

The present study, which will provide experimental data to construct preliminary transient cooling curves of nanofluid in full ranges of heat transfer regimes, is motivated by the lack of investigation on boiling heat transfer, especially film boiling, in nanofluids. The work is carried out to investigate boiling heat transfer characteristics of nanofluids during the quenching process of a high temperature silver sphere in Ag and TiO_2 nanofluids. A transient quenching experiment was chosen to investigate the quenching ability of these nanofluids by observing the entire cooling process from film boiling to natural convection heat transfer. In this paper, the experimental results of the quenching process of the sphere in Ag–water nanofluid and TiO_2–water nanofluid are described. The effects of the type of nanoparticle, nanoparticle concentration, and nanoparticle deposition on boiling heat transfer during the quenching process are investigated and compared with the boiling characteristics in pure water.

2. Experimental setup

The experimental setup consists of a 10 mm silver sphere, a gas flame heater, a data acquisition system, and a test chamber which contains de-ionized distilled water or nanofluids. The test chamber is a 150×150 mm^2 rectangular Plexiglas chamber with a height of 200 mm. A 1000 W copper immersion heater is installed on the interior bottom surface of the chamber to preheat the nanofluid to a desired temperature. The sphere which is shown in cross section in Fig. 1 is drilled to install a 1 mm O.D. k-type thermocouple. The ratio of the diameter of the thermocouple support to that of the sphere is 0.1 which is small enough to neglect heat loss through the support. A data acquisition system (LOGOSCREEN 955010) records transient temperatures of the heated sphere at the center and the liquid inside the test chamber at a sampling rate of 8 Hz.

In this study, the Ag–water nanofluid and TiO_2–water nanofluid were chosen because of the lack of boiling heat transfer investigation of these nanofluids. Ag–water nanofluids with an average particle size of 35 nm were prepared by NanoCid Company and were tested at mass concentrations of 0.5, 1, 2 and 4%. The TiO_2–water nanofluids were produced by the Physics Department of Sharif University of Technology and were tested at mass concentrations of 0.125, 0.25, 0.5 and 1%. TiO_2 nanoparticles with an average size of 25 nm were dispersed in pure water. Ultrasonic vibration was used for about 16 h to prevent nanoparticle agglomeration and to increase the stability of the suspensions.

All the experiments were done at a fluid temperature of 90 °C, so the fluid degree of subcooling was about 6 °C. The heated sphere, at a temperature of 700 °C, was immersed into the fluid.

3. Experimental results

To ensure that the surface was free of any kind of contamination or nanoparticles, the sphere was cleaned with pure ethanol and rinsed with distilled water before each test. The film boiling started immediately after the hot sphere was immersed into the subcooled liquid. A thick smooth vapor film covered the sphere during the film boiling. Fig. 2 shows the schematic image of a stable thin film around the hot sphere in slightly subcooled liquid. As the temperature of the sphere was decreased, bubble-like irregularities appeared at the liquid–vapor interface and began to grow and collapse while traveling irregular paths over the surface of the vapor shell. These perturbations triggered oscillations in the vapor shell which consequently resulted in the collapse of the vapor film. This collapse occurred with a loud noise and consequently pressure waves appeared at the surface of the liquid inside the test chamber.

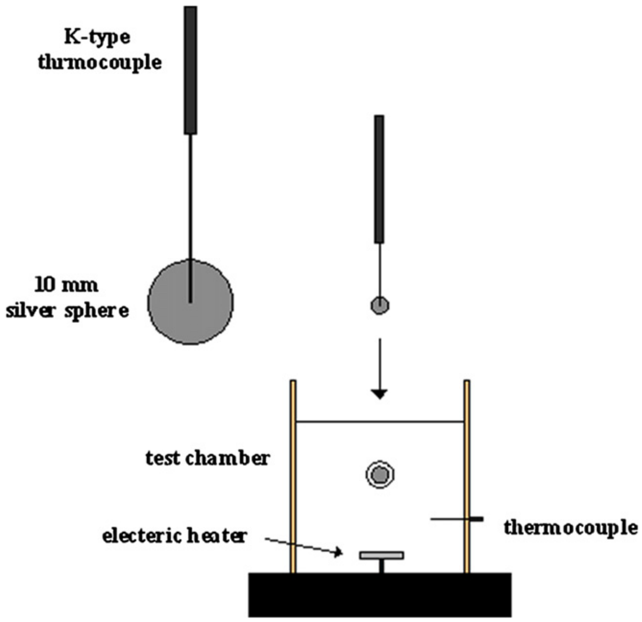

Fig. 1. Schematic of the experimental setup.

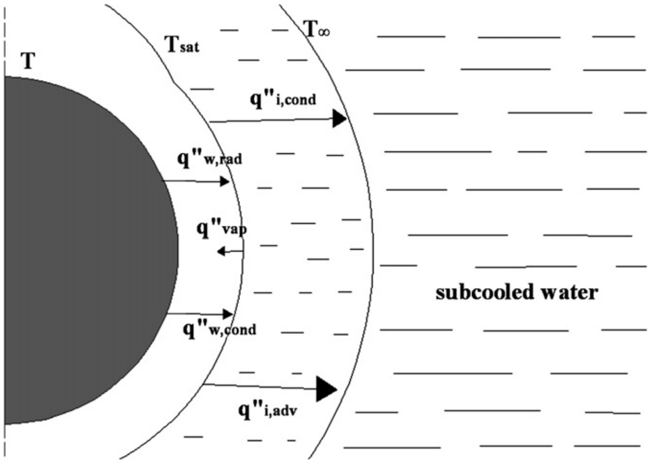

Fig. 2. Schematic image of a stable film around the hot sphere.

The whole process was visible during the quenching experiments in pure water, but the opacity of the nanofluids made it impossible to observe the boiling phenomena in them. However, it seemed that the loud noise during the collapse of the vapor film and the resulting pressure waves at the liquid surface were weaker in nanofluid experiments.

Fig. 3 shows the center temperature of the heated sphere in pure water and Ag–water nanofluids with different mass concentration during the transient quenching process. The quenching behavior of the sphere in Ag–water nanofluids is similar to that of the sphere in pure water as indicated in Fig. 3, but the quenching process takes more time in nanofluids than in pure water. After the same period of time elapse, the temperature at the center of the sphere in the Ag–water nanofluid is higher than that of the sphere in pure water. Sudden increase in cooling time indicates the reduction of heat flux from the sphere during the process in nanofluids. Fig. 3 also shows that cooling time is inversely proportional to the nanoparticle concentration.

Fig. 4 shows the temperature of the center of the sphere in pure water and the TiO_2–water nanofluids with different mass concentrations during the transient quenching process. It is obvious that the transient quenching process, as was observed in the Ag–water nanofluids, takes more time in the TiO_2–water nanofluids than in pure water and cooling time is inversely proportional to the nanoparticle concentration. In this case, change in cooling time due to change in nanoparticle concentration is not as large as that in the Ag–water nanofluids.

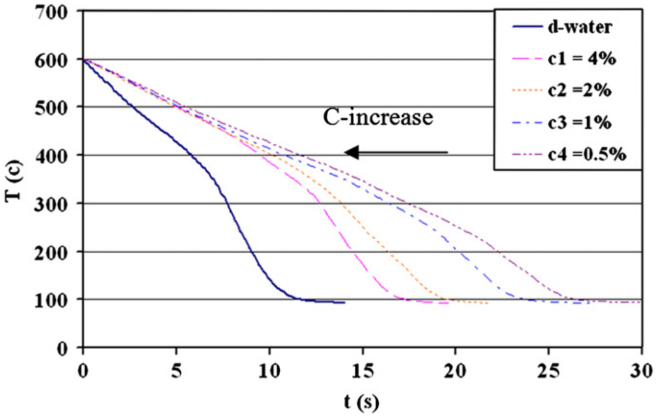

Fig. 3. Temperature at the center of the sphere in pure water and Ag–water nanofluids.

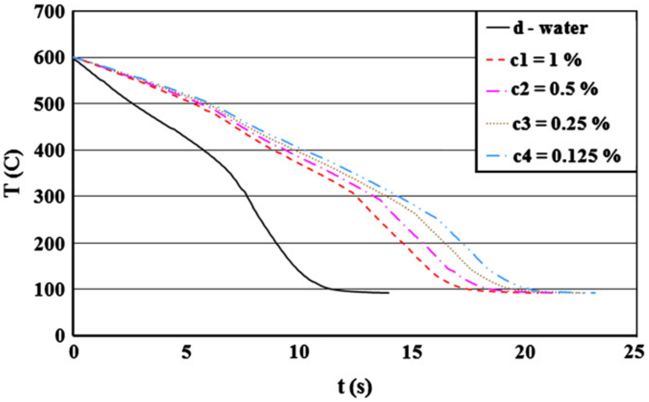

Fig. 4. Comparison between temperatures of the center of the sphere in pure water and TiO_2–water nanofluid.

Instantaneous average surface heat flux was obtained from the experimental temperature–time data. Due to the high thermal conductivity of silver, the Biot number of the sphere was less than 0.1 ($Bi < 0.1$) and hence the temperature gradients within it were assumed to be very small. Assuming the sphere to be isothermal, the lumped capacity relation determines the heat flux:

$$q'' = \frac{mc}{A}\frac{\mathrm{d}T}{\mathrm{d}t} \tag{1}$$

The same assumption was performed by Dhir and Purohit [18] and Steven and Witte [19] to obtain average surface heat flux. The determination of the heat flux then hinges upon an accurate determination of the slope of the temperature–time curve.

In this work, $\mathrm{d}T/\mathrm{d}t$ was estimated numerically using the recorded temperature histories. The thermocouples were calibrated to achieve accuracies down to 0.5°C. Neglecting all other sources of uncertainty, i.e., drift, data acquisition, data reduction (round off, truncation, and curve smoothing) and personal operation, the uncertainty in temperature data, which is mainly associated with response time of the thermocouples (0.1 s), was estimated to be ±2 percent, whereas, in worst case, the uncertainty in heat flux values, which is mainly associated with the sampling rate of the data acquisition system (8 Hz), was estimated to be ±8 percent.

In Fig. 5, the calculated heat flux values versus wall superheat in the Ag–water nanofluid with different concentrations are plotted together with that of pure water. These plots show that film boiling heat flux in Ag–water nanofluids is lower than that in pure water. The film boiling mode in nanofluids vanishes at lower temperatures

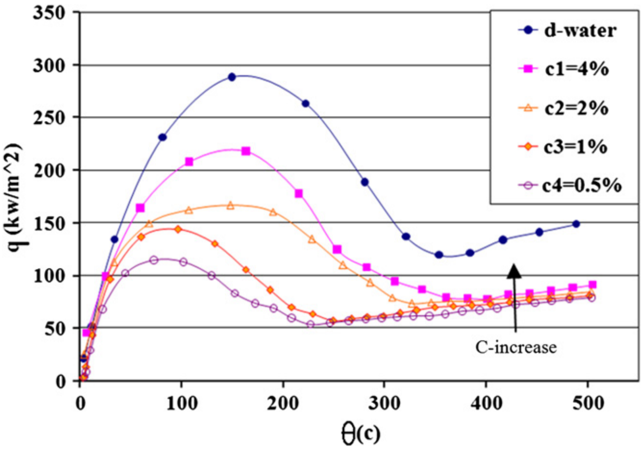

Fig. 5. Boiling heat flux in pure water and Ag–water nanofluids.

than in pure water. The minimum film boiling heat flux in nanofluids is also lower than that in pure water.

In Fig. 6, the calculated heat flux values versus wall superheat in the TiO_2–water nanofluid with different concentrations are plotted together with that of pure water. These plots show that film boiling heat flux in TiO_2–water nanofluids, as was observed in Ag–water nanofluids, is lower than that in pure water. In this case film boiling heat flux variation due to change in particle concentration is lower than that in Ag–water nanofluids.

Consider the geometry shown in Fig. 7. The liquid with a temperature of T_∞ flows around the heated sphere. If the surface wall temperature is high enough, a stable vapor film will form around the sphere. At equilibrium, the evaporation at the liquid–vapor interface causes the interface temperature to be equal to the saturation temperature at the system pressure. The energy entering the interface due to conduction from the wall through the vapor plus the absorbed radiation energy incident on the interface minus the energy removed from the interface into the liquid due to both advection and conduction must be equal to the energy absorbed to evaporate a certain amount of fluid at the interface.

It is speculated that there are three main reasons for the decrease in the heat flux from the sphere surface during film boiling when using nanofluids.

Firstly, fast accumulation of nanoparticles during the evaporation process forms a porous medium at the interface and functions as a barrier to fluid flow. When the mass flow rate of the vapor leaving the interface is greater than the mass flow rate of the working fluid supplied to the interface through the porous medium, dry out occurs and the vapor film thickness increases. This leads to a decrease in the heat flux leaving the surface of the sphere, and hence increases the film boiling time process. Therefore, the whole quenching time increases.

Secondly, the unfavorable increase in viscosity due to the presence of nanoparticles and their accumulation at the interface increases the shear at the liquid–vapor interface. Assuming the evaporation rate to be constant, the presence of nanoparticles and the increase in the shear at the liquid–vapor interface decreases the vapor removal rate from the top section of the film. Reduction in the amount of vapor removal increases the vapor film thickness. Vapor film thickness increases because of decrease in vapor velocity influenced by this higher shear. Therefore, heat transfer from the surface of the sphere decreases.

Thirdly, comparing with that of water, the emissivity of the Ag–water nanofluids is very low due to the existence of Ag particles. Therefore, the amount of the absorbed radiation energy incident on the liquid–vapor interface reduces significantly. It follows that it takes more time for the sphere to cool down (as seen in Fig. 3).

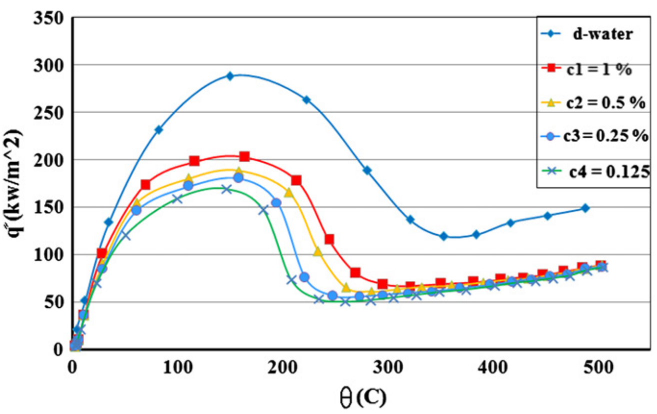

Fig. 6. Boiling heat flux in pure water and TiO_2–water nanofluids.

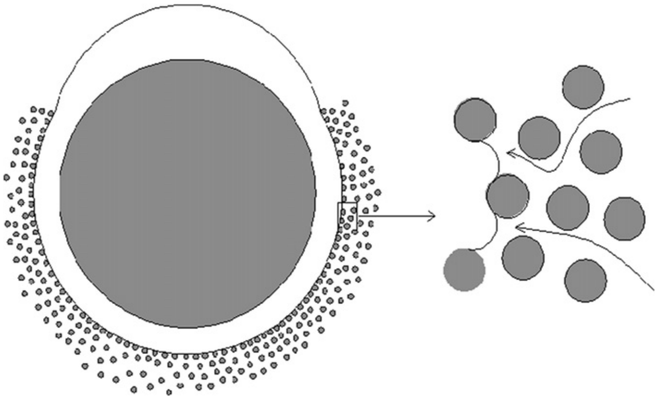

Fig. 7. Vapor film around the hot sphere in nanofluid.

The inverse proportionality between nanoparticle concentration and film boiling time can be seen in Figs. 3 and 4. As shown in Figs. 5 and 6, film boiling heat flux variation due to change in nanoparticle concentration is negligible. However, a higher concentration of nanoparticles results in higher thermal conductivity of the base fluid which causes more heat removal by the subcooled liquid through convection at the liquid–vapor interface. This reduces vapor generation at the interface which consequently causes the vapor film to collapse more rapidly. Therefore the film boiling mode vanishes at higher wall superheat in the case of high nanoparticle concentration (see Figs. 5 and 6).

Film boiling was consistently observed in the quenching tests with the clean surface of the heated sphere. On the other hand, tests with an unwashed sphere (sphere used in the tests with the TiO_2–water nanofluids) repeatedly showed no film boiling with the same experimental conditions during the quenching process. The unwashed sphere quenched more rapidly through the nucleate boiling, bypassing the film boiling mode. In these experiments the unwashed sphere surface was covered by a thin layer of TiO_2 nanoparticles. Fig. 8 shows the temperature at the center of the unwashed heated sphere in pure water and the TiO_2–water nanofluids during the transient cool down process.

In this Fig. 1 the test curve refers to the quenching experiment with a clean heated sphere in the TiO_2–water nanofluid. It is clear that as the number of experiments increases (the repetition of the same experiment), the cooling curve shifts to the left and the film boiling mode vanishes more rapidly (see test2 and test3 curves).

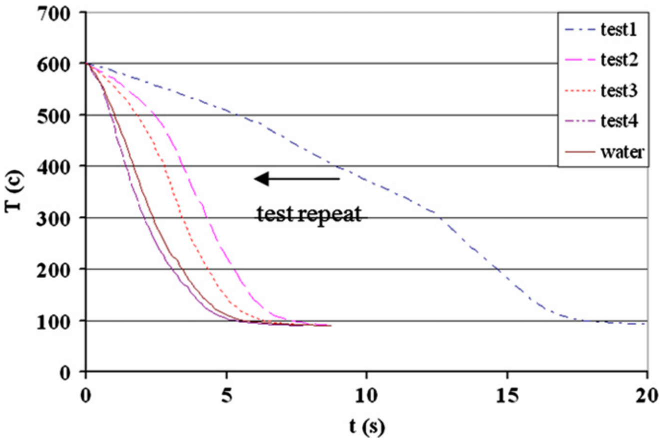

Fig. 8. Temperature at the center of the unwashed sphere in pure water and TiO_2–water nanofluids.

This is caused by increased deposition of TiO_2 nanoparticles on the sphere surface during each experiment. When the sphere surface is fully covered by a thin layer of TiO_2 nanoparticles, the film boiling mode does not occur and nucleate boiling starts immediately after the heated sphere is immersed into the liquid (see test4 curve). By quenching the unwashed heated sphere in pure water, the film boiling mode still does not occur and rapid quenching of the sphere is observed (water curve).

Fig. 9 shows the temperature at the center of the heated sphere whose surface is fully covered by a thin layer of TiO_2 nanoparticles, in pure water and TiO_2–water nanofluids during the transient cool down process. It is clear that the film boiling mode does not occur and cooling curves are approximately the same for pure water and TiO_2–water with different concentrations.

It is interesting to note that in the case of the Ag–water nanofluid, deposition of nanoparticles on the sphere surface did not occur and cooling curves were the same for consecutive experiments and film boiling mode occurred in each experiment. Thus the effect of nanoparticle deposition on the sphere surface was only investigated for the TiO_2–water nanofluid.

It is speculated that since the thermal conductivity of TiO_2 nanoparticles is less than that of silver, the deposition of TiO_2 nanoparticles on the sphere surface acts as a thermal insulator for the sphere and reduces the temperature of the sphere outer surface, thus depending on the thickness of the TiO_2 layer, the temperature difference between the sphere surface and the surrounding fluid may fall into the nucleate boiling region. In this case, the resistance to conduction within the solid might be more than the resistance to convection across the fluid around the sphere ($Bi > 0.1$). Hence the assumption of a uniform temperature distribution is no longer valid and the center temperature does not represent the temperature of the outer surface of the sphere. In addition to the mentioned fact, the silver sphere ($\epsilon = 0.025$) also undergoes emissivity changes during the tests due to the deposition of TiO_2 nanoparticles on its surface ($\epsilon = 0.9$). The increase in radiation emitted from the increase in emissivity results in higher heat transfer enhancement and faster cooling of the sphere. Therefore, the temperature of the sphere outer surface is lower and changes more rapidly when TiO_2 nanoparticles are attached to it. As a result the vapor film collapses more rapidly. This shows that film boiling is not always the heat transfer mechanism when the temperature difference between the center of the sphere and surrounding liquid is high. Nucleate boiling can be the heat transfer mechanism at high temperature difference between the sphere center and surrounding liquid when the quenching experiment is carried out with an unwashed heated sphere depending upon the deposition layer. Deposition of TiO_2 nanoparticles on the sphere surface makes it suitable for nucleate boiling to occur.

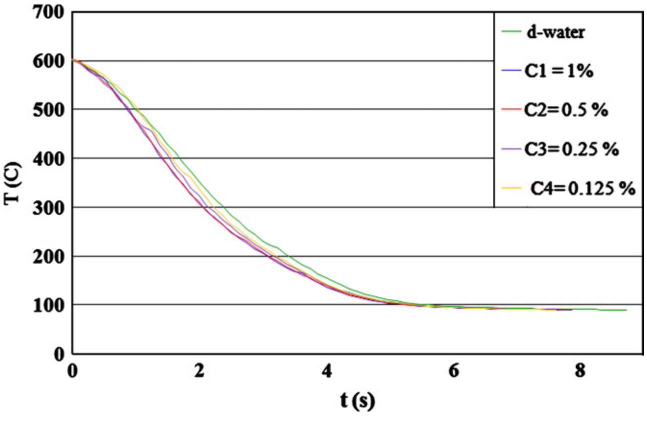

Fig. 9. Temperature at the center of the unwashed sphere in pure water and TiO_2–water nanofluids.

4. Conclusion

A set of quenching experiments of a hot silver sphere in subcooled Ag–water and TiO_2–water nanofluids was conducted. The following results were obtained:

- Quenching process of the clean heated sphere in nanofluids was similar in manner to that in pure water. Vapor film formed around the sphere immediately after the sphere was immersed into liquid. The vapor film became unstable as the sphere temperature decreased. However, the quenching process was more rapid in pure water than in nanofluids and the cooling time was inversely proportional to the nanoparticle concentration.
- Film boiling heat flux in nanofluids was lower than that observed in pure water. It was speculated that the main reason for this reduction was the accumulation of nanoparticles at the liquid–vapor interface during the film boiling process. The presence of nanoparticles at the liquid–vapor interface reduced the vapor removal rate from the film, so that the vapor film was thicker in nanofluids than in pure water and collapsed at lower wall superheat depending on the nanoparticle concentration. The minimum film boiling heat flux in the nanofluids was less than that in pure water.
- Rapid quenching of the sphere without film boiling in the TiO_2–water nanofluid was repeatedly observed when an unwashed sphere with nanoparticles deposited on its surface was used in the experiments. It was speculated that, due to the higher thermal resistance of the TiO_2 layer, nanoparticle deposition on the sphere surface acted as a thermal insulator for the sphere and reduced the temperature of the sphere outer surface. Furthermore, higher emissivity of the TiO_2 layer resulted in higher heat transfer enhancement and faster cooling of the sphere outer surface. These prevented a stable vapor film from forming around the sphere, which consequently promoted the rapid quenching of the hot sphere through the nucleate boiling mode, bypassing the film boiling mode.

Acknowledgments

This work was supported by the Iranian Nano Technology Initiative and Iranian National Science Foundation (INSF) Grant (85126/68).

References

[1] S.U.-S. Choi, Enhancing thermal conductivity of fluids with nanoparticles, developments and applications of non-Newtonian ows, ASME FED 231/MD 66 (1995) 99–103.
[2] H. Masuda, A. Ebata, K. Teramae, N. Hishinuma, Alteration of thermal conductivity and viscosity of liquid by dispersing ultra-fine particles (dispersion of c-Al_2O_3 SiO_2 and TiO_2 ultra-fine particles), Netsu Bussei (Japan) 4 (1993) 227–233.
[3] S. Lee, S.U.-S. Choi, Application of metallic nanoparticle suspensions in advanced cooling systems, in: , Recent Advances in Solids/Structures and Application of Metallic Materials, PVP 342/MD 72, ASME, 1996, pp. 227–234.
[4] Kiyuel Kwak, Chongyoup Kim, Viscosity and Thermal Conductivity of Copper Oxide Nanofluid Dispersed in Ethylene Glycol Dept. of Chemical and Biological Engineering, Korea University, Anam-dong, Sungbuk-gu, Seoul (2005), 136-713, Korea.
[5] S. Lee, U.S. Choi, S. Li, J.A. Eastman, Measuring thermal conductivity of fluids containing oxide nanoparticles, ASME J. Heat Transf. 121 (1999) 280–289.
[6] S.K. Das, N. Putra, P. Theisen, W. Roetzel, Temperature dependence of thermal conductivity enhancement for nanofluid, J. Heat Transf. 125 (2003) 567–574.
[7] H. Xie, J. Wang, T. Xi, Y. Liu, F. Ai, Q. Wu, Thermal conductivity enhancement of suspensions containing nanosized alumina particles, J. Appl. Phys. 91 (2002) 4568–4572.

[8] X. Wang, X. Xu, S.U.S. Choi, Thermal conductivity of nanoparticle–fluid mixture, J. Therm. Phys. Heat Transf. 13 (1999) 474–480.
[9] J.A. Eastman, U.S. Choi, S. Li, W. Yu, L.J. Thompson, Anomalously increased effective thermal conductivities of ethylene glycol-based nanofluids containing copper nanoparticles, Appl. Phys. Lett. 78 (6) (2001) 718–720.
[10] Y. Xuan, Q. Li, Heat transfer enhancement of nanofluids, Int. J. Heat Fluid Flow 21 (2000) 58–64.
[11] S. Zeinali Heris, M. Nasr Esfahany, S.Gh. Etemad, Experimental Investigation of Convective Heat Transfer of Al_2O_3/Water Nanofluid in Circular Tube, Department of Chemical Engineering, Isfahan University of Technology, Isfahan 84154, (2006) Iran.
[12] Dongsheng Wen, Yulong Ding, Experimental Investigation into Convective Heat Transfer of Nanofluids at the Entrance Region Under Laminar Flow Conditions, Institute of Particle Science and Engineering, University of Leeds, Leeds LS2 9JT, (2004) UK.
[13] N. Putra, W. Roetzel, S.K. Das, Natural convection of nano-fluids, Heat Mass Transf. 39 (2003) 775–784.
[14] Y.M. Xuan, Q. Li, Investigation on convective heat transfer and flow features of nanofluids, ASME J. Heat Transf. 125 (2003) 151–155.
[15] S.K. Das, N. Purta, W. Roetzel, Pool boiling characteristics of nano-fluids, Int. J. Heat Mass Transf. 46 (2003) 851–862.
[16] P. Vassallo, P. Kumar, S. Amico, Pool boiling heat transfer experiments in silica-water nanofluids, Int. J. Heat Mass Transf. 47 (2004) 407–411.
[17] H.S. Park, D. Shiferaw, B.R. Sehgal, Film boiling heat transfer on a high temperature sphere in nanofluid, in: 2004 ASME Heat Transfer/Fluid Engineering Summer Conference July 11–15, Charlote, North California USA, 2004.
[18] V.K. Dhir, G.P. Purohit, Subcooled Film Boiling Heat Transfer from Spheres, Chemical, Nuclear, and Thermal Engineering Department, School of Engineering and Applied Science University of California, Los Angeles, Los Angeles, California 90024, (1977) USA.
[19] J.W. Steven, L.C. Witte, Destabilization of Vapor Film Boiling Around the Sphere, Department of Mechanical Engineering, University of Houston, Houston, Texas 72004, (1972) USA.