International Journal of Heat and Fluid Flow 30 (2009) 700–705

Contents lists available at ScienceDirect

International Journal of Heat and Fluid Flow

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

Heat transfer enhancement using Al_2O_3/water nanofluid in a two-phase closed thermosyphon

S.H. Noie, S. Zeinali Heris *, M. Kahani, S.M. Nowee

Chemical Engineering Department, Engineering Faculty, Ferdowsi University of Mashhad, Mashhad, Iran

ARTICLE INFO

Article history:
Received 3 January 2009
Received in revised form 4 March 2009
Accepted 5 March 2009
Available online 8 April 2009

Keywords:
Al_2O_3 nanoparticle
Nanofluid
Two-phase closed thermosyphon
Heat transfer enhancement

ABSTRACT

A two-phase closed thermosyphon (TPCT) is a device for heat transmission. It consists of an evacuated-close tube filled with a certain amount of working fluid. Fluids with nanoparticles (particles smaller than 100 nm) suspended in them are called nanofluids that they have a great potential in heat transfer enhancement. In the present study, we combined two mentioned techniques for heat transfer enhancement. Nanofluids of aqueous Al_2O_3 nanoparticles suspensions were prepared in various volume concentration of 1–3% and used in a TPCT as working media. Experimental results showed that for different input powers, the efficiency of the TPCT increases up to 14.7% when Al_2O_3/water nanofluid was used instead of pure water. Temperature distributions on TPCT confirm these results too.

1. Introduction

Effective thermal management has become one of the most vital challenges in many technologies because of constant demands for faster speeds and continuous reduction of device dimensions. Recent technological advances in manufacturing have led to the miniaturization of many devices with various applications.

Thermal performance of equipments can be improved in many ways such as using two-phase close thermosyphons (TPCT) which are high efficient heat conductors and can be used to enhance heat transfer because of phase changes of working fluid inside them. TPCTs have simple structure, small thermal resistance, high efficiency and low fabrication cost making them one of the most widely used devices in many fields, such as heat recovery, electronics and solar heating systems (Noie et al., 1999; Akbarzadeh et al., 1997; Xiau et al., 1996; Liu et al., 1992; Vasiliev et al., 2008).

A typical TPCT consist an evacuated-close tube filled with a certain amount of working fluid, and hermetically sealed. When the TPCT is heated at one end, the working fluid evaporates (phase change) and rise through the hollow core to the other end of the TPCT at near sonic speed, where its thermal energy is being removed by a heat sink or other means. Then the vapor condenses and falls back to its origin. In contrast to the conventional heat pipes which capillary force returns the liquid to evaporator section, a TPCT uses gravitation to return the condensate. Since, the latent heat of evaporation is much larger than sensible heat, therefore in TPCTs working fluid transport very large amount of heat and make TPCTs 100s to 1000s times better than a solid copper rod. Key factors affecting on thermal performance of a TPCT are: filling ratio (FR), aspect ratio (AR), inclination angle, operational temperature and pressure and working fluid. Many researchers have studied these factors (Harada et al., 1980; Noie et al., 2005; Streltsov et al., 1975; Kaminaga et al., 1997; Vafai et al., 1992; Shalaby et al., 2000). Most commonly used working fluids in TPCTs are water; methanol; ethylene glycol (EG) and their mixtures which are originally poor heat transferring fluids.

Since thermal conductivity of these fluids plays an important role in these energy efficient heat transfer equipments, numerous techniques have been introduced to improve it. Because of higher thermal conductivity of solids compared to those of liquids, an innovative way of improving the thermal conductivity of a fluid is to suspend ultrafine metallic or nonmetallic solid particles. Numerous theoretical and experimental studies of suspensions containing solid particles have been conducted initiating Maxwell's theoretical work (1881) published more than a century ago. However, due to high density and large sized particles used, it was a challenge to prevent particles from settling in the suspension. The lack of stability of such suspensions induced additional flow resistance and possible erosion. Consequently fluids with nanosized particles suspended in them which later called nanofluids has been proposed by Choi (1995) from the Argonne National laboratory, USA. By suspending nanosized particles in a fluid, its heat transfer performance can be significantly improved with incurring either little or no penalty in pressure drop.

Abbreviations: CHF, critical heat flux (W); TPCT, two-phase closed thermosyphon; AR, aspect ratio (L_e/D_i); FR, filling ratio of the working fluid.

* Corresponding author. Tel./fax: +98 511 8816840.
E-mail address: zeinali@ferdowsi.um.ac.ir (S.Z. Heris).

0142-727X/$ - see front matter © 2009 Elsevier Inc. All rights reserved.
doi:10.1016/j.ijheatfluidflow.2009.03.001

Nomenclature

A	external surface of insulate tube (m^2)
C_p	specific heat of water ($J\ kg^{-1}\ K^{-1}$)
D_i	internal diameter of main tube (m)
h_{conv}	convective heat transfer coefficient ($Wm^{-2}\ C^{-1}$)
I	current (A)
k_l	liquid thermal conductivity ($Wm^{-1}\ C^{-1}$)
$k_{surr.}$	thermal conductivity of surrounding air ($Wm^{-1}\ C^{-1}$)
L_e	length of evaporator section (m)
L_t	total length of tube (m)
M	Merit number ($=[h_{fg}k_l^3\sigma_l\mu_l^{-1}]^{\frac{1}{4}}$)
m	coolant water mass rate (kg/s)
m_s	nanoparticles mass in suspension (kg)
Nu	Nusselt number ($=h_{conv.}L_t/k_{surr.}$)
Pr	Prandtl number ($=\vartheta/\alpha$)
$Q_{conv.}$	convection heat transfer rate (W)
Q_{in}	inlet heat by evaporation (W)
Q_{out}	outlet heat by condensation (W)
Q_{rad}	radiation heat transfer rate (W)
Ra	Rayleigh number ($=g\beta(T_{ins.}-T_{surr})L_t^3/\alpha\vartheta$)
T_a	adiabatic temperature (°C)
T_c	condenser temperature (°C)
T_e	evaporator temperature (°C)
T_{in}	inlet temperature of cooling water (K)
$T_{ins.}$	temperature on external surface of insulation (K)
T_{out}	outlet temperature of cooling water (K)
$T_{surr.}$	surrounding temperature (K)
V	Voltage (V)
V_t	total volume of suspension (m^3)

Greek letters

α	thermal diffusivity ($m^2\ s^{-1}$)
ε	emissivity factor of insulator
δ	Boltzmann constant in Eq. (6) ($Wm^{-2}\ K^{-4}$)
σ_l	surface tension of liquid (Nm^{-1})
η	efficiency of TPCT
ϑ	momentum diffusivity ($m^2\ s^{-1}$)
v	Nanoparticles volume fraction
ρ_s	Nanoparticles density ($kg\ m^{-3}$)

Nanofluids are also well known in production of nanostructured materials (Tseng, 2002), engineering of complex fluids (Tohver et al., 2001), as well as enhancement of wetting and spreading behavior (Wasan et al., 2003).

Alumina (Al_2O_3) and copper oxide (CuO) are the most common and inexpensive nanoparticles used in experimental investigations by many researchers. Lee et al. (1999) pioneers measuring thermal conductivity of nanofluids of various types and materials. Eastman et al. (1999) and Keblinski et al. (2002) have concluded that the effective thermal conductivity of nanofluids increases with volume fraction of nanoparticles. The dependency of thermal conductivity enhancement of nanofluids on particle shape has been emphasized by Hamilton et al. (1962) and Wang et al. (1999) and Eastman et al. (2001) have investigated the effect of particle size. In another work Das et al. (2003) have studied the temperature dependence of thermal conductivity enhancement in nanofluids experimentally.

Zienali et al. (2006, 2007) have investigated the convective heat transfer of Al_2O_3/water and CuO/water nanofluids in circular tubes and observed that heat transfer coefficient enhances by increasing the concentration of nanoparticles in the nanofluids. For Al_2O_3/water nanofluid with volume fraction of 7.5% of nanoparticles, 45% increment in the average wall heat transfer coefficient has been achieved by Palm et al. (2004) for the same Reynolds numbers. In the case of ethyl eneglycol/Al_2O_3 nanofluid, the average wall heat transfer coefficient has increased 70% for volume fraction of 7.5%. Bang et al. (2005) have considered the boiling heat transfer using Al_2O_3/water nanofluid on a horizontal smooth surface. They have showed that nanofluids have poor heat transfer coefficients compared with pure water in natural convection as well as in nucleate boiling. However, on the contrary, Tu et al. (2004) have found significant enhancement in pool boiling heat transfer coefficient of Al_2O_3 nanofluid.

Although extensive research on the TPCT and nanofluids has been conducted in literature, investigation on cases combining both the TPCT and the high thermal performance of nanofluids techniques has not been done thoroughly. Some of the studies presented in literature regarding heat pipes with nanofluids as working fluid are as follow.

Shung et al. (2005) have showed that the thermal performance of silver nanofluid heat pipe is higher than conventional ones filled with pure fluid. Tsai et al. (2004) have examined the effect of structural characteristics of nanoparticles on heat pipe thermal performance and concluded the thermal resistance of heat pipes with nanofluids was lower than that of distilled water. Naphon et al. (2008) also have used nanofluid as working fluid in a heat pipe and stated that at optimum condition for pure refrigerant, the heat pipe with 0.1% concentration of nanoparticles operates with efficiency 1.40 times higher than that with pure refrigerant. Khandekar et al. (2007) have studied thermal performance of a close two-phase thermosyphon charged with nanofluids and observed that nanofluids show inferior thermal performance than pure water. And at last but not the least, Kang et al. (2008) employed aqueous solutions of 10 and 35 nm sized silver nanoparticles in a sintered circular heat pipe. With the same loading volume, they showed that the temperature difference between two ends of heat pipe with nanofluid decreased 0.56–0.65 °C compared to DI-water.

In the present study, Nanofluid is employed as working medium for conventional TPCT to investigate the efficiency improvement of TPCT.

2. Experimental set-up

Aluminum oxide (Al_2O_3) nanoparticles with physical characteristic presented in Table 1 were used in this study.

Preparation of nanoparticle suspensions is the first step of applying nanofluids in heat transfer enhancement. In the present study, Al_2O_3 nanoparticles were dispersed in distillate water by ultrasonication without using any dispersant or stabilizer to prevent any possible changes of chemical properties of the nanofluid due to presence of additions. Nanofluids of 1%, 1.5%, 2%, 2.5% and 3% volume fraction of particles were prepared. The volume fraction and density of nanoparticles in suspension are defined as follow:

$$v = \frac{V_s}{V_t} \tag{1}$$

$$\rho_s = \frac{m_s}{V_s} \tag{2}$$

So the mass of nanoparticles required for preparation of 1 l nanofluid is determined as:

$$m_s = 1 \times 10^{-3} v \cdot \rho_s \tag{3}$$

Table 1
Physical characteristic of Al_2O_3 nanoparticle was used in this study.

Particle	Average Diameter (nm)	Superficial Density (Kg/m^3)	Actual Density (Kg/m^3)	C_P (J/kg K)	K (W/m K)
Al_2O_3	20	160–400	3700	880	46

After measuring the equivalent volume to the required mass of nanoparticle powder, they were mixed with distilled water in a flask subject to ultrasonication for about 4 h. No precipitation/settlement of nanoparticles was observed after 24 h of settling the suspension.

The system used for thermal performance measurement of TPCT is shown in Fig. 1. The heart of this system is a TPCT made of copper tube with internal diameter of 20 mm, 1 mm thickness and 1000 mm in length. The evaporator and condenser sections had 350 and 400 mm length, respectively. The electric heaters used around the evaporator section were made of a Nickel–Chrome wire having nominal power of 1000 W. An ammeter and a voltmeter were assembled in the circuit to measure the input power

$$Q_{in} = VI - Q_{loss} \tag{4}$$

where Q_{loss} is the total heat loss from the evaporator section by radiation and free convection as follow:

$$Q_{loss} = Q_{rad} + Q_{conv.} \tag{5}$$

The radiation and free convection heat transfer rates can be calculated from Eqs. (6) and (7), respectively

$$Q_{rad} = \varepsilon\delta A(T_{ins.} - T_{surr.}) \tag{6}$$

$$Q_{conv.} = h_{conv.}A(T_{ins.} - T_{surr.}) \tag{7}$$

where free convection heat transfer coefficient was determined using the following equation (Churchill et al., 1975):

$$Nu = \frac{h_{conv.}L_t}{k_{surr.}} = \left\{0.825 + \frac{0.387Ra^{1/6}}{\left[1 + \left(\frac{0.492}{\mathrm{Pr}}\right)^{9/16}\right]^{8/27}}\right\}^2 \tag{8}$$

Following the preceding calculations it was denoted that the total heat loss was about 2.49% of the input power to the evaporator section.

Local temperatures on the TPCT were measured by seven thermocouples (type-LM35). Four thermocouples were mounted on the evaporator section, one on the adiabatic section and two on the condenser section. Also two precise thermometers were used in the condenser section to read the input and output temperature of coolant water. The configuration and locations of the thermocouples on the TPCT are shown in Fig. 2. All the electrical (such as thermocouples, thermometers, ammeter and voltmeter) and mechanical equipments (such as rotameter) were calibrated initially. In addition, a data logger which converted DC current from thermocouples to digital signals made it possible to monitor all the measured data.

To be ensured there were no remaining remnants, prior to all experiments it was necessary to clean the inside of the main tube,

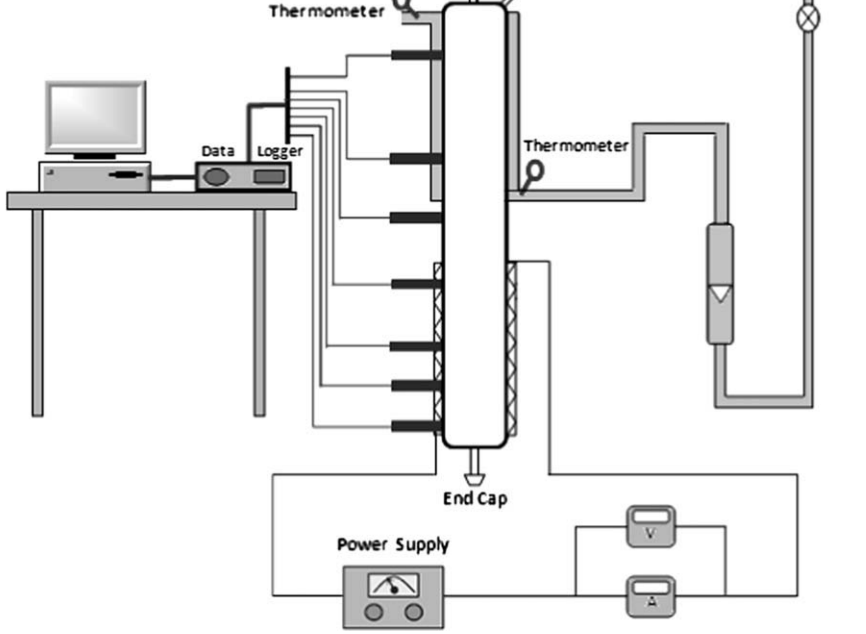

Fig. 1. Schematic of experimental set-up.

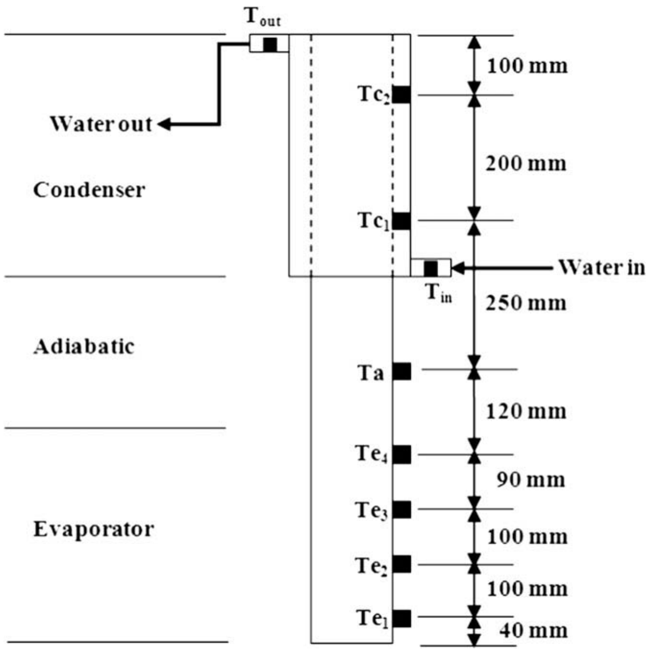

Fig. 2. Location of thermocouples on TPCT.

especially whenever there was a changeover from one nanofluid to another. This was done in three steps, cleaning with trichloroethane and methanol followed by vacuum drying. Before proceeding to test the nanofluid system, baseline experiments were conducted with pure water. Once the quality and repeatability of the baseline data was established, five water based nanofluids were used as working fluid. Park et al. (2002) expressed that when a TPCT reaches maximum heat transfer, evaporator temperature increases continually. The experiments showed that 45 min was needed for the system to reach steady state condition.

3. Experimental results

The quantity of heat transferred to the coolant water can be calculated from inlet and outlet water temperature difference, taking into account the water mass flow rate and specific heat as,

$$Q_{out} = mc_p(T_{out} - T_{in}) \tag{9}$$

The efficiency of TPCT can be expressed as a ratio of the output heat by condensation to the inlet heat by evaporation, i.e.

$$\eta = \frac{Q_{out}}{Q_{in}} \tag{10}$$

Uncertainty of the experimental data may have resulted from measuring errors of parameters such as current, voltage, inlet and outlet temperature of cooling water, mass flow rate, and can be calculated using the following relations for efficiency (Holman, 1989):

$$\max E_{\eta} = \pm[(E_{Q_{out}})^2 + (-E_{Q_{in}})^2]^{1/2} \tag{11}$$

$$\max E_{Q_{out}} = \pm[(E_m)^2 + (E_{cp})^2 + (E_{(T_{out}-T_{in})})^2]^{1/2} \tag{12}$$

$$\max E_{Q_{in}} = \pm[(E_V)^2 + (E_I)^2]^{1/2} \tag{13}$$

Because of small order of magnitude, the effect of Q_{loss} on uncertainty can be neglected .The thermocouples used have maximum precision of 0.1 °C. Flow rates were measured directly from the taken time to fill a glass vessel of known volume with 5.0% uncertainty in measurement. The maximum precision of ammeter and voltmeter was 0.1 V and 1 A, respectively. The maximum uncertainty of efficiency calculated taking into account the above considerations is 5.41%.

To compare the efficiency improvement of the TPCT filled with nanofluids and pure water, the TPCT charged with pure water was examined too. For different input powers (48.4–195.2 W), the efficiency was calculated and is presented in Fig. 3.

When the TPCT is charged with nanofluids, the efficiency is significantly enhanced, i.e. the heat transfer capability improves. For example, at the input power of 97.1 W, 1% nanofluid can improve the efficiency of the TPCT from 75.1% to 81.56%. This improvement increases with the volume concentration of nanoparticles. Also, the TPCT efficiency continues to increase as the input power increases, however it is not the same. For all working fluids, the gradient of efficiency at lower input powers is larger than the higher ones. For example when the input power increases from 48.4 to 97.1 W, the efficiency of TPCT loaded with a nanofluid of 2% concentration increase 14.7%, while for an increment of the input power from 146.3 to 195.2 W this improvement is only 2.7%.

Fig. 4a–d presents the steady state distribution of wall temperature of the TPCT. For higher input powers, the average temperatures within sections of TPCT increase.

When TPCT charged with nanofluid, temperature differences between evaporator and condenser section are less than pure water. It confirms that thermal performance of TPCT is better when nanofluid is used instead of pure water. By dispersing more Al_2O_3 nanoparticles in working fluid, the smaller rise in wall temperature of TPCT observed than pure water under various heats loading.

As Fig. 4a shown by findings, the distribution of wall temperature of TPCT containing pure water were 58, 56, 54, 55, 47, 28, 28 °C, respectively. When the TPCT is filled with nanofluids, illustrate the lower wall temperature of TPCT than that of pure water, from 52 °C to 26 °C for 1% nanofluid.

Fig. 5 represents Efficiency of TPCT versus average temperature of evaporator for different input powers. Considering the figure, efficiency of TPCT enhances with input power increasing and evaporator average temperature decreasing. The results of Figs. 4(a–d) and 5 clearly present that the addition of nanoparticles to pure water lead to evaporator average temperature decreasing noticeably and also improve the efficiency of TPCT.

The heat transfer enhancement in TPCT by nanofluid greatly depends on particle type, particle size, base fluid, and bubble nucleation size. It is helpful to review some earlier studies on nanofluids heat transfer, which most of them have shown that

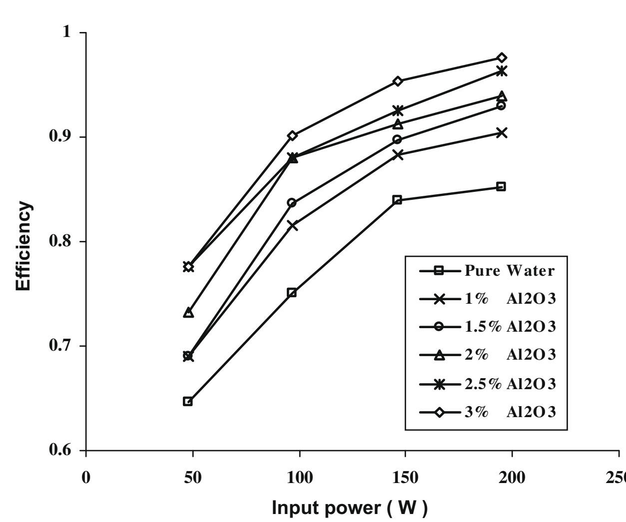

Fig. 3. Efficiency of TPCT versus input power and concentration of nanofluid.

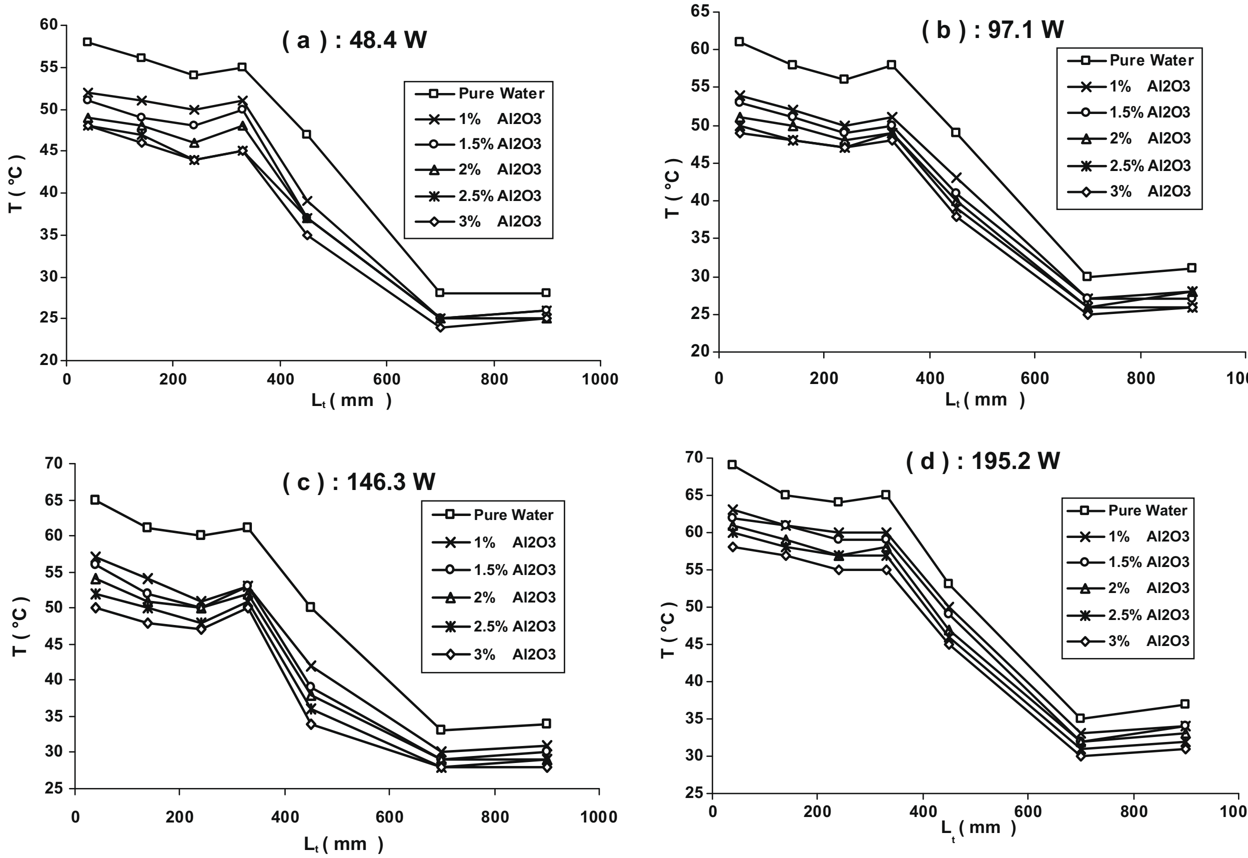

Fig. 4. (a–d) Average temperature of TPCT distribution versus input power and concentration of nanofluid.

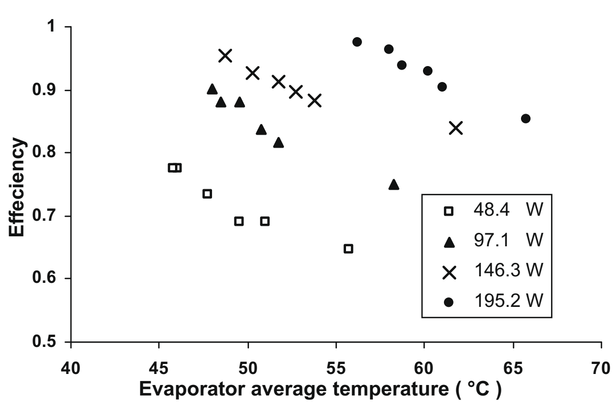

Fig. 5. Efficiency of TPCT versus average temperature of evaporator for different input powers.

the addition of nanoparticles amplify critical heat flux (You et al., 2003; Milanova et al., 2006; Kim et al., 2007). For example Kim et al. (2007) have illustrated that during nucleate boiling some nanoparticles deposit on the heater surface to form a porous layer. This layer improves the wettability of the surface considerably. You et al. (2003) have showed that the enhancement of CHF was drastic when nanofluid is used as a cooling liquid instead of pure water. They observed an approximately 200% increase in CHF for nanofluids containing 0.005 g/l of alumina nanoparticles.

The thermal conductivity of the working fluid should also preferably be high in order to minimize the radial temperature gradient. The resistance to fluid flow will be minimized by choosing fluids with high liquid density and low values of liquid viscosity (Realy et al., 2006). Using of nanoparticles in pure fluid lead to improve thermal conductivity, liquid density and viscosity (Williams et al., 2008). Considering the merit number in TPCT, the effect of nanofluid thermal conductivity enhancement is higher than viscosity increasing as follow:

$$M = \left(\frac{h_{fg} k_l^3 \sigma_l}{\mu_l} \right)^{\frac{1}{4}} \tag{14}$$

The larger the value of merit number, the more suitable is the fluid for TPCT (Realy et al., 2006). Addition of nanoparticles to fluid changes the heat transfer mechanism so that besides of thermal conductivity increase, Brownian motion, dispersion, and fluctuation of nanoparticles especially near wall it leads to increase in the energy exchange rates and augments heat transfer rate between the fluid and the evaporator section wall (Zeinali et al., 2006b). An increase in the nanoparticles volume fraction intensifies the interaction and collision of nanoparticles. Also diffusion and relative movement of these particles near the tube wall leads to rapid heat transfer from the TPCT wall to nanofluid. In other words, increasing the concentration of nanoparticles intensifies the mechanisms responsible for enhanced heat transfer. A major thermal resistance of TPCT is caused by the formation of vapor bubbles at the liquid–solid interface. A larger bubble nucleation size creates a higher thermal resistance that prevents the transfer of heat from the solid surface to the liquid (Collier et al., 1996). The suspended nanoparticles tend to bombard the vapor bubbles during the bubble formation. Therefore, it is expected that the nucleation size of vapor bubble is much smaller for fluid with suspended nanoparticles than that without them. Also during nucleate boiling some nanoparticle precipitate on surface and form a layer whose morphology depends on the nanoparticle materials. It is well known that a thin liquid microlayer developed underneath a vapor bubbled growing at a solid surface (Collier et al., 1996). Therefore, it is postulated that microlayer evaporation of the nanoparticle initially contained in it could be reason for the formation of porous layer.

4. Conclusion

This paper aims efficiency improvement of a two-phase closed thermosyphon, using Al_2O_3/water nanofluid as the working fluid. Different volume concentrations of nanoparticles (1–3%) in suspension within the TPCT were experimentally examined and results were compared with pure water, and the following remarks are concluded from the results of TPCT performance study:

(1) Nanofluids in all concentration studied showed better thermal performance than pure water. They improved efficiency of the TPCT up to 14.7%.
(2) Temperature distributions on the TPCT were lower level using nanofluid compared to pure water. Temperature differences between the evaporator and condenser sections with nanofluids were less that pure water, i.e. thermal resistance of the TPCT when charged with nanofluids was less.

The higher thermal performance TPCTs loaded with nanofluid proved its potential as substitute for conventional ones with pure water. This finding makes nanofluid attractive as working fluid in heat pipe and thermosyphon technology noting further investigation are needed.

Acknowledgments

The authors thank the Iranian Nano Technology Initiative and Iranian Fuel Conservation Company (IFCO) for financial supports.

References

Akbarzadeh, A., Wadowski, T., 1997. Heat pipe-based cooling systems for photovoltaic cells under concentrated solar radiation. Applied Thermal Engineering 16 (1), 81–87.
Bang, I.C., 2005. Boiling heat transfer performance and phenomenon of Al_2O_3–water nanofluids from a plain surface in a pool. International Journal of Heat and Mass Transfer 48, 2407–2419.
Choi, S.U.S., 1995. Enhancing thermal conductivity of fluid with nanoparticles, Developments and Applications of Non-Newtonian Flows, FED-V. 231/ MD-V, vol. 66, ASME, New York, pp. 99–105.
Churchill, S.W., Chu, H.H.S., 1975. Correlating equations for laminar and turbulent free convection from a vertical plate. International Journal of Heat and Mass Transfer 18, 1323–1325.
Collier, J.G., Thome, J.R., 1996. Convective Boiling and Condensation, third ed. Clarendon Press, Oxford, UK.
Das, S.K., Putra, N., Theisen, P., Roetzel, W., 2003. Temperature dependence of thermal conductivity enhancement for nanofluid. Journal of Heat Transfer 125, 567–574.
Eastman, J.A., Choi, S.U.S., Li, S., Soyez, G., Thompson, L.J., 1999. Novel thermal properties of nanostructures materials. Material Sciences, Forum 312–314, 629–634.
Eastman, J.A., Choi, S.U.S., Li, S., Yu, W., Thompson, L.J., 2001. Anomalously increased effective thermal conductivities of ethylene glycol-based nanofluids containing copper nanoparticles. Applied Physics Letters 78 (6), 718–720.
Hamilton, R.L., Crosser, O.K., 1962. Thermal conductivity of heterogeneous two component systems. Industrial & Engineering Chemistry Fundamentals.
Harada, K., Inoue, S., Fujita, J., et al., 1980. Heat transfer characteristics of large heat pipe. Hitachi Zosen Tech. Rev., 41.
Holman, J.D., 1989. Experimental Methods for Engineers, fifth ed. McGrow-Hill, New York.
Kaminaga, F., Hashimoto, H., Feroz, M.D., Goto, K., Matsumura, K., 1997. Heat transfer characteristics of evaporation and condensation in a two-phase closed thermosyphon. In: 10th International Heat Pipe Conference, Session H1-6, Stuttgart, Germany, pp. 1–6.
Kang, S.W., Wei, W.C., Tsai, S.H., Huang, C.C., 2008. Experimental investigation of nanofluids on sintered heat pipe thermal performance. Applied Thermal Engineering 29 (2009) 973–979.
Keblinski, P., Phillpot, S.R., Choi, S.U.S., Eastman, J.A., 2002. Mechanism of heat flow in suspension of nanosized particle (nanofluids). International Journal of Heat and Mass Transfer 45 (4), 855–863.
Khandekar, S., Joshi, Y., Mehta, B., 2007. Thermal performance of closed two-phase thermosyphon using nanofluids. International Journal of Thermal Science 47, 659–667.
Kim, S.J., Bang, I.C., Buongiorno, J., Hu, L.W., 2007. Surface wettability change during pool boiling of nanofluids and its effect on critical heat flux. International Journal of Heat and Mass Transfer 50 (19–20), 4105–4116.
Lee, S., Choi, S.U.S., Li, S., Eastman, J.A., 1999. Measuring thermal conductivity of fluids containing oxide nanoparticles. Journal of Heat Transfer 121, 280–289.
Liu, G., et al., 1992. The application of heat pipe heat exchanger in exhaust gas heat recovery system and its thermodynamic analysis. In: Proc. Eighth International Heat Pipe Conference, Beijing, China, pp. 582–585.
Maxwell, J.C., 1881. A Treatise on Electricity and Magnetism, second ed. Clarendon Press, Oxford, UK.
Milanova, D., Kumar, R., Kuchibhatla, S., Seal. S., 2006. Heat transfer behavior of oxide nanaparticles in pool boiling experiment. In: Proc. of Fourth International Conference on Nanochannels, Microchannels and Minichannels, Ireland.
Naphon, P., Thongkum, D., Assadamongkol, P., 2008. Heat pipe efficiency enhancement with refrigerant-nanoparticles mixtures. Journal of Energy Conversion and Management 50 (3), 772–776.
Noie, S.H., 2005. Heat transfer characteristics of a two-phase closed thermosyphon. Applied Thermal Engineering 25, 495–506.
Noie, S.H., Majideian, G.R., 1999. Waste heat recovery using heat pipe heat exchanger (HPHE) for surgery rooms in hospitals. Applied Thermal Engineering 20, 1271–1282.
Palm, S.J., Roy, G., Nguyen, C.T., 2004. Heat transfer enhancement in a radial flow cooling system using nanofluids. In: International Symposium on Advances in Computational Heat Transfer, Norway.
Park, Y.J., Kang, H.K., Kim, C.J., 2002. Heat transfer characteristics of a two-phase closed thermosyphon to fill charge ratio. International Journal of Heat and Mass transfer 45, 4655–4661.
Realy, D., Kew, P., 2006. Heat Pipes, fifth ed., Oxford, USA.
Shalaby, M.A., Ariad, F.F., Sultan, G.I., Awad, M.M.M., 2000. Heat transfer performance of a two-phase closed thermosyphons. In: Proc. Sixth International Heat Pipes symposium, Chaiang Mai, pp. 325–331.
Shung, W.K., Wei, W.C., 2005. Experimental investigation of silver nanofluid on heat pipe thermal performance. In: Proceedings of Tamkang University, International Nano and MEMS Workshop.
Streltsov, A.I., 1975. Theoretical and experimental investigation of optimum filling for heat pipe. Heat Transfer Soviet Research 7 (1), 23–27.
Tohver, V., Chan, A., Sakurada, O., Lewis, J.A., 2001. Nanoparticle engineering of complex fluid behaviour. Langmuir 17, 8414–8421.
Tsai, C.Y., Chien, H.T., Ding, P.P., Chan, B., Luh, T.Y., Chen, P.H., 2004. Effect of structural character of gold nanoparticles in nanofluid on heat pipe thermal performance. Materials Letters 58 (9), 1461–1465.
Tseng, W.J., Wu, C.H., 2002. Aggregation, rheology and electrophoretic packing structure of aqueous Al_2O_3 nanoparticle suspensions. Acta Materialia 50, 3757–3766.
Tu, J.P., Dinh, N., Theofanous,T., 2004. An experimental study of nanofluid boiling heat transfer. In: Proc. of Sixth International Symposium on Heat Transfer, Beijing, China.
Vafai, K., Wang, W., 1992. Analysis of flow and heat transfer characteristics of an asymmetrical flat plate heat pipe. International Journal of Heat and Mass Transfer 35, 2087–2099.
Vasiliev, L., Lossouarn, D., Romestant, C., Alexandre, A., Bertin, Y., Piatsiushyk, Y., Romanenkov, V., 2008. Loop heat pipe for cooling of high-power electronic components. International Journal of Heat and Mass Transfer 52 (1–2), 301–308.
Wang, X., Xu, X., Choi, U.S., 1999. Thermal conductivity of nanoparticle-fluid mixture. Journal of Thermophysics and Heat Transfer 13, 474–480.
Wasan, D.T., Nikolov, A.D., 2003. Spreading of nanofluids on solids. Nature 423, 156–159.
Williams, W., Buongiorno, J., Hu, L.W., 2008. Experimental investigation of turbulent convective heat transfer and pressure loss of alumina/water and zirconia/water nanoparticle colloids (nanofluids) in horizontal tubes. Journal of Heat Transfer 130, 132–234.
Wu, X.P., Johnson, P., Akbarzaseh, A., 1996. A study of heat pipe heat exchanger effectiveness in an air conditioning application. in: Proc. Fifth International Heat Pipe Symposium, Melbourne, Australia.
You, S.M., Kim, J., Kim, K.H., 2003. Effect of nanoparticles on critical heat flux of water in pool boiling heat transfer. Applied Physics Letters 83 (16), 3374–3376.
Zeinali Heris, S., Etemad, S.Gh., Nasr Esfahany, M., 2006. Experimental investigation of oxide nanofluids laminar flow convective heat transfer. International Communications in Heat and Mass Transfer 33, 529–533.
Zeinali Heris, S., Nasr Esfahany, M., Etemad, S.Gh., 2006. Investigation of CuO/water nanofluid Laminar convective heat transfer through a circular tube. Journal of Enhanced Heat Transfer 13 (4), 1–11.
Zeinali Heris, S., Nasr Esfahany, M., Etemad, S.Gh., 2007. Experimental investigation of convective heat transfer of Al_2O_3/water nanofluid in circular tube. International Journal of Heat and Fluid Flow 28, 203–210.