

New Class of Coolants: Nanofluids

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1. Introduction

Today more than ever, ultrahigh-performance cooling plays an important role in the development of energy-efficient heat transfer fluids which are required in many industries and commercial applications. However, conventional coolants are inherently poor heat transfer fluids. Nanofluid a term coined by Choi in 1995 is a new class of heat transfer fluids which is developed by suspending nanoparticles such as small amounts of metal, nonmetal or nanotubes in the fluids. The goal of nanofluids is to achieve the highest possible thermal properties at the smallest possible concentrations (preferably <1% by volume) by uniform dispersion and stable suspension of nanoparticles (preferably <10 nm) in host fluids. We have divided this chapter to four sections. Section 1 has focused on the two methods of synthesizing nanofluids and different methods for dispersing spherical and cylindrical nanoparticles such as Ag, Cu in a host fluid and also the common methods for measuring the thermal conductivity of nanofluids. Section 2 has discussed on the thermal conductivity of nanofluids respect to pure fluids to explain the effective thermal conductivity of nanofluids. In this section various theoretical models on the effective thermal conductivity of nanofluids for spherical and cylindrical nanoparticles have been investigated. Section 3 represents the limited understanding of convective heat transfer in nanofluids containing carbon nanotubes that has been developed in recent years. For example the natural and forced convection of nanofluids in a heated cavity are investigated. In recent years there are theoretical and numerical researches for studying the heat transfer effect of nanofluids in microchannels because of their high thermal conductivity. In the last section we discussed about the theoretical and experimental researches for optimizing the microchannel heatsink performance.

2. Synthesis of Nanofluids

In this section we are concerned with the different methods of synthesizing nanofluids. Also the various methods of determining the thermal conductivity of nanofluids will be introduced.

The thermal conductivity of heating or cooling fluids is a very important property in the development of energy-efficient heat transfer systems. At the same time, in all processes

involving heat transfer, the thermal conductivity of the fluids is one of the basic properties taken account in designing and controlling the process. Conventional heat transfer fluids have inherently poor heat transfer properties compared to most solids which is due to the higher thermal conductivities of solids (in orders of magnitude) compared to traditional heat transfer fluids. To overcome the rising demands of modern technology and also to reduce the limitations there is a need to develop new types of fluids that will be more effective in terms of heat exchange performance (Assael et al., 2006). Long ago the basic concept of dispersing solid particles in fluids (mm or μm sized) to enhance the thermal conductivity was introduced by James Clerk Maxwell. Although these fluids showed improved thermal conductivities but due to problems such as: sedimentation, erosion, fouling, increased pressure drop of the flow channel and also clogging of microchannels and flow passages they have never been of interest for practical applications (Trisaksri & Wongwises, 2007; Wang & Wei, 2009). However for this reason finding other ways to improve heat transfer properties of conventional fluids became a serious challenge for many researchers. By the introduction of nanotechnology which involved the synthesis of nanoparticles new ideas such as dispersing nanoparticles instead of mm or μm particles in conventional fluids arised. Nanoparticles (1-100nm) have unique properties such as: size dependent physical properties (color, conductivity), large surface area (the specific surface area of nanoparticles is 3 orders of magnitude greater than that of microparticles), large number density (for a given mass of material there are a greater number of particles as the size decreases) and surface structure (nanoparticles have $\sim 20\%$ of their atoms near the surface, allowing them to absorb and transfer heat more efficiently) and finally due to their small size they improve the stability of the suspensions. All of these properties made them very attractive and many researchers started investigating on them. In 1995 Choi, for the first time introduced the term "Nanofluids".

Nanofluids are a new class of heat transfer fluids. These fluids are developed by suspending small amounts of metal and/or non-metal nanoparticles or also nanotubes in conventional fluids (Trisaksri & Wongwises 2007). It should be noted that nanofluids consist of two constituent phases which are conventional fluids and nanoparticles although they cannot be separable. Until now most of the research has been focused on the production of nanofluids with particles such as aluminum oxide, copper, copper oxide, gold, silver, silica nanoparticles and carbon nanotubes in base fluids such as water, oil, acetone, decene and ethylene glycol (Trisaksri & Wongwises 2007). There are two different approaches for the synthesis of nanoparticles. The bottom-up approach which is the formation of nanoparticles from constituent atoms and the synthesis of nanostructures from bulk referred to the top-down approach. Also nanoparticles can be classified by the technique that has been used for their synthesis which are:

- 1- Physical methods
 - 1-1 Mechanical grinding
 - 1-2 Inert gas condensation
- 2- Chemical methods
 - 2-1 Chemical precipitation
 - 2-2 Chemical vapor deposition
 - 2-3 Micro-emulsions
 - 2-4 Spray pyrolysis
 - 2-5 Thermal spraying

Also the most common techniques for the production of carbon nanotubes are:

- 1- Arc discharge
- 2- Laser ablation
- 3- Chemical vapor deposition (CVD)

2.1. The goal and application of nanofluids

As shown in figure1 for the preparation of nanofluids the nanoparticles can be dispersed in different fluids.

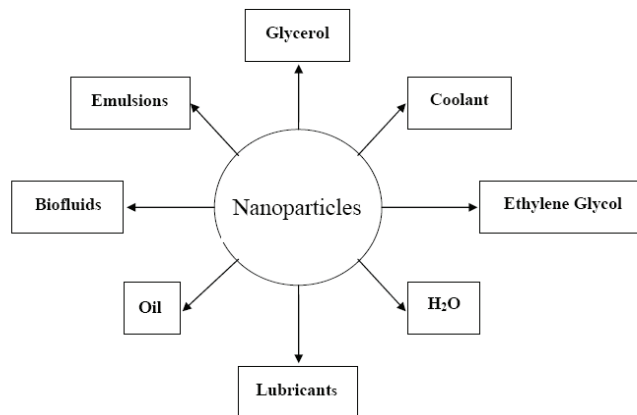


Fig. 1. A number of liquids (heat transfer fluids) that can host nanoparticles for the production of nanofluids.

The most important goal in nanofluid research is to create and develop a nanofluid with stability and ultra-high thermal conductivity for industrial applications. The use of these nanofluids can have a lot of benefits which are: the improvement of heat transfer, reduction in pumping power and lower operating costs, miniaturizing of smaller and lighter heat exchangers, reduction of emissions, suitable for small flow passages like microchannels and reduction in heat transfer fluid inventory.

There are many engineering and medical applications for nanofluids. They can be used for a wide variety of industries, ranging from transportation to energy production and supply to electronics, they can be used to cool car engines, welding equipment and high heat flux devices such as high-power microwave tubes and high-power laser diode arrays they can also flow through tiny passages in MEMS. Also magnetic nanoparticles in biofluids can be used as delivery vehicles for drugs or radiation, providing new cancer treatment techniques because magnetic nanoparticles absorb much more power than microparticles and are more adhesive to tumor cells than normal cells.

2.2. Methods for producing nanofluids

The delicate preparation of a nanofluid is important because nanofluids need special requirements such as an even suspension, durable suspension, stable suspension, low agglomeration of particles and no chemical change of the fluid. There are two fundamental methods to obtain nanofluids (Mamut 2004).

2.2.1. Two step process:

This technique is also known as Kool-Aid method which is usually used for oxide nanoparticles. In this technique nanoparticles are obtained by different methods (in form of powders) and then are dispersed into the base fluid. The main problem in this technique is the nanoparticle agglomeration due to attractive Van der Waals forces.

2.2.2. One step process:

In this process the dispersion of nanoparticles is obtained by direct evaporation of the nanoparticle metal and condensation of the nanoparticles in the base liquid and is the best technique for metallic nanofluids such as Cu nanofluids. The main problems in this technique are low production capacity, low concentration of nanoparticles and high costs. While the advantage of this technique is that nanoparticle agglomeration is minimized. The suspensions obtained by either case should be well mixed, uniformly dispersed and stable in time. Also it should be noted that the heat transfer properties of nanofluids could be controlled by the concentration of the nanoparticle and also by the shape of nanoparticles.

2.3. Methods for dispersing particles

Due to the high surface energy of nanoparticles they tend to agglomerate to decrease their surface energy. The agglomeration of nanoparticles causes rapid settling which deteriorates the properties of nanofluids. To keep the nanoparticles from agglomeration they are coated with a surfactant (steric dispersion) or charged to repulse each other in a liquid (electrostatic dispersion).

Although the addition of the dispersant could influence the thermal conductivity of the base fluid itself, and thus, the real enhancement by using nanoparticles could be overshadowed. There are other dispersion methods such as using a high-speed disperser or an ultrasonic probe/bath and also changing the pH value of the suspension (Chopkar et al., 2006). The selection of suitable dispersants depends mainly upon the properties of the solutions and particles and the use of these techniques depends on the required application of the nanofluid.

However metallic nanofluids due to their low thermal conductivity have limited interest but metallic nanofluids especially Cu nanofluids and Ag nanofluids due to their high thermal conductivity are the common nanofluids. More specifically we can say that all the metallic nanofluids compared to oxide nanofluids show much more enhancements so that metallic nanofluids and their volume percent is reduced by one order of magnitude at comparable K enhancements. There are a number of factors other than the thermal conductivity of the dispersed phase which should be considered such as the

average size of the nanoparticles, the method employed for the preparation of the nanofluids, the temperature of measurements and the concentration of the dispersed solid phase.

The thermal conductivity for some engineering liquids and bulk materials are presented in table1:

Material	Thermal Conductivity $\left[\frac{W}{mK} \right]$	Density $\left[\frac{kg}{m^3} \right]$
Water	0.613	997
Ethylene Glycol	0.252	1114
Engine Oil	0.145	884
Aluminum Oxide	40.0	3970
Silicon	148.0	2330
Aluminum	237.0	2702
Copper	401.0	8933
Gold	317.0	19300
Silver	429.0	10500

Table 1. Thermal conductivities of several liquids and solids (Mamut 2009)

The dispersion of copper (Cu) nanoparticles and alternatively carbon nanotubes (CNTs) has provided the most promising results so far, with reported thermal conductivity enhancements of up to 40% and 160% respectively in relation to the base fluid. Because of the high enhancement of the thermal conductivity of CNT nanofluids we will describe them more.

2.4. Carbon Nanotube Suspensions

Carbon nanotubes (CNT) are fascinating materials with microscale length and nanoscale diameter. They have a very high thermal conductivity (6600W/mK for single-walled CNTs) and a low density. Untreated CNTs are not miscible with water and for this reason to form CNT-nanofluids ultrasonic treatment has to be applied whether with the addition of surfactants (Anionic, Cationic or Non-ionic) or not. Usually CNTs are functionalized to easily disperse in the base fluid.

Until now the greatest increase in the enhancement of the thermal conductivity of nanofluids is reported by Choi et al. They dispersed 1 vol. % multiwalled carbon nanotubes (MW-CNTs) with mean diameters of about 25nm and lengths of 50 μ m (resulting in a length-to-diameter ratio of about 2000) in a synthetic poly (α -olefin) oil as the base fluid and observed an 160% increase (Kebllinski et al.,2005).

2.5. Possible heat transfer mechanisms

Existence of agglomerates and close packing of the dispersed phase as well as the presence and type of the dispersants can negatively influence the increase of the thermal conductivity. On the other hand a lot of parameters are responsible for the unique thermal behavior of nanofluids which are: the particle size and shape, the length-to-diameter ratio, homogenization time, volume fraction of the dispersed phase, interfacial resistance, the ordered structure of the liquid at the solid-liquid interfaces and the Brownian motion of the

nanoparticles enabling the formation of loosely packed clusters and convection-like effects at the nanoscale (Assael et al., 2006).

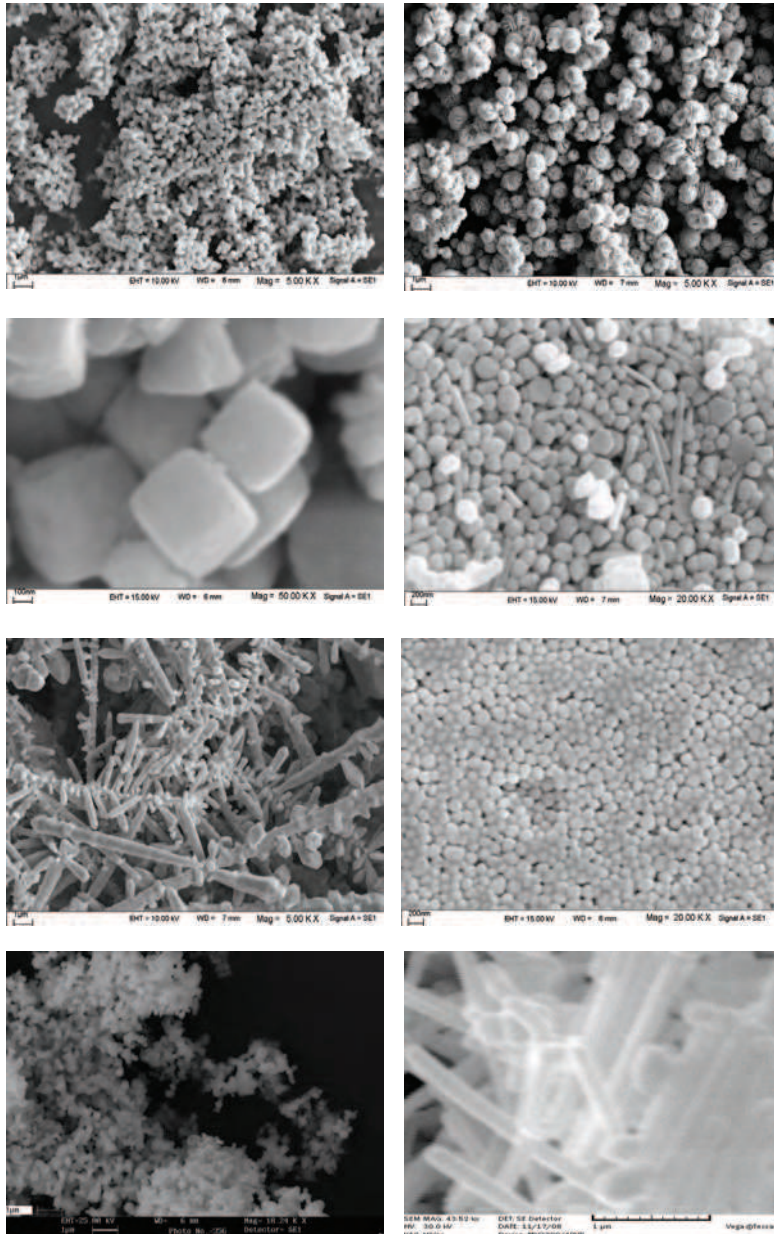


Fig. 2. SEM images of Silver micron particles, nanoparticles and nanowires with different morphologies (Dalalli Isfahani et al., 2009).

2.6. Measurement of the thermal conductivity of nanofluids

Many researchers have reported experimental studies on the thermal conductivity of nanofluids. The transient hot wire method (THW), temperature oscillation, transient planar source (TPS) and the steady-state parallel plate method have been employed to measure the thermal conductivity of nanofluids. However, THW method is one of the most accurate for determining thermal conductivities of materials and for this reason it has been extensively used. The THW technique works by measuring the temperature/time response of the wire to an abrupt electrical pulse. The wire is used as bath heater and thermometer. A derivation of Fourier's law and temperature data were used to calculate the thermal conductivity. The results from all of the available experimental studies indicated that nanofluids containing a small amount of nanoparticles have substantially higher thermal conductivity than those of base fluids. The major advantage of this method lies in its almost complete elimination of the effects of natural convection whose unwanted presence creates problems for measurements made with a steady-state apparatus. In addition the method is very fast relative to steady-state techniques.

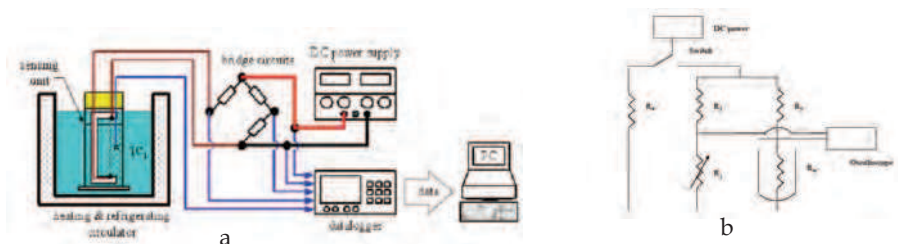


Fig. 3. (a): Experimental apparatus, (b) : schematic diagram of hot-wired apparatus(FOO , 2005).

2.7. The affecting parameters on the thermal conductivity

Overallly we can say that the smaller the size the greater the stability of colloidal dispersion, the greater the stability of colloidal dispersion the greater the probability of interaction and collision among particles and collision among particles and fluid and the greater the effective heat energy transport inside the liquid (Xue 2003).

Thermal conductivity enhancement ratio ($K_{\text{effective}} = K_{\text{nanofluid}}/K_{\text{basefluid}}$) and the parameters that most affect the thermal conductivity of nanofluids are:

- 1- Particle volume fraction
- 2- Particle material
- 3- Base fluids
- 4- Particle size
- 5- Temperature

2.8 Important points about the heat transfer of nanofluids

Finally it should be noted that the most important reason of using nanofluids is to improve the heat transfer of fluids. Our experience in this field has showed that other properties besides the thermal conductivity such as the C_p , α , heat fusion and etc. of the nanoparticle have great impact on the heat transfer of nanofluids. This point has not been mentioned else

ware. Most of the researchers have mainly focused on the thermal conductivity of nanofluids without considering these properties. This is the main key in making useful nanofluids for practical applications. Some other key points for nanofluids are:

- 1- The thermal conductivity enhancement ratio increases with increasing particle volume fraction.
- 2- The sensitivity to volume fraction depends on particle material and base fluid (the sensitivity is higher for particle material with higher thermal conductivity and base fluid with lower thermal conductivity).
- 3- The thermal conductivity of nanofluids shows higher sensitivity to temperature than that of the base fluid, consequently the thermal conductivity enhancement ratio shows also high sensitivity to temperature.
- 4- The particle shape also affects the thermal conductivity. Elongated particles show higher thermal conductivity enhancement ratio than spherical particles.
- 5- The additives used to prevent particle agglomeration seem to increase the thermal conductivity enhancement ratio.
- 6- The thermal conductivity enhancement ratio increases with acidity.
- 7- For the suspensions containing the same base liquid and nanoparticles, the thermal conductivity enhancements were highly dependent on the specific surface area (SSA) of the nanoparticles.
- 8- For the suspensions using the same nanoparticles, the enhanced thermal conductivity ratio decreased with increasing thermal conductivity of the base fluid.

3. Dynamic models of thermal conductivity in nanofluids

In recent years nanofluids has proved the enhancement in thermal conductivity of pure fluids. At the 1995 annual winter meeting of the American Society of Mechanical Engineers, Choi (1995) presented the remarkable possibility of doubling the convection heat transfer coefficients using ultrahigh-conductivity nanofluids instead of increasing pumping power by a factor of 10. The high thermal conductivity enhancement of nanofluids cannot be predicted by any of the classical models. Typically, the classical theories (Maxwell 1881) consider the effect of particle concentration, particle and fluid conductivity and the particle shape effect (Hamilton and Crosser 1962). Traditional solid/liquid conductivity theories for large particles have also been studied. The traditional models are in lack of any predicted dependency of conductivity on spherical particle size. However, it is still difficult to find a suitable high thermal conductivity fluid for microchannel heat sinks. In fact, thermal conductivity of fluids plays an important role in the development of energy-efficient heat transfer fluids (Ryu et al., 2002; Ryu, et al., 2003; Jang et al., 2006; Chein et al., 2005; Min et al., 2004; Xie et al., 2002; Keblinski et al., 2002; Choi et al., 2001; Eastman, 2001; Xie et al., 2003). The resulting heat transfer nanofluids posses significant high thermal conductivity compared to unfilled liquids. It was demonstrated that thermal conductivities predicted by traditional theoretical models such as Hamilton and Crosser's (1962) are much lower than the measured data for metallic and oxide nanofluids. To develop such theories, Wang et al. (1999) were the first to propose new static and dynamic mechanisms, they suggested for the first time that nanoparticle size is important in enhancing the thermal conductivity of nanofluids. They also attributed enhanced conductivity to the chain structure of nanoparticle clusters. Xuan and Li (2000) suggested several possible mechanisms for

enhanced thermal conductivity of nanofluids, such as the increased surface area of nanoparticles, particle-particle collisions, and the dispersion of nanoparticles. Keblinski et al. (2002) proposed four possible microscopic mechanisms for the anomalous increase in the thermal conductivity of nanofluids: Brownian motion of the nanoparticles, molecular-level layering of the liquid at the liquid-particle interface, the ballistic rather than diffusive nature of heat conduction in the nanoparticles, and the effects of nanoparticle clustering. Xuan et al. (2003) developed a dynamic model into which the effects of Brownian motion of nanoparticles and the aggregation structure of nanoparticle clusters (i.e., fractals) are taken. Yejine (2005) attempted to investigate theoretically the mechanism of the effective thermal conductivity of nanofluids. They investigated a theoretical model which includes particle-fluid mixture; the liquid molecules close to a particle surface which are known to form layered structures and behave much like a solid (nanolayer), with the thickness of nanometer. Also the nanoparticle motion causes micro-convection of the suspending fluid, and thus enhances the overall heat transfer in nanofluids. Jang and Choi (2004) have constructed a theoretical model based on kinetics, Kapitza resistance, and convection. They have derived a general expression for thermal conductivity of nanofluids involving three modes. Patel et al., (2008) investigated the mechanisms of conduction in liquids and conduction through solid nanoparticles and the micro-convective heat transfer to the nanoparticles due to their Brownian motion in the liquid, which coupled in a more logical manner. These investigations show that nanofluids have higher heat transfer relative to conventional fluids, and also a better stability compared to fluids with suspended microparticles, making nanofluids useful. Several factors such as gravity, Brownian motion, layering at the solid/liquid interface, ballistic phonon transport between the particles and nanoparticle clusters, and the friction between the fluid and the solid particles contributes to the increase in nanofluid heat transfer.

In addition, the effects of nanolayer thickness, dispersion and volume fraction of nanoparticles enhance the heat transfer. Also, heat transfer nanofluids with carbon nanotubes are expected to possess even better heat transfer properties due to the non spherical shape of carbon nanotubes. Carbon nanotubes (CNTs) have extremely high thermal conductivity, which, at room temperature is over 3,000 times greater than that of water and over 10,000 times greater than that of engine oil (Hone et al., 1999; Berber et al., 2000; Kim et al., 2001). Therefore, fluids containing suspended carbon nanotubes are expected to exhibit significantly higher thermal conductivity relative to conventional spherical nanofluids. Sabbaghzadeh and Ebrahimi (2007) improved the semi theoretical model for effective thermal conductivity of nanofluids containing spherical nanoparticles which presented by Jang and Choi, (2004) for nanofluids containing cylindrical nanoparticles (CNTs). However four heat transfer modes exist in nanofluids. As it has been shown in figure 4, four heat transfer modes exist in nanofluids containing cylindrical nanoparticles (Fig. 4), which are by base fluid (mode 1), nanoparticle (mode 2), nanolayer (mode 3) and micro-convection (mode 4). In addition a nanofluid consisting of base fluid and complex nanoparticles is statistically homogeneous and isotropic. As shown in figure 4, the first mode is defined by collisions among the base fluid molecules, which physically represents the thermal conductivity of the base fluid.

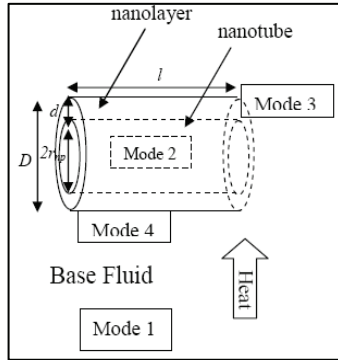


Fig. 4. Shows a cylindrical nanoparticle in base fluid and modes of energy transport in nano fluids. The mode of thermal interactions of dynamic nanoparticles with base fluid molecules (fifth mode) is not shown.

If the energy carrier travels freely over the mean-free path, l_f , (which is the collision between two fluid molecules) then the amount of transferred energy can be presented by the following equation, while, in contrary with the previous works, effect of the nanolayer thickness has not been neglected (Eastman et al., 2001).

$$l_U = -\frac{1}{3} l_f c_v \bar{u} (1 - f_{np} - f_{nl}) \frac{dT}{dz} = -K_f \frac{dT}{dz} (1 - f_{np} - f_{nl}) \tag{1}$$

where c_v , \bar{u} , K_f and T are the heat capacity per unit volume, mean speed, thermal conductivity of the base fluid and temperature of the base fluid molecules respectively, and f_{np} is the volume fraction of the original cylindrical nanoparticles which is given by

$$f_{np} = n \pi r_{np}^2 l_{np} \tag{2}$$

where n is the number of particles per unit volume, r_{np} is the nanoparticle radius, l_{np} is the cylinder length, and f_{nl} is the volume fraction of the nanolayer which is given by

$$f_{nl} = n \pi d_{nl} \left((r_{np} + d_{nl})^2 - r_{np}^2 \right) \Rightarrow f_{nl} = f_{np} M \tag{3}$$

Where

$$M' = \left((d_{nl} / r_{np} + 1)^2 - 1 \right) \tag{4}$$

and d_{nl} is the thickness of nanolayer. The second mode is the thermal diffusion in the nanoparticles which are covered by a nanolayer in the fluid

$$J_U = -\frac{1}{3}l_{np}c_v\bar{u}f_{np} \frac{dT}{dz} = -\kappa K_{np} \frac{dT}{dz} f_{np} \tag{5}$$

where K_{np} is the thermal conductivity of nanoparticle and κ is a constant related to the Kapitza resistance in the order of 0.01(Fand, 1965). The third mode is the nanolayer thermal diffusion in the fluid

$$J_U = -\frac{1}{3}l_f c_v \bar{u} f_{nl} \frac{dT}{dz} = -K_{nl} \frac{dT}{dz} f_{nl} \tag{6}$$

where K_{nl} is thermal conductivity of the nanolayer. The thickness, the microstructure and the physicochemical properties of these nanolayers are highly dependent on the suspended nanoparticles, the base fluid, and the interaction between them. There is no available expression for the calculation of nanolayer thermal conductivity, but as these molecules have an intermediate state between the bulk liquid and solid, therefore it is reasonable to consider this conductivity between these two states. If the thermal conductivity distribution inside the nanolayer is $k(r)$ ($r_{np} < r < r_{np} + d_{nl}$, see figure 1), then the thermal resistance of the nanolayer, R_{nl} is given as follows:

$$R_{nl} = \int_{r_{np}}^{r_{np}+d_{nl}} \frac{dr}{2\pi r l_{np} k(r)} \tag{7}$$

R_{nl} can also be expressed by the average thermal conductivity of the nanolayer, K_{nl} , as follows

$$R_{nl} = \frac{\ln(1 + d_{np} / r_{np})}{2\pi K_{nl} l_{np}} \tag{8}$$

From Eqs. (7) and (8), we have

$$K_{nl} = \frac{\ln(1 + d_{np} / r_{np})}{\int_{r_{np}}^{r_{np}+d_{nl}} \frac{dr}{rk(r)}} \tag{9}$$

We clearly know $k(r)$ is a nontrivial problem due to the complexity of physicochemical interactions between the nanoparticles and the fluid. For simplicity, we assumed a linear variation of $k(r)$, which is (Xie et al., 2003)

$$k(r) = \frac{K_f - K_{np}}{d_{nl}} r + \frac{K_{np}(r_{np} + d_{nl}) - K_f r_{np}}{d_{nl}} \tag{10}$$

by substituting Eq. (10) into (9), the following expression can be derived

$$K_{nl} = \frac{K_f r_{np} (M \varepsilon_p - 1) \ln(M)}{d_{np} (\ln(M \varepsilon_p))} \quad (11)$$

Where $M = 1 + d_{nl} / r_{np}$, and $\varepsilon_p = K_{np} / K_f$ is the ratio of the thermal conductivity of the nanoparticle to that of the base fluid. Finally the fourth mode is thermal interaction of dynamic complex nanoparticles (original nanoparticles and nanolayers) with base fluid molecules. So, the last mode can be defined by

$$J_U = h(T_{np} - T_f)(f_{nl} + f_{np}) = h \delta_T (f_{nl} + f_{np}) \times \frac{(T_{np} - T_f)}{\delta_T} \approx -h \delta_T (f_{nl} + f_{np}) \frac{dT}{dz} \quad (12)$$

Where $\delta_T \sim 3d_f / \text{Pr}$ is the thickness of the thermal boundary layer, in which d_f is the diameter of the base fluid molecules, and Pr is the Prandtl number defined by

$$\text{Pr}_f = \nu_f / \alpha_f \quad (13)$$

where α_f is the thermal diffusivity of the base fluid and ν_f is the kinematic viscosity of the base fluid. Fand (1965) has shown that if the flow direction is perpendicular to the cylinder axes (figure 4) then the heat transfer coefficient from liquid to cylinder, is given by:

$$h = \frac{K_f}{D} \left(0.35 + 0.56 \text{Re}_f^{0.52} \right) \text{Pr}_f^{0.3} \quad (14)$$

The relation is valid for $10^{-1} < \text{Re}_f < 10^5$, and D is the diameter of the complex nanoparticle as shown in figure 1. The Reynolds number Re_f is defined as follows:

$$\text{Re}_f = \frac{\bar{u} l_{np}}{\nu_f} \quad (15)$$

Where \bar{u} is the mean velocity of the complex nanoparticles.

From the molecular heat theory, \bar{u} is determined by Kim et al. (2001)

$$\bar{u} = \left(\frac{3k_B T}{m_{np}} \right)^{1/2} \quad (16)$$

where $k_B = 1.38 \times 10^{-23} \text{JK}^{-1}$ is the Boltzman constant, T is the particle temperature and m_{np} is the mass of the complex nanoparticle, and can be calculated as follows:

$$m_{np} = \pi r_{np}^2 l_{np} \rho_{np} \left[(\rho_{nl} / \rho_{np}) M' + 1 \right] \quad (17)$$

The last mode is the collision between nanoparticles due to Brownian motion. Spherical nanoparticle collision due to Brownian motion is a very slow process (Eastman et al., 2001; Ryu et al., 2002), also Brownian motion for cylindrical particles such as CNTs can be neglected. With neglecting the last mode, the following expression for the thermal conductivity of nanofluids containing cylindrical nanoparticles is derived:

$$K_{eff} = K_f (1 - f_{np}(1 + M')) + f_{np} (\kappa K_{np} + K_{nl} M') + f_{np} (1 + M') \frac{df}{D} (0.35 + 0.56 Re_f^{0.52}) Pr_f^{0.3} K_f \quad (18)$$

The thermal conductivity of suspended nanoparticles, k_p , involving in the Kapitza resistance is two order of magnitude less than the thermal conductivity of nanoparticles., Jang and Choi (2004) have constructed a theoretical model for spherical nanoparticles as follows:

$$k_{eff} = k_{BF} (1 - f) + \beta k_p f + C_1 \frac{df}{D} k_{BF} Re_{BF}^2 Pr_{BF} \quad (19)$$

where $C_1 = 6 \times 10^6$, β is constant related to Kapitza resistance, and f is volume fraction of nanoparticles. In the case of cylindrical shape carbon nano tubes the results are shown in figure 5. The normalized thermal conductivity k_{eff} / k_{BF} for the nanotube in engine oil suspensions as a function of the volume fraction of nanotubes is shown in figure (5-a) and in figure 5-b for distilled water. As it is clear from figure 5-a, by increasing the nanoparticle volume fraction, the thermal conductivity increases, which has a good agreement with experimental results (shown as solid circles), also by increasing the nanolayer thickness thermal conductivity will be increased. Figure 5 also shows that the effect of nanolayer thickness will become more significant by increasing the volume fraction of nanoparticles. Understanding the fundamentals of energy transport in nanofluids is important for developing extremely energy-efficient nanofluids for a range of heat transfer applications. In this section we developed a theoretical model for explaining the enhancement in the effective thermal conductivity of nanotubes (with cylindrical shape). The results show that the thermal conductivity increases if the thickness of nanolayers increases.

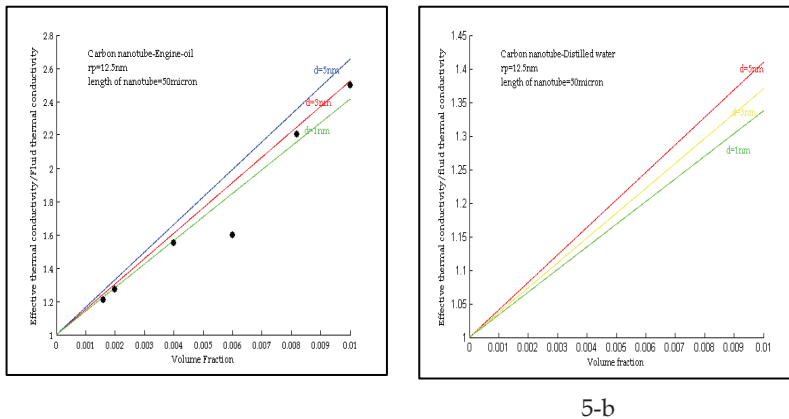


Fig. 5. Shows normalized thermal conductivity for the nanotube-in-engine oil suspensions at experimental (Fig. 5-a, solid circles) vs theory case (Fig. 5-b, solid lines) and nanotube in-distilled water (Fig. (5-b): as a function of the volume fraction of nanotubes with various nanolayer thicknesses.

4. Convection in nanofluids

Heat transfer contains several modes which one of them is convection that is the heat transfer from a fluid to the wall or at opposite direction. Compared to the experimental and theoretical study of the thermal conductivity of nanofluids the study on the heat transfer convection is very limited. It is very important to know that enhancement in thermal conductivity of nanofluid necessarily does not increase the heat transfer capability of it. The physical properties of nanofluids compared to pure fluid such as viscosity, heat capacity, density and stability of nanoparticles in the fluid maybe deteriorated. Convection in nanofluid is broadly divided in two types: natural convection and force convection. Natural convection is the type of convection which the flow is generated by buoyancy force during cooling or heating of the fluid. Force convection is the convection which the flow is due to external forces such as pump, fan, compressor and etc. (Raj Kemal et al, 2007). The law of convection is Fourier's conduction law (Incropera 2002):

$$Q = hA(T_W - T_f) \quad (20)$$

Where Q is the amount of heat transfer between the wall and the fluid in motion, A is the solid-liquid interface area, T_W is the wall temperature, and T_f is the fluid temperature. In nanofluids two methods can be used for the study of heat transfer (Khanafer et al., 2003): which is assumed that both the fluid phase and nanoparticles are in thermal equilibrium state and they flow at the same velocity which is named as single phase model. In the other model the fluid is considered to be a single fluid with two phases, and the coupling between them is strong which each phase has its own velocity vectors, and within a given volume fraction there is a certain volume fraction of each phase which is named as mixture model. In nanofluids due to the small particles are suspended in a ordinary fluid and their higher stability the single phase model is better applicable.

4.1. Governing Equations of Fluid Flow and Heat Transfer

Consider a two-dimensional enclosure of height H and width W filled with a fluid as shown in Fig. 6. The horizontal walls are assumed to be insulated, nonconductive and impermeable to mass transfer. The fluid in the enclosure is Newtonian, incompressible, and laminar. Moreover, it is assumed that both the fluid phase and nanoparticles are in thermal equilibrium state and they flow at the same velocity. For natural convection the right vertical wall is maintained at a high temperature T_H while the left vertical wall is kept at a low temperature T_L (Fig.6 a). In the case of no velocity on the cavity walls natural convection is dominated and in the case of velocity (V_p) on at least one of the walls the force convection is added to natural convection and convection mode is named as mix convection (Fig.6 b). In the first stage we considered a natural convection and then force convection will be applied. It is assumed that the dispersed nanoparticle of the nanofluid has a uniform cylindrical shape and size.

The variation of density in the buoyancy force is based on the Boussinesq approximation. The initial and boundary conditions for natural convection in the present investigation are presented as:

$$in\ t=0\ u=v=T=0\ for\ \begin{cases} 0 \leq x \leq W \\ 0 \leq y \leq H \end{cases} \tag{21}$$

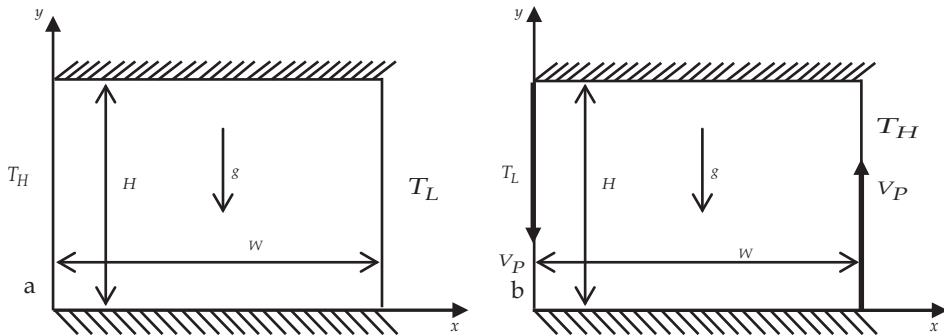


Fig. 6. Schematic of the physical model: a (natural convection) and b (force convection).

$$in\ t)0:\ \begin{cases} u=v=\frac{\partial T}{\partial y}=0\ for\ \begin{cases} 0 \leq x \leq W \\ y=0, H \end{cases} \\ T=T_L, u=v=0\ for\ \begin{cases} 0 \leq y \leq H \\ x=0 \end{cases} \\ T=T_H, u=v=0\ for\ \begin{cases} 0 \leq y \leq H \\ x=W \end{cases} \end{cases} \tag{22}$$

The governing equations for the present study considering the above mentioned assumptions are written in dimensional form and the well-known stream function vorticity formulation in which the primary variables are replaced by stream function ψ and vorticity ω are used to mainly to avoid the pressure term in the momentum equation. This requires complicated algorithms in incompressible flow as follows:

Vorticity equation

$$\frac{\partial \omega}{\partial t} + u \frac{\partial \omega}{\partial x} + v \frac{\partial \omega}{\partial y} = \frac{\mu_{eff}}{\rho_{nf}} \nabla^2 \omega + \frac{\beta_{nf}}{\rho_{nf}} g \frac{\partial T}{\partial x} \quad (23)$$

Energy equation

$$\frac{\partial T}{\partial t} + u \frac{\partial T}{\partial x} + v \frac{\partial T}{\partial y} = \frac{\partial}{\partial x} \left(\frac{K_{eff}}{(\rho c_p)_{nf}} \frac{\partial T}{\partial x} \right) + \frac{\partial}{\partial y} \left(\frac{K_{eff}}{(\rho c_p)_{nf}} \frac{\partial T}{\partial y} \right) \quad (24)$$

Kinematics equation

$$\frac{\partial^2 \psi}{\partial x^2} + \frac{\partial^2 \psi}{\partial y^2} = -\omega \quad (25)$$

The effective density of a nanofluid at a reference temperature is given by:

$$\rho_{nf} = f_{np} \rho_{np} + (1 - f_{np}) \rho_f \quad (26)$$

where ρ_f , ρ_{np} and f_{np} are the density of base fluid, density of nanoparticles, and the volume fraction of the nanoparticles, respectively. The effective viscosity of a fluid with a viscosity μ_f containing a dilute suspension of small rigid cylindrical particles is given by Brinkman equation (Brinkman 1952):

$$\mu_{eff} = \mu_f / (1 - f_{np})^{2.5} \quad (27)$$

The heat capacitance and thermal expansion coefficient of the nanofluid can be presented as

$$(\rho c_p)_{nf} = f_{np} (\rho c_p)_{np} + (1 - f_{np}) (\rho c_p)_f \quad (28)$$

$$\beta_{np} = (1 - f_{np}) \rho_f \beta_f + f_{np} \rho_{np} \beta_{np} \quad (29)$$

and the effective thermal conductivity of the solid-liquid mixture is considered as equation (18)

while the specific velocity is as follows:

$$V_p = \sqrt{g\beta_f\Delta TH} \tag{30}$$

The above equations for natural convection can be cast in non-dimensional form by incorporating the following dimensionless parameters

$$\begin{cases} X = \frac{x}{H} & Y = \frac{y}{H} & \tau = \frac{tV_p}{H} & \Omega = \frac{\omega H}{V_p} \\ U = \frac{u}{V_p} & V = \frac{v}{V_p} & \Psi = \frac{\psi}{HV_p} & \theta = \frac{T - T_L}{T_H - T_L} \end{cases} \tag{31}$$

$$\frac{\partial \Omega}{\partial \tau} + U \frac{\partial \Omega}{\partial X} + V \frac{\partial \Omega}{\partial Y} = \Gamma_{\Omega} \left(\frac{\partial^2 \Omega}{\partial X^2} + \frac{\partial^2 \Omega}{\partial Y^2} \right) + \lambda \frac{\partial \theta}{\partial X} \tag{32}$$

$$\frac{\partial \theta}{\partial \tau} + U \frac{\partial \theta}{\partial X} + V \frac{\partial \theta}{\partial Y} = \Gamma_{\theta} \left(\frac{\partial^2 \theta}{\partial X^2} + \frac{\partial^2 \theta}{\partial Y^2} \right) \tag{33}$$

$$\frac{\partial^2 \Psi}{\partial X^2} + \frac{\partial^2 \Psi}{\partial Y^2} = -\Omega \tag{34}$$

In the above equations Γ_{Ω} and Γ_{θ} are as:

$$\Gamma_{\Omega} = \frac{1}{(1 - f_{np})^{2.5} \left((1 - f_{np}) + f_{np} \frac{\rho_{np}}{\rho_f} \right) \sqrt{Gr}} \tag{35}$$

$$\Gamma_{\theta} = \frac{1}{Pr \sqrt{Gr}} \frac{K_{eff}}{k_f} \left((1 - f_{np}) + f_{np} \frac{(\rho c_p)_{np}}{(\rho c_p)_f} \right)^{-1} \tag{36}$$

while the Grashof number is $Gr = \frac{g\beta_f\Delta TH^3}{\nu_f^2}$, and Prandtl number is $Pr = \frac{\nu_f}{\alpha_f}$. The aspect ratio

is defined as $A = \frac{W}{H}$ and is assumed unity in this investigation. The physical dimension of the enclosure H is chosen to be 1 cm.

In equation (11) the coefficient λ that appears next to the buoyancy term is given by

$$\lambda = \left[\left(1 + \frac{(1-f_{np}) \rho_f}{f_{np} \rho_{np}} \right)^{-1} \frac{\beta_{np}}{\beta_f} + \left(1 + \frac{f_{np} \rho_{np}}{(1-f_{np}) \rho_f} \right)^{-1} \right] \quad (37)$$

The local variation of the Nusselt number of the fluid on the hot wall can be expressed as

$$Nu = - \frac{K_{eff}}{k_f} \frac{\partial \theta}{\partial X} \Big|_{X=0} \quad (38)$$

while the average Nusselt number is given by:

$$\overline{Nu} = - \int_0^1 \left(\frac{K_{eff}}{k_f} \frac{\partial \theta}{\partial X} \Big|_{X=0} \right) dY \quad (39)$$

In mix convection at least one of the cavity walls is moved. In this work we supposed that the left wall is moving downward and the right wall is moving upward, also the left wall is kept at low temperature and the right wall is at high temperature. For this configuration the natural convection and force convection are in the same direction and the dimensionless form of the governing equations is presented versus wall velocity. The governing equations for mix convection can be cast in non-dimensional form as the same with natural convection except that the speed of the wall has a specific value which is named as the specific velocity. Also the dimensionless equations have the same form in the two type convection with this exception that the coefficients Γ_Ω , Γ_θ , and λ are defined as follows:

$$\Gamma_\Omega = \mu_{eff} / (\rho_{nf} \nu_f \text{Re}) \quad (40)$$

$$\Gamma_\theta = \alpha_{nf} / (\alpha_f \text{Pr Re}) \quad (41)$$

$$\lambda = (\beta_{nf} / \beta_f \rho_{nf}) Ri \quad (42)$$

and also $\text{Re} = (HV_p) / \nu_f$ is Reynolds number, and $Ri = Gr / \text{Re}^2$ is Richardson number.

The numerical simulation for natural convection was developed over a wide range of Rayleigh numbers ($10^4, 10^5$), volume fraction of nanoparticles ($0 < f_{np} < 1$), and nanoparticle diameter $d_{np}(nm) = 10$ and also the nanolayer thickness $d_{nl}(nm) = 5$.

The average Nusselt number at the left wall for various Rayleigh numbers and different nanoparticle volume fractions ($0 < f_{np} < 1$), and particle diameter $d_{np}(nm) = 10$ and nanolayer thickness $d_{nl}(nm) = 5$ of nanoparticles are presented in Figure 7. As it can be seen from this figure with the increase of the volume fraction of the nanoparticle, increase in average Nusselt number for high value of the Rayleigh number is more noticeable while for the low value it is weaker. The numerical simulation for mix convection for Richardson numbers $(1.0, 10.0), Gr = 10^4$ and the same other parameters with the natural convection are down and the results are presented in Figure 8. Also enhancement in the average Nusselt number for mix convection in different Richardson number versus nanoparticles volume fraction are shown in Figure 10. This figure shows that with the increase in the volume fraction of nanoparticles, more increase in average Nusselt number for low Richardson number (high Reynolds number) was observed.

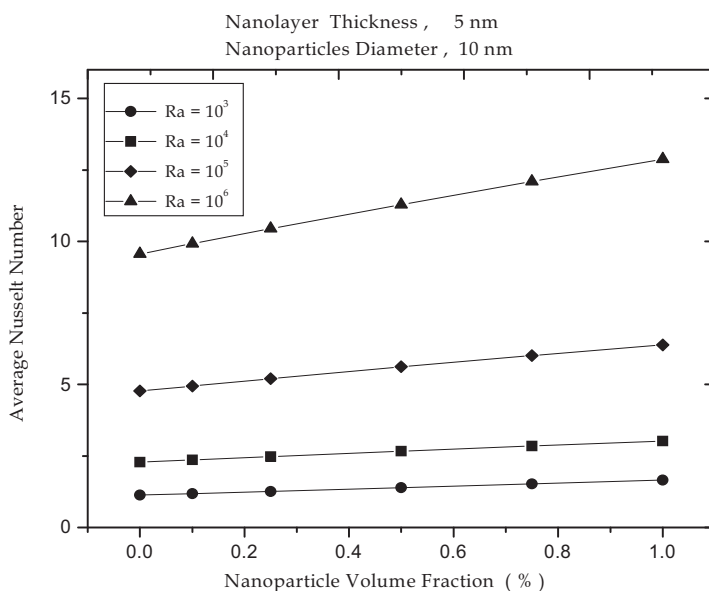


Fig. 7. Variation in average Nusselt number for natural convection in nanofluid versus the volume fraction for different Rayleigh numbers ($d_{np} = 10(nm), d = 5(nm)$)

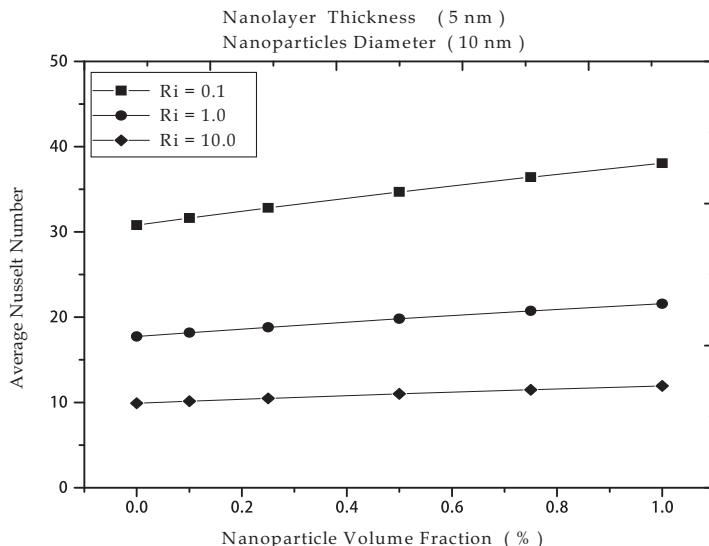


Fig. 8. Variation in average Nusselt number for mix convection in nanofluid versus nanoparticles volume fraction for different Richardson numbers ($d_{np}(nm) = 10$, $d_{nl}(nm) = 5$)

5. Performance analysis of nanofluid-cooled microchannel heat sinks

With the advances in computing technology over the past few decades, electronics have become faster, smaller and more powerful. In most cases, the chips are cooled using forced air flow. However, when dealing with a component that contains billions of transistors working at high frequency, the temperature can reach a critical level where standard cooling methods are not sufficient. In addition to high-performance electronic chips, high heat flux removal is also required in devices such as laser diode arrays and high-energy mirrors. In the last two decades, many cooling technologies have been pursued to meet the high heat dissipation rate requirements and maintain a low junction temperature. Among these efforts, the microchannel heat sink (MCHS) has received much attention because of its ability to produce high heat transfer coefficient, small size and volume per heat load, and small coolant requirements. Recent progress in MCHS development was provided by Kandlikar et al. (2003).

A MCHS typically contains a large number of parallel microchannels with a hydraulic diameter ranging from 10 to 1000 μm . A coolant is forced to pass through these channels to carry the heat away from a hot surface. The MCHS cooling concept was proposed by Tuckerman and Pease (1981). Since then, MCHS performances with different substrate materials and channel dimensions have been studied extensively in the past two decades. These studies can be categorized into theoretical (Knight et al., 1992; Ambatipudi and Rahman, 2000), numerical (Fedorov and Viskanta, 2000; Lee et al., 2005; Li et al., 2004; Li and Peterson, 2006), and experimental approaches (Qu and Mudawar, 2002; Tiselj et al., 2004). In the theoretical approach, the main objective is to develop design schemes that can be used to optimize MCHS performance. Most studies in this approach employed the classical fin

theory which models the solid walls separating microchannels as thin fins. The heat transfer process is simplified as one dimensional, constant convection heat transfer coefficient and uniform fluid temperature. However, the nature of the heat transfer process in MCHS is conjugated heat conduction in the solid wall and convection to the cooling fluid. The simplifications used in the theoretical approach usually under- or over predict the MCHS performance.

To overcome the shortcomings associated with MCHS thermal performance analysis using fin theory, several investigators proposed modeling the MCHS as a porous medium. In the study by Kim and Kim (1999), laminar heat transfer in MCHS was analyzed using a modified Darcy model for fluid flow and two-equation model for heat transfer. They found that their results agreed well with those predicted using fin theory models (Knight et al., 1992) and experimental measurements by Tuckerman and Pease (1981). Zhao and Lu (2002) further extended the model developed by Kim and Kim (1999) to study the channel geometries, effective thermal conductivities and porosities on the MCHS thermal performance. Because conjugated heat transfer is involved in MCHS, and it is believed that the porous medium model is better than the classical fin theory for describing the MCHS thermal performance.

Although high thermal performance can be achieved using MCHS but further improvement is still needed to cope with the increasing demands for various device applications. From the heat transfer point of view, improving MCHS thermal performance enhances the heat transfer characteristics inside the MCHS. Extensive reviews on the techniques for heat transfer enhancement in macroscale dimensions were provided by Bergles (2002) and Webb (1993). One of the methods for enhancing heat transfer is the application of additives in the working fluids. The basic idea is to enhance the heat transfer by changing the fluid transport properties and flow features of the metal particles embedded in the liquid fluid. In earlier studies to enhance the heat exchanger performance. However, a serious clogging problem occurred due to the particle sedimentation. Recent interest based on this concept focused on heat transfer enhancement using a nanofluid in which the nanoscale metallic or non-metallic particles were suspended in the base fluids. Several experimental and analytical studies showed that nanofluids have higher thermal conductivity than pure fluids and therefore greater potential for heat transfer enhancement (Wang et al., 1999; Koo and Kleinstreuer, 2004).

Using a nanofluid as the heat transfer working fluid has gained much attention in recent years. Xuan and Roetzel (2000) proposed two theoretical models to predict the heat transfer characteristics of the nanofluid flow in the tube. Li and Xuan (2002), Xuan and Li (2003) and Pak and Cho (1998) experimentally measured the convection heat transfer and pressure drop for nanofluid tube flows. Their results indicated that the heat transfer coefficient was greatly enhanced and depended on the Reynolds number of the flow, particle Peclet number, particle size and shape, and particle volume fraction. These studies also indicated that the presence of nanoparticles did not cause an extra pressure drop in the flow. Recently, Yang et al. (2005) carried out an experimental study attempting to construct a heat transfer correlation among the parameters that affected heat transfer. For a laminar flow regime in a circular tube, they indicated that the heat transfer coefficient for the nanofluid flow had a lower increase than predicted by the conventional heat transfer correlation for the homogeneous or particle-suspended fluid. Ding et al. (2006) reported the heat transfer coefficient data for force convection in circular tubes using a carbon nanotube (CNT)

nanofluid. In most of the studies mentioned above, the nanofluid heat transfer flow characteristics were carried out in macro-scale dimensions. Only a few studies addressed the nanofluid flow and heat transfer in micro-scale dimensions. In numerical aspect, Koo and Kleinstreuer (2005) and Jang and Choi (2006) studied the MCHS performance numerically using different models for the effective thermal conductivity of the nanofluids. Sabbaghzadeh and Ebrahimi (2007) derived a general expression for the effective thermal conductivity of nanofluid containing cylindrical nanoparticles by considering the nanolayer effect. Our objective is to present the numerical method for explaining the nanolayer effect in the cooling performance of MCHS with carbon nanotube fluid suspensions.

5.1 Governing Equation

The problem of forced convective flow through a microchannel heat sink of water-based nanofluids containing CNTs with 25nm diameter and various nanolayer thicknesses is numerically considered. Figure 9 shows the physical and numerical domains. The top surface is insulated and the bottom surface is uniformly heated. A coolant passes through the microchannel heat sink and takes the heat away from a heat-dissipating component attached below.

5.2. Numerical results:

Based on the numerical results (Ebrahimi et al,2009), figure 10 shows colored temperature contours of a cross-sectional area of a microchannel heat sink containing water, CNT water-based nanofluids ($f_{np} = 0.1\%$, $d_{np} = 25$ (nm)), with various nanolayer thicknesses while

the pumping power was fixed at 2.27 W and the heat flux was fixed at 300 W/cm^2 . Figure 10 also shows that with increasing the nanolayer thicknesses, the temperature gradients decrease. So it is beneficial to increase nanolayer thicknesses by CNTs surface treatment.

For nanofluids containing carbon nanotubes with 0.1% volume fraction, in fixed pumping power of 2.5W, the thermal resistance of microchannel heat sink will be decreased nine percent in respect to water. Analytical and numerical investigations show that using CNTs with good surface treatment increases heat removal in microchannel heat sinks.

A combination of microchannel heat sink (smallcharacteristic length) with nanofluids has been introduced as a new method for high cooling performance. The temperature contours of microchannel heat sink with nanofluids containing cylindrical nanoparticles have been numerically investigated. We have shown that by increasing the nanolayer thickness, enhancement in thermal conductivity and decrease in Nusselt number could remarkably be observed. The temperature gradient in microchannel heat sink will be decreased if nanolayer thickness increases. The thermal resistance of microchannel heat sinks with nanofluids containing CNTs is reduced with respect to nanofluids containing spherical nanoparticles.

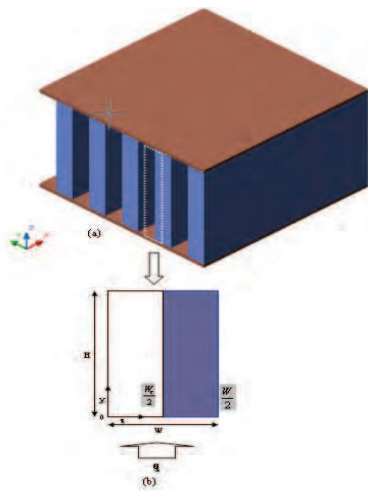


Fig. 9. Schematic of a microchannel heat sink: (a) physical domain, (b) numerical domain.

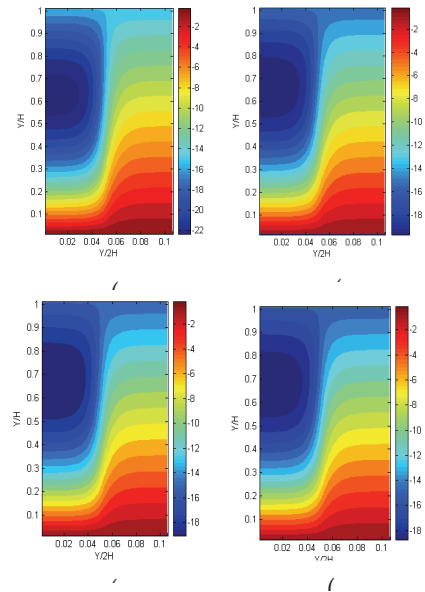


Fig. 10. Temperature counters for distilled water, 300 W/cm^2 , $K_f=0.6 \text{ W/mK}$ (a), and MWCNTs dispersed in water with 0.1% volume fraction and $d_{n1}=1(\text{nm})$, $K_{nf}=0.75\text{W/mK}$ (b), $d_{n1}=3(\text{nm})$, $K_{nf}=0.8\text{W/mK}$ (c), and $d_{n1}=5(\text{nm})$, $K_{nf}=0.83\text{W/mK}$ (d).

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The main purpose of this book is to describe important issues in various types of devices ranging from conventional transistors (opening chapters of the book) to molecular electronic devices whose fabrication and operation is discussed in the last few chapters of the book. As such, this book can serve as a guide for identifications of important areas of research in micro, nano and molecular electronics. We deeply acknowledge valuable contributions that each of the authors made in writing these excellent chapters.

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