IMPROVEMENT OF HEAT TRANSFER COEFFICIENTS IN A SHELL AND TUBE HEAT EXCHANGER USING CNT / WATER NANOFLUID

J.Ganesh Kumar

Associate Professor, Department of Mechanical Engineering, Mohamed Sathak Engineering College, Kilakarai, Ramanathapuram District, Tamilnadu, India

A.Sankara Narayanan

P.G Student, Department of Mechanical Engineering, Mohamed Sathak Engineering College, Kilakarai, Ramanathapuram District, Tamilnadu, India

Abstract

The main aim of the present experimental investigations to study the heat transfer characteristics of nanofluids mixed with base fluid in certain proportion flowing in a tube. Heat exchangers are widely used in various Engineering applications which include power plants, nuclear reactors, refrigeration and air conditioning systems, chemical processing and food industries. Nanofluid is a novel heat transfer fluid prepared by dispersing nanometer-sized solid particles in traditional heat transfer fluid to increase thermal conductivity and heat transfer performance. In this study heat transfer characteristics of CNT / Water nanofluid flowing inside the shell and tube heat exchanger has been investigated experimentally.

In this paper, thermal conductivity of carbon nanotubes' (CNTs) nanofluid is studied experimentally. CNT nanofluids were stabilized using gum arabic (GA). The concentration of CNTs was varied from 0.01–0.1 wt% while the concentration of GA was varied from 1–2.5 wt%, respectively. The effect of particle volume fraction and temperature on the thermal conductivity enhancement of the nanofluids was also studied. A simple thermal conductivity model which demonstrates the effect of diameter and aspect ratio of the CNTs and takes into account the effect of temperature on thermal conductivity enhancement is presented. Good agreement between experimental and estimated values proves that the proposed model can provide precise prediction of the thermal conductivity of fluid containing CNTs.

Keywords: *CNTs, thermal conductivity, nanofluid*

1. Introduction

Adding small amounts of nanoparticles to fluids in heating or cooling processes is one of the methods being studied to enhance the convective heat transfer rates between the fluid and the surface. Compared to the thermal conductivity of solids, conventional fluids have very low thermal conductivity. Recent advancement in nanotechnology has made it possible to produce particles of the order of nanometers (preferably less than 100 nm). An innovative idea of suspending these nanoparticles in fluids and utilizing them for heat transfer enhancements. CNTs are a one-dimensional nanomaterial which has unique thermal, mechanical, and optical properties. Due to their high molecular weight they are considered as insoluble in almost all known solvents. However, they can be dispersed with the aid of dispersants and other functionalization strategies. CNTs generally tend to aggregate into bundles of ropes due to the very high surface energy. It is difficult to separate these bundles into individual tubes which is a serious hurdle in the way of real applications. The insolubility of CNTs in most solvents is due to the lack of side groups or other functionalities on CNTs that can interact with the surrounding solvent to overcome the large inter tube Vander Waals interactions. The effective thermal conductivity of the resulting nanofluids shows considerable enhancement compared with that of traditional heat transfer fluids. This paper presents thermal conductivity enhancements of CNT–water nanofluids stabilized by GA. The stability of these suspensions is presented in our previously published paper [6] which demonstrates the various factors affecting the stability. This work presents the thermal conductivity of pure water, GA solution, and a CNT-suspended nanofluid which gives a clear idea on the percentage enhancement using nanoparticles alone and the role of dispersant.

Nomenclature

A: heat transfer area, m2
d_p: diameter of the particle, m
D_p: diffusivity of the particle, m2/s
J_x: heat current vector, W
k_p: particle thermal conductivity, W/mK
k_f: fluid thermal conductivity, W/mK
k_B: Boltzmann constant, m2 kg/s2K
l_p: length of the particle, m
N: number of Brownian particles, –
n_f: number of fluid molecules per unit volume,m^3
n_p: number of particles per unit volume, m^3
q: overall heat transfer rate, W
r_p: radius of the particle, m
r_f: radius of the fluid molecule, m
T: temperature, K
t: time, s
u, v, w: velocity components, m/s
μ_f: fluid viscosity, kg/ms
ζ: drag on the particles, Pas
τ: increment time, s
φ: volume fraction of the particle.

2. Material and Methods

The CNTs used in this study were rendered from the Chinese Academy of Science. These CNTs had the following characteristics: an average diameter of 20 nm, a length of approximately 35 μm, and the purity of the CNT was greater than 95%. The thermal conductivity value of the CNT is 3000 W/mK and has a density of 2.1 g/cc, respectively. The gum arabic (GA) used in this study is a natural polysaccharide, is 100% pure and organic, and was received in the form of large granules from Gum Arabic Co, Sudan. Due to its hygroscopic nature, it was made into powdered form only prior to use.

3. Experimental Studies

Stable CNT-dispersed nanofluids in GA solutions are prepared using homogenization and sonication of the nanofluids. CNT, GA, and water were mixed in a measured amount and homogenized at 2800 rpm using a high-speed homogenizer for 10 mins and sonicated for 2–24 hrs using a water bath sonicator. GA concentration was also varied from 0.25–5.0 wt% for each CNT concentration. Stability studies were carried out using UV is spectrophotometer as a function of sediment time. Figure 1 shows a stable nanofluid prepared using GA with 10 minutes of high-speed homogenization and 4 hours of sonication. The CNT concentration used in this study ranges from 0.01–0.1 wt% and the GA concentration was varied from 1–2.5 wt%. Thermal conductivity of pure water, GA solution, and CNT nanofluid was measured at temperatures varying from 27–60 °C. Thermal conductivity of nanofluids was measured using a KD_2 Pro, thermal conductivity meter (Decagon USA). Before measuring the thermal conductivity, the probe was calibrated using the standard glycerin solution. The thermal conductivity of the GA solutions and nanofluids was measured by completely immersing the test sample in a constant water bath. About readings were recorded for each sample and the readings with $r2 > 0.9995$ were averaged to get the thermal conductivity value.

4. Thermal Conductivity Model

From a theoretical point of view, the enhanced thermal conductivity is much lower than the measured thermal conductivities. Conventional models for thermal conductivity of suspensions have been listed in Table 1, where k_{eff} is the effective thermal conductivity of the suspension, k_f and k_p are the thermal conductivities of the suspending medium and solid particle respectively, n_s is a shape factor for the particle, and φ is the particle volume fraction. The shape factor, n_s, is given by $n = 3/\lambda$, where λ is defined as the ratio of the surface area of a sphere with a volume equal to that of the particle to the actual surface area of the particle.

Fig. 1. Stable CNT Nanofluids after 10 min Homogenization and 4 hr Sonication

Model	Expression
Maxwell [7]	$k_{eff} = \frac{k_p + 2k_f + 2(k_p - k_f)\phi}{k_p + 2k_f - 2(k_p - k_f)\phi} k_f$
Hamilton and Crosser [8]	$k_{eff} = \frac{k_p + (n_s - 1)k_f - (n_s - 1)\phi(k_f - k_p)}{k_p + (n_s - 1)k_f + \phi(k_f - k_p)} k_f$
Jeffrey [9]	$k_{eff} = k_f \left\{ \begin{array}{l} 1 + \frac{3\phi(k_p/k_f - 1)}{k_p/k_f + 2} + 3\phi^2 \left(\frac{k_p/k_f - 1}{k_p/k_f + 2} \right)^2 \\ \left[1 + \frac{1}{4}\left(\frac{k_p/k_f - 1}{k_p/k_f + 2} \right) + \frac{3}{16}\left(\frac{k_p/k_f - 1}{k_p/k_f + 2} \right)\left(\frac{k_p/k_f + 2}{2k_p/k_f + 3} \right) + .. \right] \end{array} \right\}$
Davis [10]	$k_{eff} = k_f \left\{ 1 + \frac{3\phi(k_p/k_f - 1)\left[\phi + f\phi^2 + O\phi^3\right]}{(k_p/k_f + 2) - (k_p/k_f - 1)\phi} \right\}$

Table 1. List of Conventional Thermal Conductivity Models

Here *f* and *O* are higher-order terms, due to pair interactions, respectively. These models cannot be readily applied to CNT nanofluids because of their lack of accuracy of the particle size and length of the tube and, thus, these models deviate far from the experimental data. It is believed, however, that in the modeling of the thermal conductivity for CNTs, the aspect ratio is of great importance.

In this study, the thermal conductivity model proposed for CNT-based nanofluids has been derived from Patel's model. The initial model cannot be readily applied for CNT nanofluids as it is valid for only spherical particles. The present thermal conductivity model consists of two parts. The first part is based on thermal conductivity dependence on particle volume fraction, shape, aspect ratio, and thermal conductivities of the particle and fluid medium. The next part describes the dependence of thermal conductivity of nanoparticles on temperature and fluid viscosity which is directly related to Brownian motion. Here, for the sake of the model, the liquid medium is also assumed as particles which are surrounded by other nanoparticles. Since heat transfer is a surface phenomenon, its magnitude will increase with an increase in the surface area of all the particles. In the case of nanoparticles, the surface area to volume ratio is much higher compared to those of microparticles. The large total surface area of nanoparticles explains the anomalous increase in heat transfer rate or effective thermal conductivity, even when a small volume fraction of nanoparticles are homogeneously suspended in the base fluid.

5.1 Experimental Results

5.1.1 Effect of GA Concentration

Figures 2(a) and 2(b) present the effect of GA concentration on thermal conductivity enhancement at room temperature (25 °C). It is observed that, at room temperature, there is negligible enhancement in the thermal conductivity of the GA solution. The enhancement is a maximum of 2.0% at 2.5 wt% of GA. Thus, at room temperature the GA does not play a significant role in thermal conductivity enhancement, because of the very low thermal conductivity value of GA of the order of 0.12 W/mK.

5.1.2 Effect of CNT Concentration

The effect of CNT concentration on thermal conductivity enhancement at room temperature (25 °C) is shown in Figs. 3(a) and 3(b). From Fig. 3 it observed that the thermal conductivity increases with an increase in CNT concentration and the enhancement is from 3.0–3.1% for CNTs with a concentration of 0.01–0.1 wt% and at 25°C. The results show that one of the factors affecting the thermal conductivity enhancement is particle concentration.

A nonlinear behavior in thermal conductivity is also observed from Fig. 3. The present results show very high thermal conductivity compared to literature values as observed from Fig. 4. Present experimental results give the highest thermal conductivity enhancement at very low CNT concentration as compared to other groups of researchers [17–20]. An important parameter responsible for higher thermal conductivity enhancement is stability which plays a major role in homogeneously dispersing the CNTs in the aqueous solution and thus minimizing the effect of sedimentation. Apart from stability it should be noted that the particle aspect ratio, temperature, particle specification, purity, method of preparation, and surfactant used also affects the thermal conductivity results. Table 2 gives the details of the experiments of all the researchers compared in Fig. 4.

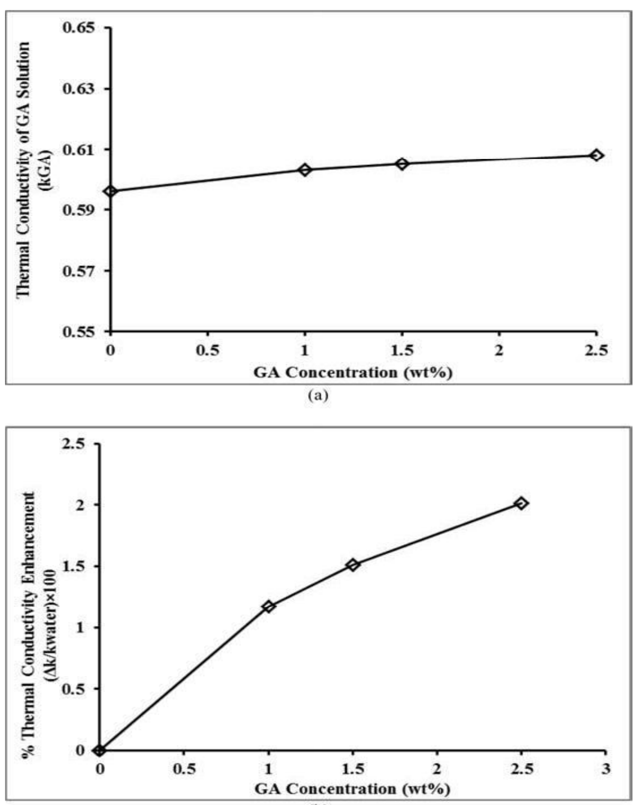

Fig. 2. Effect of GA Concentrations on Thermal Conductivity of Water: (a) Effective Thermal Conductivity; (b) Percentage Enhancement.

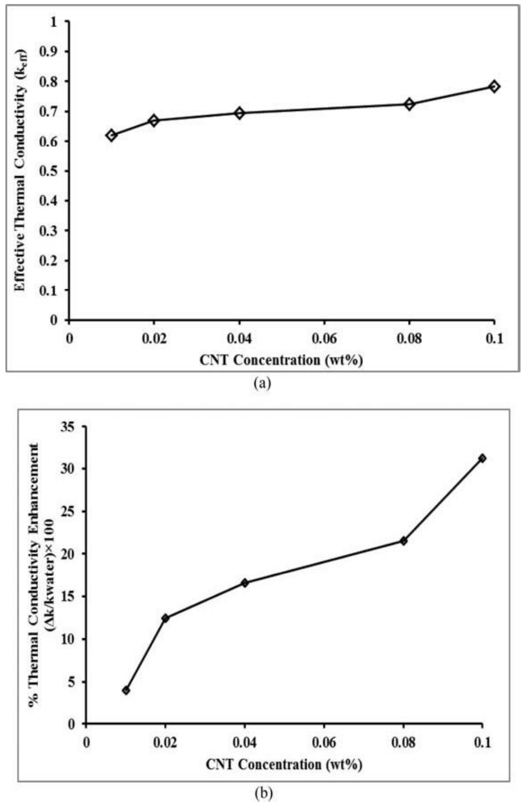

Fig. 3. Effect of CNT Concentrations on Thermal Conductivity of CNT Nanofluid: (a) Effective Thermal Conductivity; (b) Percentage Enhancement

From Table 2, it is evident that the CNT nanofluids prepared by other research groups are not very stable and also the stability of these nanofluids is not quantitatively analyzed. Thus, the discrepancies in the experimental results not only with the present experimental results but also among the other group of researchers are quite noticeable.

5.1.3 Effect of Temperature

The effect of temperature on GA solution and CNT/GA nanofluid is studied for GA concentrations of 1.0–2.5 wt% and CNT concentrations of 0.01–0.1 wt%, respectively, from 25–60 °C as shown in Figs. 7(a) and 7(b).

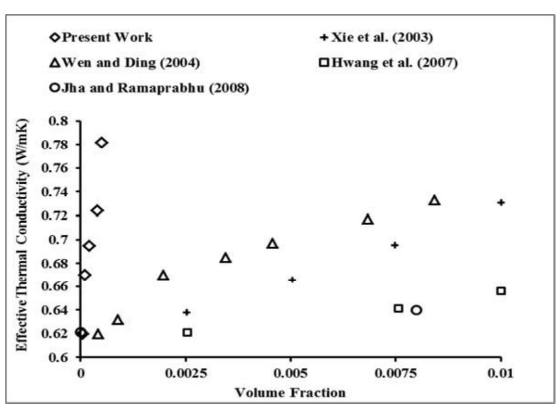

Fig. 4. Comparison on Thermal Conductivity of CNT/Water nanofluids

From Fig. 5(a), it is observed that in the presence of GA, the thermal conductivity of the base fluid is increased with an increase in temperature and it is more pronounced after 40 °C. The enhancement is also observed to be a function of GA concentration. However, in the presence of CNTs the enhancement is much greater as compared to GA alone as observed from Fig. 5(b). Brownian motion of the nanoparticles at the molecular and nanoscale level is a key mechanism governing the thermal behavior of nanofluids, which is also a strong function of temperature. Thus, it is clear from the above figures that the surfactant/dispersant added to stabilize the nanoparticles in the suspension does not have a significant role in thermal conductivity enhancement. Similarly, a non-linear thermal conductivity enhancement was also observed by Wen and Ding for CNT/water nanofluid. The enhancement leveled off at 30 °C and no reasons were given for such a behavior.

Author	Particle size	Preparation method	Stability
Present	d_p=20nm; l_p=30um	GA dispersant	Highly stable
Xie et al.[17]	d_p=20nm; l_p=30um	Treated with nitric acid and pH adjustment	Settled after 2 months
Wen and Ding [18]	d_p=40nm; l_p=30um	NaSDDBS surfactant	No studies
Hwang et al. [19]	d_p=30nm; l_p=50um	SDS surfactant	Stability measured using UV- Vis
			spectrometer, unstable
Jha and Ramaprabhu [20]	d_p=30nm;l_p=30um	Treated with nitric acid, and functionalized to add –COOH group.	20days

Table 2. Comparison on Experimental Details of CNT Nanofluids

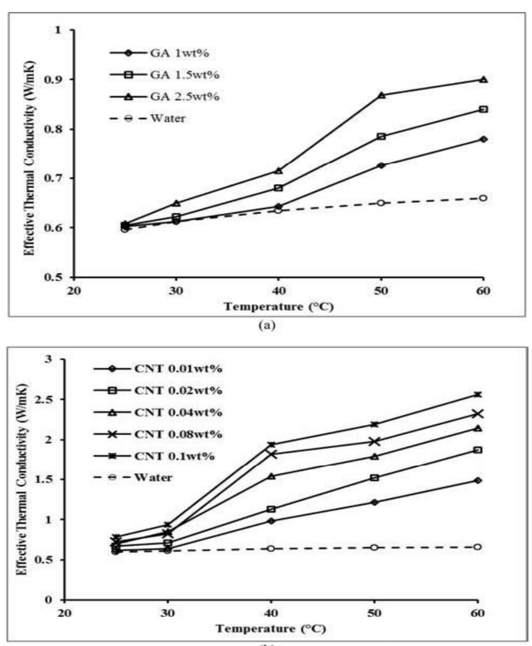

Fig. 5. Effect of Temperature on Thermal Conductivity of (a) GA Solution and (b) CNT Nanofluid

Figure 6 shows the effect of measurement time on thermal conductivity of the nanofluid at two different temperatures (25 °C and 60 °C) and CNT concentrations, respectively. It is clear from the figure that the suspension was stable throughout the thermal conductivity measurements even at higher temperature values and there is a negligible difference in the value of thermal conductivity with time. Further, during the measurement, the nanofluid was stable at all the temperature values studied and no precipitation or sedimentation was observed by Wen and Ding. The surfactant (NaDDBS) used by Wen and Ding failed at elevated temperatures and sedimentation of the nanofluid was observed.

From Table 3, it is observed that for the CNT concentrations used in this present study, the enhancement in thermal conductivity is from 4.0–125% for 0.01 wt% and 37–287% for 0.1 wt% for temperatures in the range of 25–60 °C, respectively. The large enhancement in thermal conductivity at low particle concentrations is also dependent upon the stability of the suspension. This concludes that there are several factors on which the thermal conductivity enhancement is dependent such as stability, volume fraction of the nanoparticles, dispersant concentration, aspect ratio of the CNTs, and temperature.

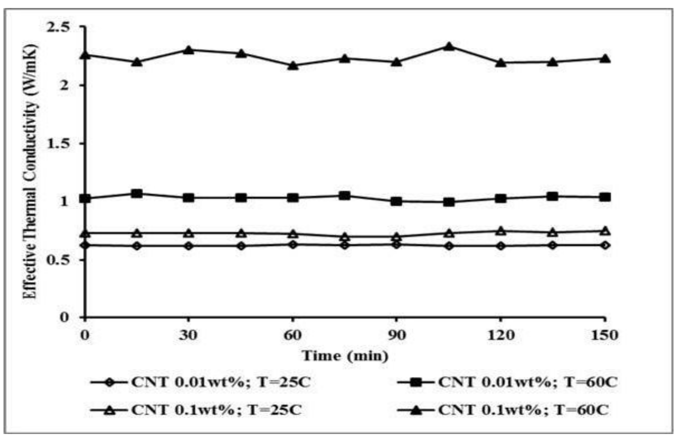

Fig. 6. Effect of Measurement Time on Thermal Conductivity of CNT/GA Nanofluid

Table 3. Thermal Conductivity Enhancement of CNT Nanofluids in the Presence of GA

CNT (wt %)	% Enhancement in thermal conductivity with respect to water and GA as a dispersant				
	25°C	30°C	40°C	50°C	60°C
0.01	4.03	10.9	42.6	87.2	125.6
0.02	12.4	22.4	78	133.7	183.3
0.04	20.8	38.7	114.7	175.2	224.2
0.08	31.6	50.9	164.6	204.5	251.5
0.1	37.4	73.6	189.8	236.8	287.5

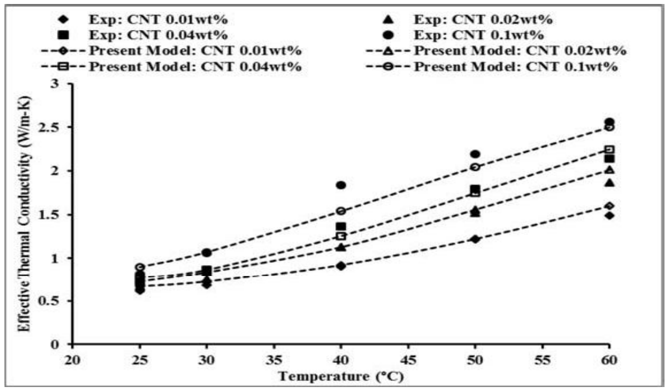

Fig. 7. Comparison of Present Experimental Work with Proposed Model as a Function of Temperature

Figure 7 shows the model comparison with the present experimental work as a function of temperature. The model could effectively predict the effect of temperature on the thermal conductivity enhancement of CNT nanofluids. This excellent agreement of experimental data with the proposed model also suggests that the effect due to the length and diameter of the CNT and the temperature of measurement cannot be ignored in the thermal conductivity of nanofluids.

6. Conclusion

Highly stable CNT nanofluids were obtained in the presence of GA. It can be concluded that the thermal conductivity enhancement not only depends on the volume fraction and temperature but also on the stability of the nanofluids. A model for the effective thermal conductivity of CNT-based nanofluids was validated with present and previous experimental results within the accuracy limits. Compared to the conventional models, the present model not only considers the dependence of thermal conductivity on the CNTs, base fluid, and volume fraction but also temperature, length, and aspect ratio. This model presents a simple form and gives excellent agreement with the experimental data.

References

1. Masuda H, Ebata A, Teramae K, Hishinuma N. Alteration of thermal conductivity and viscosity of liquid by dispersing ultrafine particles (dispersion of c-Al2O3, SiO2, and TiO2 ultra-fine particles). Netsu Bussei 1993.
2. Choi SUS. Enhancing thermal conductivity of fluids with nanoparticles. ASME Fluids Eng Div (Publ) 1995.
3. Baughman RH, Zakhidov AA, de Heer HA. Carbon nanotubes—The route towards applications. Science 2002.
4. Coleman JN, Khan U, Blau WJ, Gunko YK. Small but strong: A review of the properties of carbon nanotube-polymer composites. Carbon 2006.
5. Nuriel S, Liu L, Barber HA, Wagner HD. Direct measurement of nanotube surface tension. Chem Phys Lett 2005.

6. Rashmi W, Ismail, AF Sopyan I, Jameel AT, Yusof F, Khalid M, Mujawar M. Stability and thermal conductivity enhancement of carbon nanotube (CNT) nanofluid using gum Arabic. J Experi Nanosci, iFirst 1-13 2011;(DOI:10.1080/ 17458080.2010.487229).
7. Maxwell JC. A treatise on electricity and magnetism. Clarendon Press; 1873.
8. Hamilton RL, Crosser OK. Thermal conductivity of heterogeneous two-component systems. Ind Eng Chem Fundam 1962.
9. Jeffrey DJ. Conduction through a random suspension of spheres. Proc Royal Soc London 1973.
10. Davis RH. The effective thermal conductivity of a composite material with spherical inclusions. Int J Thermo Phys 1983.
11. Hemanth Kumar D, Patel HE, Rajeev Kumar VR, Sundararajan T, Pradeep T, Das SK. Model for heat conduction in nanofluids. Phys Rev Lett 2004.
12. Patel HE. Experimental and theoretical investigation on thermal conductivity enhancement of nanofluids. PhD Thesis, Indian Institute of Technology Madras Chennai, India, 2004.
13. Hansen JP, McDonald IR. Theory of simple liquids. Academic Press; 1976.
14. Einstein A. Über Die Von Der Molekularkinetischen Theorie Der Wärme Geforderte Bewegung Von In Ruhenden Flüssigkeiten Suspendierten Teilchen. Annalen der Physik 1905.
15. Shukla RK, Dhir VK. Study of the effective thermal conductivity of nanofluids. In: Proceedings of IMECE 2005 ASME International Mechanical Engineering Congress And Exposition, Orlando, Florida, USA, 2005.
16. Dhont JKG. An introduction to dynamics of colloids. 2 Elsevier Netherland; 2003.
17. Xie H, Lee H, Youn W, Choi SUS. Nanofluids containing multiwalled carbon nanotubes and their enhanced thermal conductivities. J App Phy 2003.
18. Wen D, Ding Y. Experimental investigation into convective heat transfer of nanofluids at the entrance region under laminar flow conditions. Int J Heat Mass Transfer 2004.
19. Hwang Y, Lee JK, Lee CH, Jung YM, Cheong SI, Lee CG, Ku BC, Jang SP. Stability and thermal conductivity characteristics of nanofluids. Thermochim Acta 2007.
20. Jha N, Ramaprabhu S. Synthesis and thermal conductivity of copper nanoparticle decorated multiwalled carbon nanotubes based nanofluids. J Phys Chem C 2008.