Modeling of Thermal Conductivity of Carbon Nanotubes-Refrigerants Fluids

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Abstract: A model has been presented to predict the thermal conductivity of CNT nanofluid systems based on several dimensionless groups including thermal conductivity of base fluid, CNTs and dimensions of nanotubes. According to the investigations, the thermal conductivity of CNT nanofluids increases nonlinearly when the concentration of CNTs are increased. The new model showed to have a great agreement with experimental data for a series of CNT–R113 (Cl2FC-CClF2) nanofluids.

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1. Introduction:

Nowadays nanofluids have shown to play a great role in many processes such as power generation, chemical production, refrigeration, transportation and many other sectors. An enhancement to thermal conductivity of these fluids makes industry more efficient and permits smaller devices and systems to be manufactured. Many investigations have been conducted to improve the thermal conductivity of heat transfer fluids (Lee et al., 1999; Wang et al., 1999; Xie et al., 2002; Murshed et al., 2005; Hwang et al., 2007; Michael et al., 2007).

One technique is to add particles with different materials which their size ranges from micrometer to millimeters to the base fluid which has shown improved thermal properties. Unfortunately, instability and clogging characteristics of these suspensions has been observed (Xuan and Li, 2000; Eastman et al., 2001; Das et al., 2003; Patel et al., 2003; Murshed et al., 2005).

Nano fluids have been developed by advances in nanotechnology. These fluids are suspensions of nanometer sized materials, in comparison with the base fluid, nanofluids have been shown to have higher thermal conductivities, more stability and the ability to not to clog even in micro sized channels. Because of their great heat transfer conductivity they are under investigation to increase heat transfer of a system (Lee et al., 1999; Wang et al., 1999; Xie et al., 2002; Murshed et al., 2005; Hwang et al., 2007; Michael et al., 2007).

As the result of recent studies carbon nanotubes were proved to have the capability to enhance the effective thermal conductivity of base fluid heat transfer (Choi et al., 2001; Xie et al., 2003; Liu et al., 2005; Ding et al., 2006; Hwang et al., 2006).

CNTs were observed to have relatively high thermal conductivity ranging from 600 to 6000 W/(mK) (Kim et al., 2001; Xue, 2005; Hwang et al., 2006).

The recent models developed by researchers could not predict the behavior of CNT nano fluids (Maxwell, 1904; Hamilton and Crosser, 1962). The reason why those models predict values that are far from experimental data is most probably because they neglect the effect of particle size and the solid - liquid interfacial properties. However these factors are proved to influence the thermal conductivity of nanofluids (Keblinski et al, 2002).

At the solid interface a layer of molecules have been formed which acts as an interfacial shell which possess a greater thermal conductivity with respect to bulk liquid, which leads to more heat transfer.

In this study a model has been developed based on dimensionless groups which are able to predict the thermal conductivity of CNT based nanofluids.

2. Thermal conductivity modeling:

Many models have been presented for effective thermal conductivity of nanofluids, the most relevant are as follows:

Maxwell model:

Maxwell model predicts the effective thermal conductivity of dilute solutions and is the basis of subsequent models. That is the classical theory of conduction to a sphere which was developed by Maxwell 1904.

$$\frac{k_{eff}}{k_m} = 1+\frac{3(\alpha-1)v}{(\alpha+2)-(\alpha-1)v} \qquad (1)$$

Where k_{eff} and k_m are the thermal conductivities of nanofluid and base fluid respectively. α is the ratio of thermal conductivity of the particle to that of the base fluid, and v is the volume fraction of the dispersed particles.

Hamilton & Crosser (H-C) model:

This model which is a modification of Maxwell equation, can predict non-spherical particles behavior (Hamilton and Crosser, 1962).

$$\frac{k_{eff}}{k_m}=\frac{\alpha+(n-1)-(n-1)(1-\alpha)}{\alpha+(n-1)+(1-\alpha)v} \qquad (2)$$

n is shape factor and is equal to 3 for spherical particles.

Xue model:

Thermal conductivity of CNT nano tubes is expressed by Xue model.(Xue,2006)

$$9(1\text{-}v)\frac{k_{eff}-k_m}{2k_{eff}-k_m}+v\left[\frac{k_{eff}-\frac{Lk_c}{L+2R_kk_c}}{k_{eff}+0.14d\left(\frac{k_c}{L+2R_kk_c}-\frac{k_{eff}}{L}\right)}\right]+$$
$$4v\left[\frac{k_{eff}-\frac{dk_c}{d+2R_kk_c}}{2k_{eff}+0.5\left(\frac{dk_c}{d+2R_kk_c}-k_{eff}\right)}\right]=0 \qquad (3)$$

Where k_c is thermal conductivity of CNTs. L and d are length and diameter of the CNTs, respectively, and R_k is the thermal resistance of the nanotube-fluid interface. For the recent study R_k is considered as 13.9E-7 $m^2 KW^{-1}$.

In this section an expression has been derived by appropriate dimensionless groups to study the effective thermal conductivity of CNTs nanofluids. This model relates effective thermal conductivity of the base fluid, CNT shell and also physical dimensions of the CNTs.

$$k_{eff}=f(k_m,k_c,d,L,v_c,) \qquad (4)$$

Where k_m is the therml conductivity of the suspending fluid, k_c is the thermal conuctivity of the CNTs, d is the diameter of the CNTs, L is the length of the CNTs and v_c is the volume fraction of CNTs. Following dimensionless groups obtained from dimensional analysis:

$$\pi_1=\frac{L}{d} \qquad (5)$$

$$\pi_2=\frac{k_m}{k_c} \qquad (6)$$

$$\pi_3=\frac{k_{eff}}{k_m} \qquad (7)$$

$$\pi_4=v_c \qquad (8)$$

π_3 is considered to be a function of the other dimensionless groups as follows:

$$\frac{k_{eff}}{k_m}=g\left(\frac{k_m}{k_c},\frac{L}{d},v_c\right) \qquad (9)$$

The effective thermal conductivity of the nanofluid is supposed to be considerably larger than that for the pure fluid as Moghadasi et al. 2009 mentioned:

$$k_{eff}> k_m \rightarrow \left(\frac{k_{eff}}{k_m}\right)>1\rightarrow\left(\frac{k_{eff}}{k_m}\right)=1+R \qquad (10)$$

Where R is an enhancement factor which is presented in the following:

$$R=\delta\left[\left(\frac{L}{d}\right)^{\alpha},\left(\frac{k_m}{k_c}\right)^{\beta},(v_c)^{\gamma}\right] \qquad (11)$$

By combining equations (10) and (11), a general expression including dimensionless groups for the effective conductivity of nanofluids is obtained:

$$\frac{k_{eff}}{k_m}=1+\delta\left[\left(\frac{L}{d}\right)^{\alpha},\left(\frac{k_m}{k_c}\right)^{\beta},(v_c)^{\gamma}\right] \qquad (12)$$

It is hypothesized that the function is in the following form:

$$\delta\left[\left(\frac{L}{d}\right)^{\alpha},\left(\frac{k_m}{k_c}\right)^{\beta},(v_c)^{\gamma}\right] = \left(\frac{L}{d}\right)^{\alpha}\left(\frac{k_m}{k_c}\right)^{\beta}(v_c)^{\gamma} \qquad (13)$$

$$\frac{k_{eff}}{k_m}=1+\left(\frac{L}{d}\right)^{\alpha}\left(\frac{k_m}{k_c}\right)^{\beta}(v_c)^{\gamma} \qquad (14)$$

A multidimensional curve fitting program has been used to fit the equation (11) on experimental data obtained from literature (Jiang et al., 2009).The parameters α,β,γ calculated by the program are listed in Table 1.

The results derived from previous models are compared with the new model and experimental data from literature. In order to compare the results, mean average relative errors are calculated and listed in Table 2.

Thermal conductivities of CNTs and R113 considered to be 6000 W/(mK) and 0.06726 W/(mK) respectively (Jiang et al., 2009).

Table 1 The constants of the new model

γ	α	β
0.190 3	**0.8901**	**0.3198**

Table 2 The mean average relative errors of models (%)

	CNT NO1 .	CNT NO2 .	CNT NO3.	CNT NO4.
MAXWELL	18.273	19.71	34.43	40.34
H-C	18.273	19.71	34.43	40.34
XUE	17.69	14.91	33.72	37.76
New model	8.16	18.24	6.25	21.74

3. Results:

The effective thermal conductivity of nanofluids has been shown to significantly increase with particle volume fraction. A linear increase with temperature has been observed in the effective thermal conductivity of nanofluids (Murshed, 2007).

The diameter and aspect ratio of CNT can influence the thermal conductivity of CNT nano refrigerents (Jiang, 2009).

It is clear from Figure1 and Figure 2 that the new model is in better agreement with experimental data over a range of CNT concentrations compared to previous models. As cited in Table2 the mean average relative errors of CNT (*d*=80 nm, a_R =18.8) and CNT (*d*=80 nm, a_R =100) are 8.1688 and 6.2596 which proves claim.

The previous models predict a linear line over experimental data, by contrast the new model relates effective thermal conductivity with nano particle volume fraction in an exponential mode.

Maxwell and H-C models were developed for large particles and failed to closely predict the behavior of CNT-R113 nanoparticles. In the H-C model dimensions of nanoparticles are not taken into account then in comparison with the new model it deviates much more from experimental data.

Despite the Xue model has more parameter than the equation (14), it poorly fits the experimental data .The poor fit is clear for d=80nm, a_R=18.8 and d=15nm, a_R=100 CNT-R113 nanofluids.

The new model is in a simple form and takes the most important factors governing the effective thermal conductivities of CNT nanofluids into account. This model has been shown to have a great agreement with thermal conductivity experimental data.

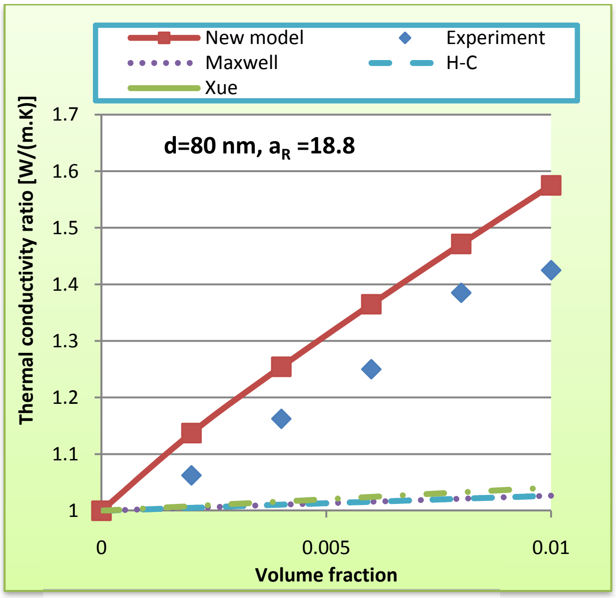

Figure 1. Thermal conductivities of carbon nanotubes (*d*=80 nm, a_R =18.8) versus volume fraction for various models and experimental data.

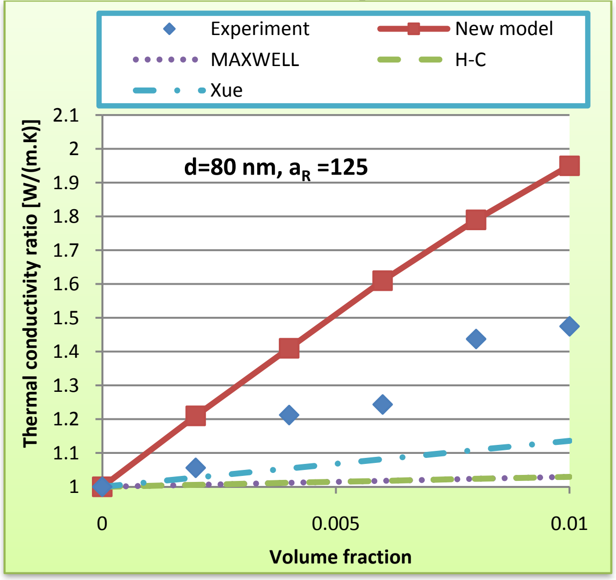

Figure 2. Thermal conductivities of carbon nanotubes (*d*=80 nm, a_R =125) versus volume fraction for various models and experimental data.

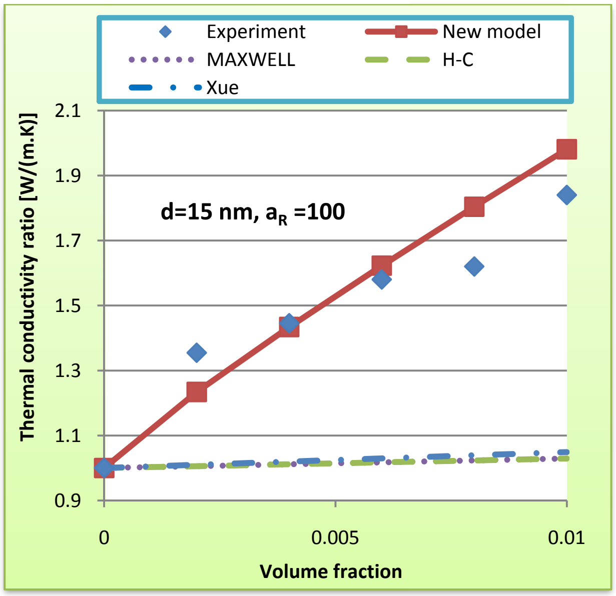

Figure 3. Thermal conductivities of carbon nanotubes (*d*=15 nm, a_R =100) versus volume fraction for various models and experimental data.

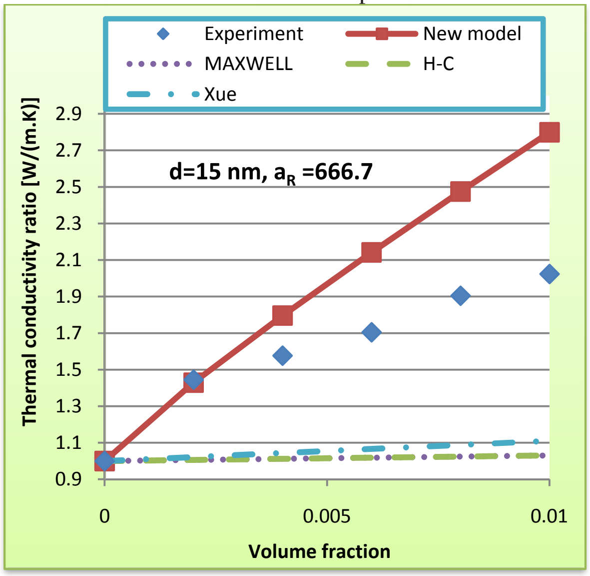

Figure 4. Thermal conductivities of carbon nanotubes (*d*=15 nm, a_R =666.7) versus volume fraction for various models and experimental data.

4.Conclusion:

The model is in good agreement with experimental data compared to several recently developed models. This model is in a simple form and its exponential form leads to better covering of experimental thermal conductivity CNT-R113 nanofluid data. Furthermore not only the model consider dependence of thermal conductivity on the CNT particle, base fluid and volume fraction but also on the dimensions of particles, which play an important role in effective thermal conductivity. The model can readily be applied to the other CNT nanofluid systems.

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