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Application of nanofluids in computer cooling systems (heat transfer performance of nanofluids)

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ABSTRACT

Nanofluids are stable suspensions of nano fibers and particles in fluids. Recent investigations show that thermal behavior of these fluids, such as improved thermal conductivity and convection coefficients are superior to those of pure fluid or fluid suspension containing larger size particles. The use of enhanced thermal properties of nanofluids for the cooling of computer microchips is the main aim of this research. Base fluid used, was various compositions of a mixture of deionized water and ethylene glycol. Three nanoparticles of silica, alumina and titania were used, each with three different volumetric concentrations in the base fluid. The effect of the flow rate of nanofluid in the cooling process has also been investigated. Results show enhanced heat transfer in the cooling of the microchip as indicated in the considerable reduction of the operating temperature of processor when using the nanofluid as compared to application of pure fluid. As expected it was observed that an increase in the flow rate of the nanofluid resulted in decrease in the processor temperature. The largest decrease observed was for alumina nanofluid, which decreased processor temperature from 49.4 to 43.9 °C for 1.0% of volumetric concentration and flow rate of 1.0 L per minute when compared with the pure base fluid with the same flow rate. Results suggest that there should be a balance between volumetric concentration of nanoparticles and the flow rate to satisfy the economy and power consumption of cooling the system.

1. Introduction

In electronic industry, improvement of the thermal performance of cooling systems together with the reduction of their required surface area has always been a great technical challenge. Research carried out on this subject can be classified into three general approaches; finding the best geometry for cooling devices, decreasing the characteristic length and recently increasing the thermal performance of the coolant. The latest approach is based on the discovery of nanofluids. Nanofluids are liquid–solid suspensions in which particles with the size of 1–100 nm are suspended in a heat transfer fluid. Nanofluids are expected to have a better thermal performance than conventional heat transfer fluids due to the high thermal conductivity of suspended nanoparticles. In recent years there have been several investigations showing enhancement of thermal conductivity of nanofluids. Eastman et al. [1] investigated the thermal conductivity of nanofluid of 0.3% volume fraction of copper nanoparticles in ethylene glycol. Using the hot-wire method; they observed over 40% enhancement of thermal conductivity in comparison with pure base fluid. They also found that decreasing the size of nanoparticles had an important role in the improvement of thermal conductivity. Steady-state parallel-plate method was used by Wang et al. [2] to measure the effective thermal conductivity of Al_2O_3 and CuO nanoparticles in water and ethylene glycol. The average size of particles was 28 and 23 nm, respectively. They also reported an increase in thermal conductivity of nanofluids compared to the pure base fluids. The reasons for these unusual growths in thermal conductivity of nanofluids have been investigated by Keblinski et al. [3] and Eastman et al. [4]. In their works, Brownian motion of nanoparticles, molecular-level layering of base fluid at the interface, the effect of heat transfer in nanoparticles and the influence of particle clustering were introduced as possible mechanisms for the increase of thermal conductivity. Investigating on stationary nanofluids, they realized that the effect of Brownian motion could be neglected compared to the greater effect of thermal diffusion. Wang et al. [2] suggested that thermal conductivity of nanofluids is a function of particle structure and microscopic motion in which microscopic motion consists of Brownian motion and inter-particle forces.

For heat transfer applications of flowing fluids, convective heat transfer coefficient is a better indicative parameter than the thermal conductivity. For force convective heat transfer, Lee and Choi [5]

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investigated the heat transfer in parallel channels using an unspecified nanofluid. They found that the thermal resistance decreased by approximately one half when changing some parameters such as fluid velocity and thickness of fluid layer. Empirical study of convective heat transfer for water based Cu nanofluid was performed by Xuan and Lee [6]. They used a straight tube with constant heat flux on the wall and observed an increase in the rate of heat transfer when compared to pure water at same flow conditions. They also claimed that the friction coefficient of low volume fractions nanofluids did not have significant difference with that of pure liquid and therefore does not have a sensible impact on the pumping power. Ma et al. [7] used a system consisting of nanofluid and oscillating heat pipe to improve heat transfer efficiency of coolant. Their experimental results showed that for input power of 80 W, diamond nanofluid can reduce the temperature raise between evaporator and condenser from 40.9 to 24.3 °C. In 2005, Chein and Huang [8] used Cu-water nanofluid as the coolant to analyze convective heat performance of a silicon microchannel heat sink. They found that the heat sink performance was greatly improved for two specific geometries of the heat sink with no extra pressure drop. Jang and Choi [9] numerically analyzed the cooling performance of a microchannel heat sink with diamond (2 nm) and copper (6 nm) water based nanofluids. The performance of a microchannel heat sink was seen to be improved by about 10% for diamond nanofluid (1 vol. %) in comparison with pure base fluid. In 2009, Kang et al. [10] employed the silver-water nanofluids as the coolant for a convectional sintered circular heat pipe of 1 mm wick-thickness. For 30–50 W input power, the temperature difference in the heat pipe decreased by 0.56–0.65 °C compared to pure base fluid. They also showed that the effect of nanoparticle size on the performance of heat pipe was negligible. Ho et al. [11] performed series of experimental investigations on forced convective cooling performance of a microchannel heat sink using alumina-water nanofluids. Their results showed that the nanofluid-cooled heat sink had higher heat transfer coefficient and therefore, lower thermal resistance when compared to water-cooled system. They also observed a marked increase in the dynamic viscosity of the nanofluid and a slight increase in friction factor of the flowing nanofluid as compared with the base fluid. Roberts and Walker [12] investigated the convective performance of water based 20–30 nm alumina nanofluids in an available computer liquid cooling kit. Their findings showed that addition of nanoparticles up to 1.5% by volume resulted in thermal performance enhancement of the cooling system.

The current work investigated the cooling performance of a water cooling kit with the addition of nanofluids. A real computer setup with a quad-core processor has been used to determine the effect of use of nanofluid on the cooling system in real practical condition.

2. Nanofluid preparation and characterization

Preparation of stable and suitable nanofluid with low or no agglomeration of nanoparticles is the first step in any nanofluid experiments. In this investigation, nanofluids have been prepared using the two-step method. First nanoparticles are prepared as dry powder and are then dispersed into the base fluid. In order to maintain the stability of the suspension and to minimize the agglomeration and settling of the nanoparticles, some techniques such as the use of ultrasonic mixer, addition of surfactants and pH level control of the fluid are usually used. In this investigation, an ultrasonic mixer (Bandelin SonoPlus HD 3200) is used to obtain stable and uniform distribution of nanoparticles in the suspension. This sonicator produces ultrasonic pulses with the maximum power of 150 W at 20 kHz frequency.

Three types of nanoparticles, alumina, silica and titania have been used in the research. The characteristic properties and volume fractions of nanoparticles are listed at Table 1. In preparation of the nanofluids, no additive or stabilizer was used. Each sample was stored for at least 24 h to ensure of the stability of the suspension. The results of samples in which any visible sign of settling of nanoparticles was observed in less than 24 h, were not considered in the analysis. Titania and silica nanofluids showed great stability even after one week. The base fluid was a mixture of deionized water (75% vol.) and ethylene glycol (25% vol.). Ethylene glycol used was from Merck Co. with 99.9% of purity.

It should be noted that as it was intended to carry out the nanofluid preparation without using any stabilizer and surfactant, the volumetric concentration for TiO_2 and Al_2O_3 were limited to 0.5% and 1%, respectively. For concentrations higher than these, fast sedimentation of particles was observed.

The optimum time of sonication was determined using particle size distribution of Scanning Electron Microscope (SEM) images. Images are retrieved from Hitachi S4160 equipment. Fig. 1 shows SEM image of Al_2O_3 nanofluid with 0.25% of volume loading. As it can be seen, from the comparison of indicated particle surrounded by borders in the pictures, which has a diameter of 42.97 nm, the particle sizes are around 20–40 nm which indicate slight breakage of particles.

3. Experimental setup

For the experimental setup, commercial liquid cooling kit of 3D Galaxy II from Gigabyte was used. The system consisted of a quad-core processor (Phenom II X4 965). The operating parameters of the processor such as voltage and frequency have been raised from nominal conditions to produce more heat under operation. The schematic of experimental setup is shown in Fig. 2.

For better contact between water block and processor's integrated heat spreader, a high conductive thermal paste was used. Covering of Integrated Heat Spreader (IHS) and water block contact interface with this thermal paste, ensures maximum possible heat transfer between coolant and the processor.

The cooling kit is customized in such a way to measure flow rate and fluid temperature before and after the block. In order to control the flow rate of the coolant, a valve was installed after the pump just before the flowmeter. The flow rate of the coolant was one of the parameters which has been investigated. Three values of 0.5, 0.75 and 1.0 L per minute were used for the flow rate of the coolant in the system. The cooling process is started by pumping the coolant into the system. The coolant enters the water block and absorbs the heat produced by the processor. Leaving the processor, it cools down by passing through the radiator and the process is repeated. The temperature of the coolant was measured at the inlet and outlet of the water block by two PT-100 thermocouples. These temperatures were used to calculate the convective heat transfer coefficient at the water block.

Table 1
Nanoparticles specification and properties.

Particle type	Density (kg/m^3)	Average particle size (nm)	Specific surface (m^2/g)	Manufacturer	Used volume concentrations (%)
SiO_2	2200	14	200	Wacker	0.5, 1.0, 1.5
TiO_2	4230	21	50 ± 10	PlasmaChem	0.1, 0.25, 0.5
Al_2O_3	3950	40	40	PlasmaChem	0.5, 0.75, 1.0

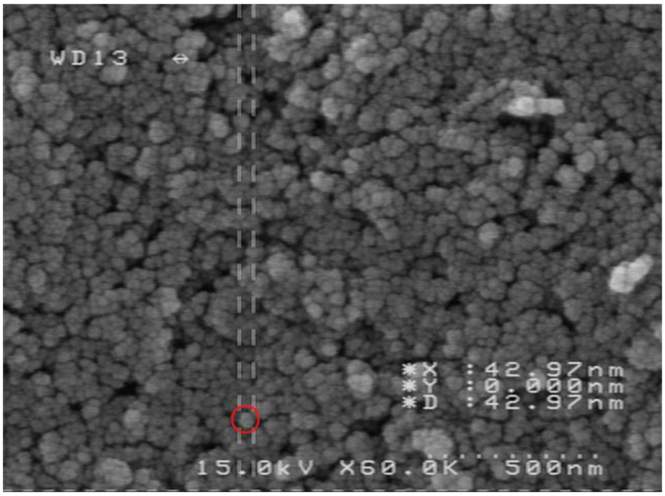

Fig. 1. SEM image of Al_2O_3 nanofluid with 0.25% of volume concentration.

The temperatures were measured with accuracy of ±0.1 °C, and the flow rates were determined using flowmeter with ±0.08 L/min accuracy on 1 L/min. Also, the accuracy of scale used to prepare nanofluids was ±0.001 gr.

The pump used on 3D Galaxy II cooling kit is able to provide flow rates up to 8 L/min with maximum power consumption of 6.5 W. The experiments carried out in this research were for maximum flow rate of 1 L/min resulting in very low pump power consumption, which is considerably lower than the nominal power consumption mentioned. Therefore, although using nanofluid in comparison to base fluid results in higher viscosity and density resulting in higher pressure drop, the increase does not affect the power consumption of the cooling kit. As a result, the effect of increased viscosity of nanofluid on pressure drop has not been considered in this work.

4. Results

The best criterion for evaluating the thermal performance of a flowing fluid is the convective heat transfer coefficient. In this experiment, heat transfer coefficient of the coolant to the water block has been calculated as the most indicative parameter. According to the Newton's cooling law, the rate of heat transfer between the wall of water block and the coolant is:

$$q = hA\Delta T_m \tag{1}$$

In which q is the rate of heat generation in the processor, h is convective heat transfer coefficient, A is heat transfer area, and ΔT_m is the Log mean temperature difference between the wall and the fluid in contact with the wall.

The temperature of wall and processor are assumed to be equal. Using thermal paste between wall and processor IHS and also design of IHS is rightly assumed to satisfy this assumption [13]. Therefore, we have: $T_w = T_{core}$.

Eq. (1) would be written as:

$$q = hA\frac{T_{out} - T_{in}}{ln\frac{T_{core} - T_1}{T_{core} - T_2}} \tag{2}$$

The temperature of the coolant rises when passing through the water block and therefore the heat absorbed by the coolant is:

$$q = \dot{m}c_{eff}(T_{out} - T_{in}) \tag{3}$$

$$q = \rho_{eff}Qc_{eff}(T_{out} - T_{in}) \tag{4}$$

Where Q is flow rate and ρ_{eff} and c_{eff} are the effective density and specific heat capacity of nanofluid respectively. The last two parameters are calculated according to rules governing the physical principle of the mixtures:

$$\begin{aligned}(\rho c)_{eff} &= \rho_{eff}\left(\frac{q}{m\Delta T}\right)_{eff} = \rho_{eff}\frac{q_f + q_p}{\left(m_f + m_p\right)\Delta T} \\ &= \rho_{eff}\frac{(mc)_f\Delta T + (mc)_p\Delta T}{\left(m_f + m_p\right)\Delta T} = \frac{(\rho c)_f V_f + (\rho c)_p V_p}{\rho_f V_f + \rho_p V_p} \\ &= (1 - \varnothing_p)(\rho c)_f + \varnothing_p(\rho c)_p \end{aligned} \tag{5}$$

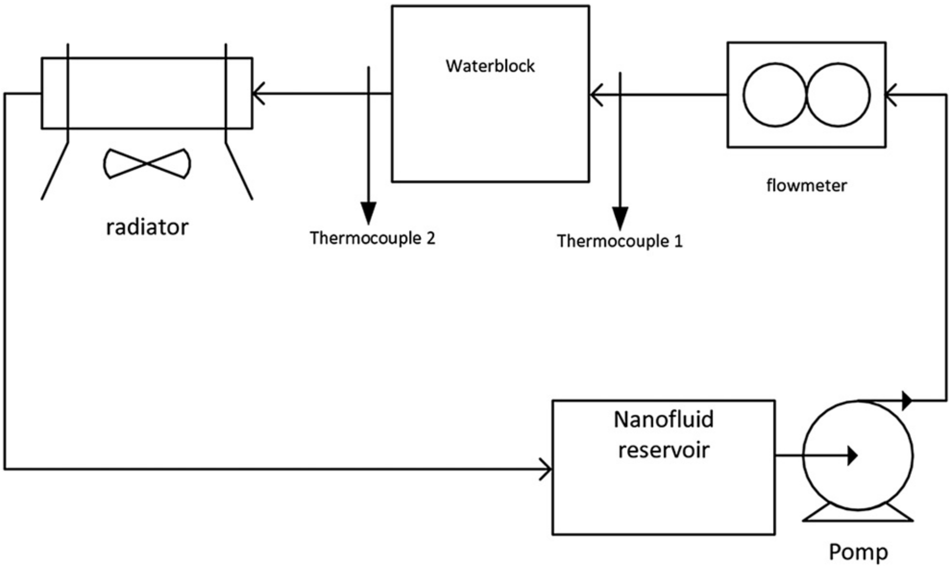

Fig. 2. Schematic of experimental setup.

$$
\begin{aligned}
\rho_{\mathrm{eff}}\left(\frac{q}{m\Delta T}\right)_{\mathrm{eff}} &= \rho_{\mathrm{eff}}\frac{q_{\mathrm{f}}+q_{\mathrm{p}}}{\left(m_{\mathrm{f}}+m_{\mathrm{p}}\right)\Delta T} = \frac{(\rho c)_{\mathrm{f}}V_{\mathrm{f}}+(\rho c)_{\mathrm{p}}V_{\mathrm{p}}}{\rho_{\mathrm{f}}V_{\mathrm{f}}+\rho_{\mathrm{p}}V_{\mathrm{p}}} \\
&= \left(1-\varnothing_{\mathrm{p}}\right)(\rho c)_{\mathrm{f}}+\varnothing_{\mathrm{p}}(\rho c)_{\mathrm{p}} \rightarrow c_{\mathrm{eff}} \\
&= \frac{\left(1-\varnothing_{\mathrm{p}}\right)(\rho c)_{\mathrm{f}}+\varnothing_{\mathrm{p}}(\rho c)_{\mathrm{p}}}{\left(1-\varnothing_{\mathrm{p}}\right)\rho_{\mathrm{f}}+\varnothing_{\mathrm{p}}\rho_{\mathrm{p}}} \qquad (6)
\end{aligned}
$$

By equating Eqs. (2) and (4), the convective heat transfer coefficient is calculated as:

$$
h = \frac{\rho_{\mathrm{eff}}Qc_{\mathrm{eff}}\left(T_{\mathrm{out}}-T_{\mathrm{in}}\right)}{A\dfrac{\mathrm{T_{out}}-\mathrm{T_{in}}}{\ln\dfrac{\mathrm{T_{core}}-\mathrm{T_1}}{\mathrm{T_{core}}-\mathrm{T_2}}}} = \frac{\rho_{\mathrm{eff}}Qc_{\mathrm{eff}}\ln\dfrac{\mathrm{T_{core}}-\mathrm{T_2}}{\mathrm{T_{core}}-\mathrm{T_1}}}{A} \qquad (7)
$$

4.1. Convective heat transfer coefficients

Figs. 3–5 show the calculated heat transfer coefficients as the function of volume concentrations for the three types of nanofluids at three different flow rates.

As expected, for all cases, the heat transfer coefficient of base fluid increases with addition of nanoparticles. For 0.5% volumetric concentration of alumina nanofluid, at flow rate of 1.0 L per minute, a two fold increase in the convection coefficient was observed.

Also for SiO_2 nanofluid, a more significant increase in the convective heat transfer is observed, which can be attributed to the higher particle concentrations used. Longer stability of this nanofluid, even without addition of the stabilizer, makes the use of higher concentrations possible. These nanofluids were stable even after one month after preparation which is an important issue for the use of coolants in this type of cooling systems.

Comparison of convective heat transfer coefficients as a function of the Reynolds number are illustrated in Fig. 6. The Reynolds number was calculated using:

$$
Re = \frac{\rho_{\mathrm{eff}}ud_{\mathrm{H}}}{\mu_{\mathrm{eff}}} \qquad (8)
$$

Where u, ρ, and μ are respectively the velocity, the density and the viscosity of nanofluid, and d_{H} is the hydraulic diameter of the water block. The viscosity of nanofluid is calculated using Ref.[14].

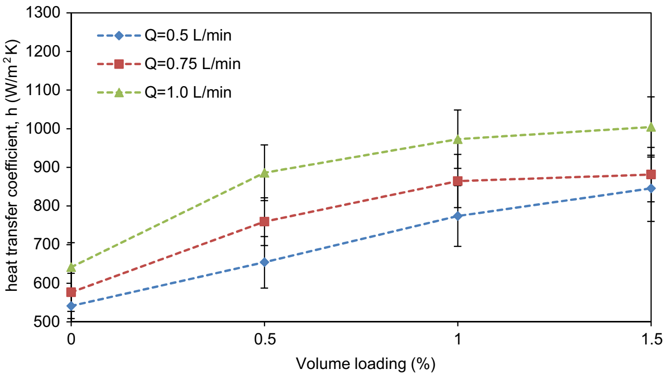

Fig. 3. SiO_2 nanofluid convective heat transfer coefficient.

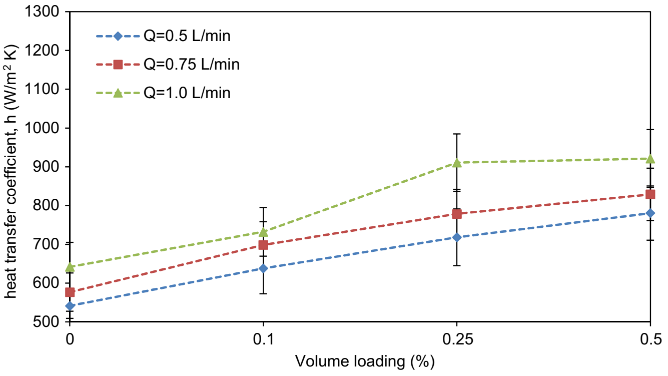

Fig. 4. TiO_2 nanofluid convective heat transfer coefficient.

$$
\frac{\mu_{\mathrm{eff}}}{\mu_{\mathrm{f}}} = \frac{1}{1-34.87\left(d_{\mathrm{p}}/d_{\mathrm{f}}\right)^{-0.3}\varphi^{1.03}} \qquad (9)
$$

Where φ is the volume concentration of nanoparticles. Also, d_{f} is calculated from:

$$
d_{\mathrm{f}} = \left(\frac{6M_{\mathrm{f}}}{N\pi\rho_{\mathrm{f0}}}\right)^{1/3} \qquad (10)
$$

Where M_{f} is molecular weight of the base fluid, N is Avogadro's Number, and ρ_{f0} is the density of the base fluid at 20 °C.

For all the experiments, the heat transfer coefficient is enhanced with increase in Reynolds number. In addition to flow velocity, density and viscosity of the coolant also changes with the change of nanoparticle concentration. In fact, for any given flow rate, increase in concentration of nanoparticles will result in reduction of Reynolds number.

4.2. Processor operating temperature

Decreasing the processor operating temperature is the main purpose of using nanofluids in liquid cooling systems. This temperature is measured while applying a constant processing load on the processor resulting in the highest operating temperature. The internal temperature sensor of the processor is used to measure the temperature. The measured operating temperatures are illustrated in Figs. 7–9. As expected, adding any of the nanofluids to the cooling system reduced the processor operating temperature in comparison to when pure base fluid is used.

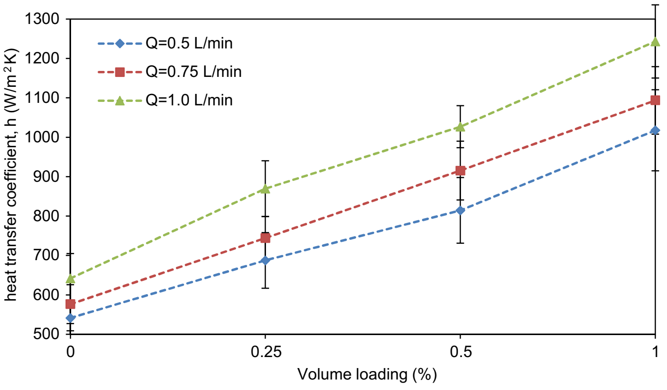

Fig. 5. Al_2O_3 nanofluid convective heat transfer coefficient.

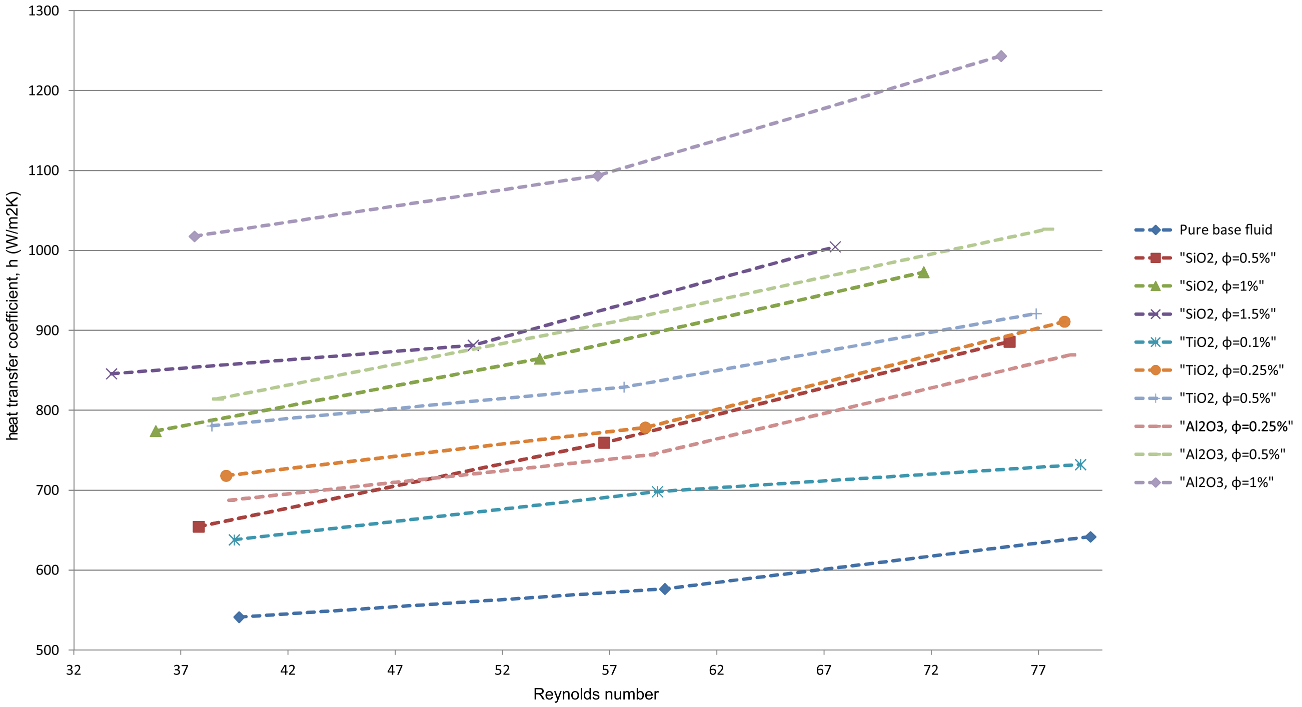

Fig. 6. Convective heat transfer coefficient relating to Reynolds number.

Temperatures relating to pure base fluid are shown by 0% of particle loading. Again, alumina nanofluid showed the greatest decrease on the measured temperature.

Although adding a small amount of nanoparticles to the base fluid resulted in a significant decrease in processor operating temperature, increasing the concentration of the nanoparticles resulted in a lower reduction in this parameter. This fact has been observed for all three nanoparticles used in this study. As it can be seen in from the figures, increasing both concentrations of nanoparticles and flow rate of coolant in the system, resulted in lower operating temperature of the processor. However increasing these parameters would effect on operating costs. Increasing the flow rate will result in higher power consumption and also more noise generation by the cooling system which is not desirable. Adding more nanoparticles to the base fluid will increase the cost of the coolant and possible instability of nanofluid which should be avoided. Therefore, an optimum value for flow rate and particle concentration should be determined to satisfy the economy of the system the for real practical operating conditions.

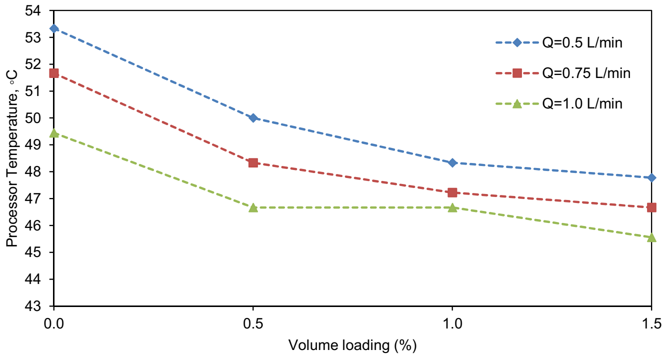

Fig. 7. Processor operating temperatures for SiO_2 nanofluid.

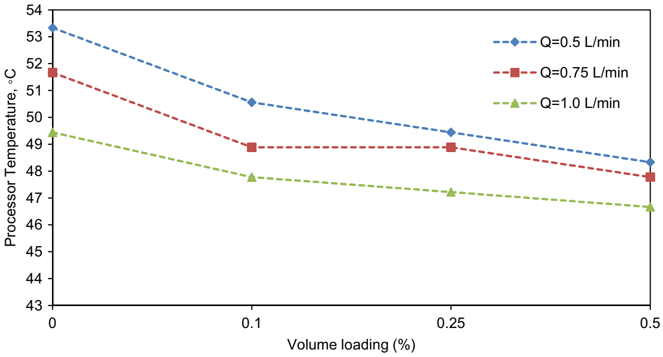

Fig. 8. Processor operating temperatures for TiO_2 nanofluid.

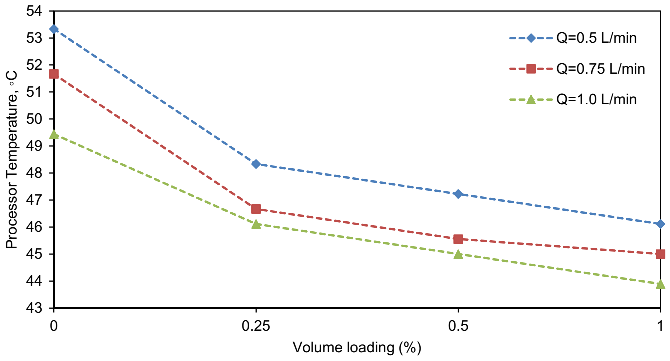

Fig. 9. Processor operating temperatures for Al_2O_3 nanofluid.

5. Conclusions

To choose suitable nanofluid for computer cooling systems, these parameters should be considered:

- Better thermal performance in comparison to common thermal fluid such as water and ethylene glycol;
- No chemical and corrosion impact on cooling system;
- Stability of suspension;
- Economical aspects over its cooling performance.

In this research, thermal properties and the effect of using nanofluids on cooling performance of liquid cooling systems were investigated. Three nanoparticles of alumina, silica and titania were used with a mixture of water/ethylene glycol as the base fluid. Using these nanofluids resulted in the considerable reduction of processor operating temperature as compared to the pure base fluid. However, the diversity of nanoparticles suggests that there may be other nanoparticles with better thermal performance, which could have more favorable effect on the cooling system. It can be predicted that better heat transfer performance can be achieved using carbon nanotube in the base fluid, but the cost of nanoparticles and in general the economy of the cooling system should not be neglected. Therefore, exploiting nanofluids can only be performed if the final cost of the cooling system with nanofluid is in a reasonable range. Stability of nanofluid is the other challenging aspect of their use as coolants. The selection criteria of nanoparticles for cooling systems are as follows:

- High stability in selected base fluid and lower tendency to agglomeration and settling;
- High thermal performance in suspension even at low concentrations;
- Availability and reasonable price;
- Non-toxic and environmental friendly.

It seems that nanofluids have a good prospective for new computer cooling systems, specially for data centers, computer servers and any electronic systems in which heat generation is a major problem. Decreasing operation temperatures, reducing the volume of cooling system and reduction of required power for pumping the coolant through the system are main advantages of using nanofluids in the liquid cooling system compared to common water cooling kits. In fact, more research is needed to determine the stability of nanofluid in cooling systems and their influence on parts of the system.

Nomenclature

A	Heat transfer area [m^2]
c	Specific heat capacity [kJ/kg.°K]
d	diameter [m]
m	Mass [kg]
Q	Volumetric flow rate [m^3/s]
q	Heat rate [W]
T	Temperature [°K]
u	Velocity [m/s]
V	Volume [m^3]
ρ	Mass density [Kg/m^3]
φ	Volume fraction
M	Molecular weight
N	Avogadro's Number

Subscripts:

core	processor
eff	effective
f	fluid
H	hydraulic
nf	nanofluid
p	particle
w	wall

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