Original Research Article

Calculation the Thermal Conductivity of Nanofluids containing Aligned Ultralong Single Walled Carbon Nanotubes

ABSTRACT

The thermal conductivity of carbon nanotubes (CNTs) depends on their length and the diameter. At room temperature, the thermal conductivity of CNTs increases as its length increases as well as its diameter decreases. Aligned long single-walled carbon nanotubes (AL-SWCNTs) are expected to be an ideal candidate for heat transfer materials owing to their small diameter, very long length and high thermal conductivity. In this work, we propose a theory model for thermal conductivity of AL-SWCNTs in nanofluids. The calculation results showed that the thermal conductivity enhancement of AL-SWCNTs nanofluids was about 18.5 times higher than that of MWCNTs nanofluids. The calculation results have confirmed the advantage of the AL-SWCNTs as excellent additive for nanofluids.

Keywords: Aligned long SWCNTs, additive, nanofluid, thermal conducvitity

1. INTRODUCTION

Since the discovery of the carbon nanotube (CNT) in 1991 [1] there have been extensive studies of its physical and chemical properties. Carbon nanotubes (CNTs) have attracted much attention because of their unique structure and remarkable mechanical, thermal and electrical properties [2-6]. Single-walled carbon nanotubes (SWNTs) are nanometer-diameter cylinders consisting of a single graphene sheet wrapped up to form a tube [7]. Yu [8] and Pop [9] and their coworkers measured the thermal conductivity of SWCNTs, and found that the thermal conductivity is near 3500 W $m^{-1}K^{-1}$ at room temperature for an SWCNT. Fujii et al [10] found in the experiment that the thermal conductivity of a carbon nanotube at room temperature increases as its diameter decreases. Mingo et al [11] found that the thermal conductivity of CNTs increases as its length increases, and thermal conductivity of CNTs reached about 4000 W $m^{-1}K^{-1}$ at 316 K with the tube length reaching one meter. However, long CNTs in composite are usually crooked; this reduces the effective thermal conductivity of CNTs [20]. Therefore, aligned long single-walled carbon (AL-SWCNTs) become the most ideal material for heat transfer owing to their small diameter, large length, unique thermal conductivity, and high orientation for heat transfer [21].

In recent years, the problem of heat dissipation with features and strengthening functions of products has become more significant. Many approaches can improve the cooling system performance. The most feasible one is to enhance the heat transfer (dissipation) performance through the working fluid without modifying the mechanical designs or key components of the system. Recent studies have shown that the thermal conductivity of the suspension which contains suspended metallic or nonmetallic nanoparticles can be much higher than that of the base fluid, and it was called as “nanofluid”[12]. On this basis, adding certain kinds of nanomaterials into base fluid is considered to be a novel approach to enhance the thermal conductivity in heat transfer medium [13]. Results showed that the thermal conductivity enhancements of nanofluids could be influenced by multifaceted factors including the volume fraction of nanoparticles, the tested temperature, thermal conductivity of the base fluid, nanoparticle size, pretreatment process, and the additives of the fluids [14, 15].

CNTs have been used as additives in liquids to increase the thermal conductivity, one of the most important issues in industry [16]. Owing to their very high thermal conductivity (above 2000 W/m.K compared to thermal conductivity of Ag 419 W/m.K) [17], CNTs become ones of the most suitable nano additives to fabricate the nanofluid for thermal dissipation in many industrial and consumer products [18, 19].

As mentioned above, AL-SWCNTs are most ideal additive for nanofluids owing to their small diameter, large length, unique thermal conductivity, and high orientation for heat transfer. In this paper, we present the calculation results on thermal conductivity enhancements of several AL-SWCNTs nanofluids.

2. CALCULATION METHOD

A model for thermal conductivity of nanofluids is derived from Hemanth et al (2004), which is given for nanoparticle suspensions [22]. This model assumed that there are two parallel paths of heat flow through the suspension, one through the liquid particles and the other through the nanoparticles. In this model, the effective thermal conductivity is expressed as [22]:

$$k_{eff} = k_m\left[1+\frac{k_p \varepsilon r_m}{k_m(1-\varepsilon)r_p}\right] \tag{1}$$

where k, r denote the thermal conductivity and radii; ε denote the volume fraction of the nanoparticles. Subscripts "*m*" and "p" denote quantities corresponding to the liquid medium and solid nano particles, respectively.

Sarit K Das et al (2008) [23] derived the expression for thermal conductivity enhancement in carbon nanotubes suspensions denoting the liquid molecule radii and CNTs diameter to be r_l and r_s as well as volume fraction of the nanoparticles as ε and the volume fraction of the liquid as (1 – ε). The effective thermal conductivity of CNTs nanofluids is expressed as [23]:

$$k_{eff} = k_l\left[1+\frac{k_s \varepsilon r_l}{k_l(1-\varepsilon)r_s}\right] \tag{2}$$

where, subscripts "*l*" and "*s*", denote quantities corresponding to the liquid medium and carbon nanotubes, respectively.

However, calculated results of the H E Patel model are higher than the experimental results. This is because the shape of CNTs are cylindrical rather than spherical, and CNTs are very good thermal conductors along the tube but good insulators laterally to the tube axis. Therefore, we developed a modified model for accurately predicting the CNT-nanofluids' thermal conductivity, which takes into consideration cylindrical shape as well as good thermal conductors along the tube of CNTs. In this modified model, we obtained the effective thermal conductivity of CNT-nanofluids is expressed as [26]:

$$\frac{k_{eff}}{k_l} = 1+\frac{1}{3}\frac{k_{CNT}\varepsilon r_l}{k_l\left(1-\varepsilon\right)r_{CNT}} \tag{3}$$

where, subscripts "*l*" and "*CNT*", denote quantities corresponding to the liquid medium and carbon nanotubes, respectively. The our modified model was compared to some experimental data of several other research groups, and the results show that modified model has correctly predicted the trends observed in experimental data. The modified model was published in Physics of Fluids in March 2015 [26].

Equation (3) shows that: the thermal conductivity of CNTs nanofluids strongly depend on diameter, volume fraction, and thermal conductivity of CNTs. As we know, thermal conductivity of SWCNTs higher than that of MWCNTs, and thermal conductivity of a carbon nanotube increases as its diameter decreases as well as its length increases [10, 11]. In other hand, the thermal conductivity of CNTs nanofluids also depend on effective length of CNTs (as figure 1) [20]. Therefore, AL-SWCNTs are the best additives for nanofluids. According to the dependence of thermal conductivity of SWCNTs on its length and diameter, (which were reported by Yu et al [8], Fujii et al [10] and Mingo et al [11]) and the model of Sarit K Das et al (2008) [23], we calculated thermal conductivity enhancement of AL-SWCNTs nanofluids by using our modified model.

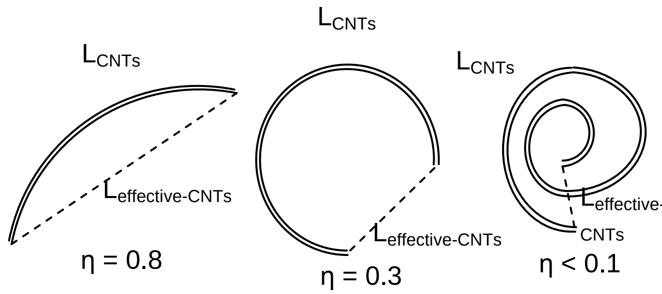

Figure 1. The effective length of some types CNTs

3. RESULTS AND DISCUSSION

3.1. Thermal conductivity of AL-SWCNTs based distilled water

The diameters of SWCNTs in our calculation were 3nm, 9.8 nm, 16.1 nm, and 28.2 nm, respectively; the lengths of SWCNTs were in the range of 2.76 – 3.70 µm. Table 1 shows the dependence of thermal conductivity of SWCNTs on its diameters at room temperature. In the calculation, thermal conductivity of distilled water (DW) and the radius of water molecule were 0.6 W/mK and 0.1 nm, respectively. The volume concentrations of SWCNTs in DW were in the range of 0.1 % – 1 %. Figure 2 shows the dependence of thermal conductivity enhancement of AL-SWCNTs nanofluids on diameter and volume concentration of AL-SWCNTs.

Table 1. The dependence of thermal conductivity of SWCNTs on its diameters at room temperature

Diameter of SWCNTs	Thermal conductivity of SWCNTs	References
3 nm	2800 W/mK	[8]
9.8 nm	2100 W/mK	[10]
16.1 nm	1600 W/mK	[10]
28.2 nm	500 W/mK	[10]

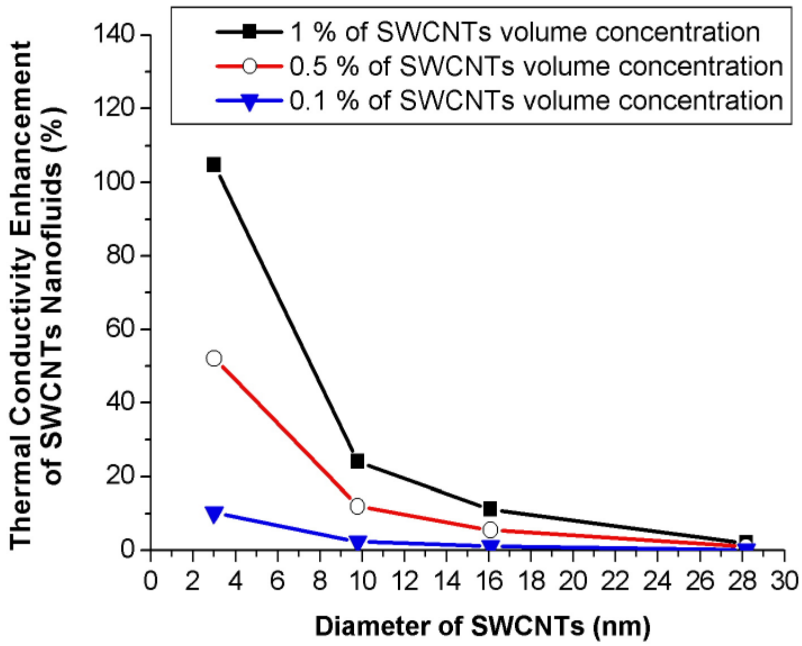

Figure 2. The dependence of thermal conductivity enhancement of AL-SWCNTs based DW on its diameter

Figure 2 showed that the thermal conductivity enhancement of SWCNTs based DW increased as volume concentration of SWCNTs increased. At 1% of volume concentration, the thermal conductivity enhancements of SWCNTs based DW were 104.7%, 24.1%, 11.2%, and 2% corresponding to diameters of SWCNTs were 3 nm, 9.8 nm, 16.1 nm, and 28.2 nm, respectively. These results indicated that thermal conductivity of SWCNTs based DW increased as diameter of SWCNTs decreased. In order to predict the effect of AL-SWCNTs length to the thermal conductivity of AL-SWCNT based DW, we choose 3 nm of the AL-SWCNTs diameter, and from 3 μm to 200 μm of the AL-SWCNTs lengths. Table 2 shows the dependence of thermal conductivity of AL-SWCNTs on its length at room temperature. Figure 3 shows the dependence of thermal conductivity enhancement of AL-SWCNTs nanofluids on length and volume concentration of AL-SWCNTs.

Table 2. The dependence of thermal conductivity of AL-SWCNTs on its length at room temperature

Length of AL-SWCNTs	**Thermal conductivity of AL-SWCNTs**	**References**
~ 3 μm	2800 W/mK	[8], [11]
10 μm	3000 W/mK	[11]
20 μm	3600 W/mK	[11]
30 μm	3900 W/mK	[11]
40 μm	4100 W/mK	[11]
80 μm	4600 W/mK	[11]
130 μm	5000 W/mK	[11]

170 μm	5000 W/mK	[11]
200 μm	5000 W/mK	[11]

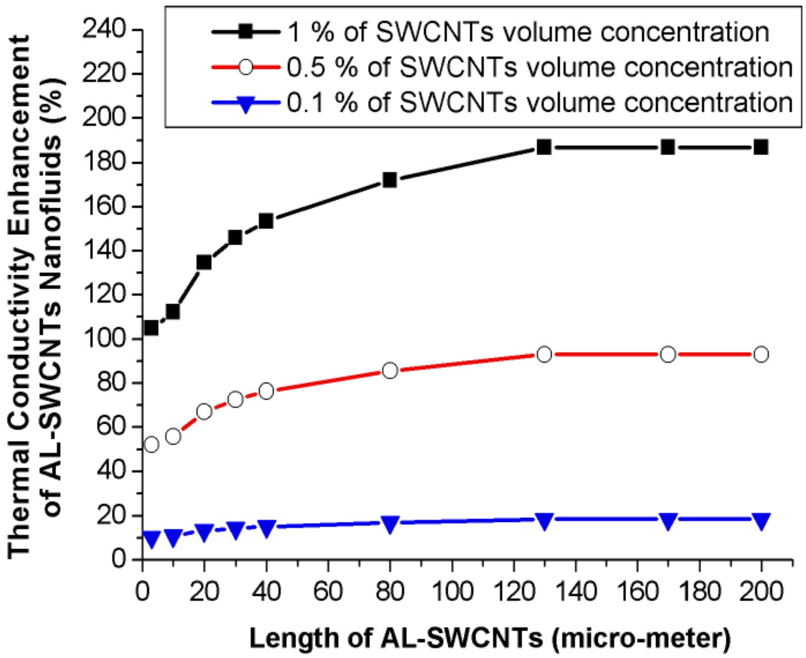

Figure 3. The dependence of thermal conductivity enhancement of AL-SWCNTs based DW on its length and volume concentration

Figure 3 show that the thermal conductivity enhancement of AL-SWCNTs based DW increased as concentration of AL-SWCNTs increased. At 1% of volume concentration, the thermal conductivity enhancements of AL-SWCNTs based DW were 104.6%, 112.2%, 134.7%, 145.9%, 153.4%, 172.1% and 187.1% corresponding to the lengths of AL-SWCNTs were 3 μm, 10 μm, 20 μm, 30 μm, 40 μm, 80 μm and 130 μm, respectively. These results indicated that thermal conductivity of AL-SWCNTs based DW increased as length of SWCNTs increased. However, thermal conductivity enhancement of AL-SWCNTs based DW reached saturated value at 187.1% when length of AL-SWCNTs reached 130 μm. Experimental data of Hwang et al (2006) [24] and Lifei Chen et al (2008) [25] indicated that the thermal conductivity enhancement of MWCNTs based DW was about 10% as volume concentration of MWCNTs was 1%. Therefore, thermal conductivity enhancement of AL-SWCNTs nanofluids was 18.7 times higher than that of MWCNTs nanofluids at 1% of CNTs volume concentration.

3.2. Thermal conductivity of AL-SWCNTs based ethylene glycol

Similarly, we calculated the thermal conductivity enhancement of AL-SWCNTs based ethylene glycol (EG) with the diameter and length of AL-SWCNTs were 3 nm and 3 μm - 200 μm, respectively. In the calculation, thermal conductivity of EG and the effective radius of EG molecule were 0.26 W/mK and 0.12 nm, respectively. The volume concentrations of AL-SWCNTs in EG were in the range of 0.1 % – 1 %. Figure 4 shows the dependence of thermal conductivity enhancement of AL-SWCNTs based EG on the length and volume concentration of AL-SWCNTs.

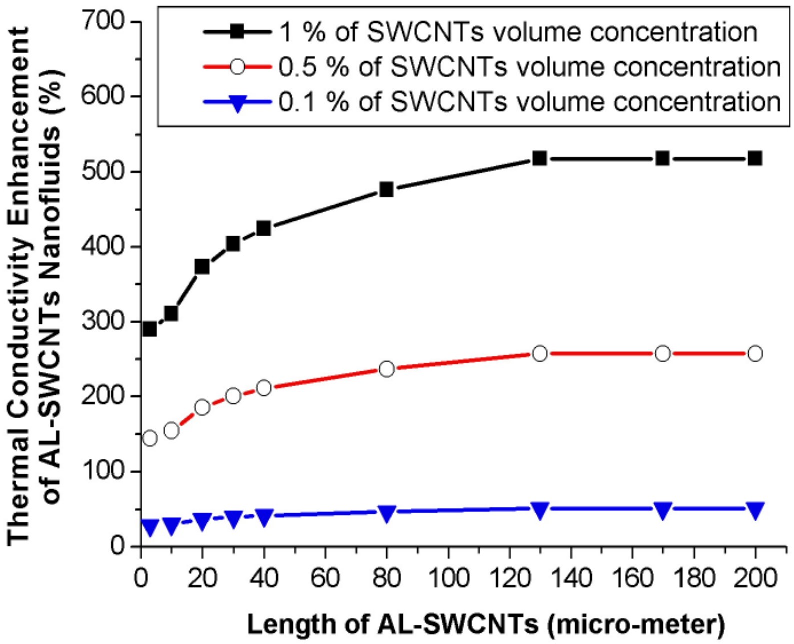

Figure 4. The dependence of thermal conductivity enhancement of AL-SWCNTs based EG on its length and volume concentration

Figure 4 showed that the thermal conductivity enhancement of AL-SWCNTs based EG increased as concentration of AL-SWCNTs increased. At 1% of volume concentration, the thermal conductivity enhancements of AL-SWCNTs based EG were 290.1%, 310.8%, 373.0%, 404.0%, 424.8%, 476.6% and 518.0% corresponding to the lengths of AL-SWCNTs were 3 µm, 10 µm, 20 µm, 30 µm, 40 µm, 80 µm and 130 µm, respectively. These results indicated that thermal conductivity of AL-SWCNTs based EG increased as length of SWCNTs increased. However, thermal conductivity enhancement of AL-SWCNTs based EG reached saturated value at 518% when length of AL-SWCNTs reached 130 µm. Experimental data of Hwang et al (2006) [24] indicated that the thermal conductivity enhancement of MWCNTs based EG was about 28% when volume concentration of MWCNTs was 1%. Therefore, thermal conductivity enhancement of AL-SWCNTs based EG was 18.5 times higher than that of MWCNTs based EG at 1% of CNTs volume concentration.

4. CONCLUSION

The thermal conductivity enhancements of AL-SWCNTs nanofluids were calculated and compared to that of MWCNTs nanofluids. The thermal conductivity enhancement of AL-SWCNTs nanofluids reached saturated values when length of AL-SWCNTs reached 130 µm. At 1% of CNTs volume concentration and 130 µm of CNTs length, the thermal conductivity enhancements of AL-SWCNTs based DW and AL-SWCNTs based EG were 187.1% and 777%, respectively. These results showed that the thermal conductivity enhancement of AL-SWCNTs nanofluids was about 18.5 times higher than that of MWCNTs nanofluids. The calculation results have confirmed the advantage of the AL-SWCNTs as excellent additive for nanofluids.

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