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Measurement and model on thermal conductivities of carbon nanotube nanorefrigerants

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ABSTRACT

The objective of this study is to test thermal conductivity characteristics of CNT nanorefrigerants and to build a model for predicting the thermal conductivities of CNT nanorefrigerants. The influences of CNT diameters and CNT aspect ratios on nanorefrigerant's thermal conductivity were reflected in the experiments, and R113 was used as the host refrigerant for the convenience of the experiments. The experimental results show that the thermal conductivities of CNT nanorefrigerants are much higher than those of CNT–water nanofluids or spherical-nanoparticle-R113 nanorefrigerants. Experiments also show that the smaller the diameter of CNT is or the larger the aspect ratio of CNT is, the larger the thermal conductivity enhancement of CNT nanorefrigerant is. The existent models for predicting thermal conductivity of CNT nanofluid, including Hamilton–Crosser model, Yu–Choi model and Xue model, were verified by the experimental data of CNT nanorefrigerants' thermal conductivities. The verification shows that Yu–Choi model has the mean deviation of 15.1% and it is more accurate than the other two models. A modified Yu–Choi model was presented by improving the empirical constant of Yu–Choi model, and the mean deviation of the modified Yu–Choi model from the experimental results is 5.5%.

1. Introduction

The nanofluid is a new type of heat transfer fluid by suspending nano-scale materials in a conventional host fluid and has higher thermal conductivity than the conventional host fluid [1–10]. The nanorefrigerant is one kind of nanofluid and its host fluid is refrigerant [11]. A nanorefrigerant has higher heat transfer coefficient than the host refrigerant and it can be used to improve the performance of refrigeration systems [11,12]. The heat transfer coefficient of a fluid with higher thermal conductivity is lager than that of a fluid with lower thermal conductivity if the Nusselt numbers of them are the same. So researches on improving thermal conductivities of nanorefrigerants are necessary.

There are two methods to improve the thermal conductivity of a nanorefrigerant. The first one is to increase the volume fraction of nano-scale materials in the nanorefrigerant, and the second one is to use nano-scale materials with high thermal conductivity. As the increase of the volume fraction of nano-scale materials may result in deposition of the nano-scale materials and instability of the nanorefrigerant, the usage of the first method is limited and the second one becomes quite interesting. The thermal conductivity of a carbon nanotube (CNT) is much higher than the thermal conductivity of a metal nanoparticle or a metal oxide nanoparticle [13,14], therefore CNTs become very valuable nano-scale materials in the application of the second method to improve the thermal conductivity. The effects of CNTs on enhancing the thermal conductivities of nanofluids have been validated in a CNT–oil nanofluid [15] and a Cu–oil nanofluid [16], and it is believed that CNTs will also have their capability of enhancing thermal conductivities of nanorefrigerants.

Experiments showed that the effect of a CNT on thermal conductivity enhancement of nanofluid depends on the diameter and the aspect ratio (ratio of length to diameter) of the CNT [17–21]. In order to get a suitable CNT for nanorefrigerant, the thermal conductivity characteristics of CNT nanorefrigerants with different CNTs' diameters and aspect ratios should be studied experimentally and theoretically. Then a model for predicting thermal conductivity of a CNT nanorefrigerant should be proposed and the input variables of the model should include the diameter and the aspect ratio of a CNT.

Thermal conductivities of some CNT nanofluids, such as CNT–water [17,21], CNT–oil [15], CNT–decene [18] and CNT–ethylene glycol [18], have been experimentally investigated. But there is no experimental research on CNT nanorefrigerants, and the influences of the CNT diameter and the CNT aspect ratio on the nanofluid's thermal conductivity have not been reported in the existing researches. Comparing to sufficient models for thermal conductivities of nanofluids containing spherical nanoparticles, there are only three models for CNT nanofluids, i.e. Yu–Choi model [19], Xue model [20] and Hamilton–Crosser model [22]. Hamilton–

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Nomenclature

d	diameter of carbon nanotube	m
k_{nf}	thermal conductivity of nanofluid or nanorefrigerant	$W\,m^{-1}\,K^{-1}$
k_f	thermal conductivity of pure fluid or refrigerant	$W\,m^{-1}\,K^{-1}$
k_{CNT}	thermal conductivity of carbon nanotube	$W\,m^{-1}\,K^{-1}$
L	length of carbon nanotube	m
R	electric resistance	Ω
r	radius	m
W	power	W
t	measuring time	s
φ	volume fraction of carbon nanotube in fluid or refrigerant	
W	power	W
α	temperature coefficient	K^{-1}
ΔT	temperature rise	K
κ	thermal diffusivity of fluid	$m^2\,s^{-1}$

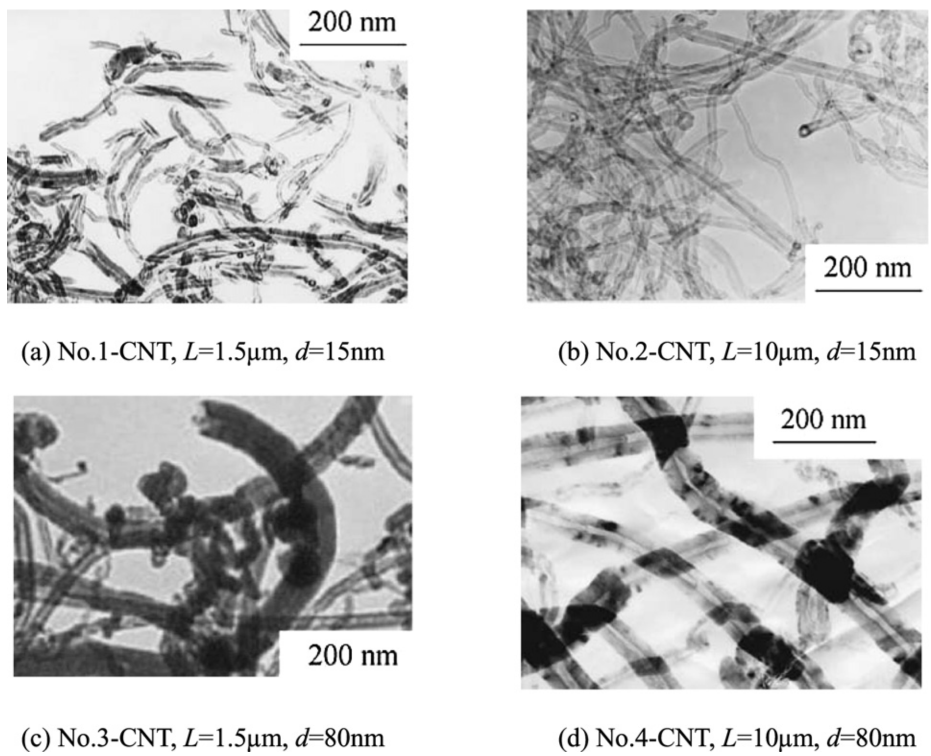

Fig. 1. Transmission electron microscope photos of the CNTs.

Crosser model and Yu–Choi model show their suitability for CNT–oil nanofluid [19] while Xue model shows its suitability for CNT–decene nanofluid and CNT–ethylene glycol nanofluid [20]. However, the applicability of these three models for CNT nanorefrigerants has not been validated.

The objective of this study is to know thermal conductivity characteristics of CNT nanorefrigerants by experiments and then to build a model for predicting the thermal conductivities of CNT nanorefrigerants. The experiments should reflect the influences of CNT diameters and CNT aspect ratios. In order to build a suitable model for the thermal conductivity of CNT nanorefrigerants, it is better to validate and to find a suitable model from the existing models for CNT nanofluids, i.e. Yu–Choi model, Xue model and Hamilton–Crosser model, or to build a new model based on the existing models.

2. Preparation and characterization of CNTs and CNT nanorefrigerants

2.1. Preparation and characterization of CNTs

Four kinds of CNTs employed in this research are produced by the chemical vapor deposition (CVD) method [23]. The CVD method can offer several advantages over the sputtering and evaporation methods which are other two common methods for preparing nano-scale materials. It can provide good coverage, reduced system complexity, and high purity deposits.

The four kinds of CNT are numbered as Nos. 1 to 4 in this research. The transmission electron microscope photos of the CNTs are shown in Fig. 1. The diameters of Nos. 1-, 2-, 3- and 4-CNTs are 15, 15, 80, and 80 nm, respectively; and the aspect ratio of Nos. 1-, 2-, 3- and 4-CNTs are 100.0, 667.7, 18.8 and 125.0, respectively. The detailed parameters of the CNTs are listed in Table 1.

Table 1
Parameters of CNTs.

Item	No.1-CNT	No.2-CNT	No.3-CNT	No.4-CNT
Mean diameter (d)	15 nm	15 nm	80 nm	80 nm
Mean length (L)	1.5 μm	10 μm	1.5 μm	10 μm
Aspect ratio	100.0	666.7	18.8	125.0
Purity	>95%	>95%	>95%	>95%
Amorphous carbon	<2%	<2%	<2%	<2%
Ash	<0.2 wt%	<0.2 wt%	<0.2 wt%	<0.2 wt%
Specific surface	160–180 $m^2\,g^{-1}$	160–180 $m^2\,g^{-1}$	55–65 $m^2\,g^{-1}$	55–65 $m^2\,g^{-1}$

2.2. Preparation and characterization of CNT nanorefrigerants

R113 (Formula: $Cl_2FC\text{-}CClF_2$; CAS Number: 76-13-1) is chosen as the refrigerant in experiment based on the following two reasons: (1) R113 is in the liquid state at room temperature and atmospheric pressure, and so it is easy to prepare a nanorefrigerant based on R113 instead of commonly used refrigerants; (2) The thermal conductivity deviation of R113 from other refrigerants such as R134a and R410A, is quite smaller than that of refrigerants from water, oil, decene and ethylene glycol, and so thermal conductivity characteristics of nanorefrigerant based on R113 can reflect those of other nanorefrigerants.

Experiments showed that CNTs would aggregate and form non-homogeneous and unstable clusters in the CNT nanofluids [17,21]. However, the ultrasonic processor can make the CNTs well dispersed in the refrigerant [17,21]. So an ultrasonic processor with 300 W power supply is used in the experiment.

The detailed procedure on CNT nanorefrigerant's preparation is as follows.

Step 1: Weighing the CNT by a digital electronic balance, and putting them into a vessel.
Step 2: Weighing the pure refrigerant by a digital electronic balance, and putting them into the vessel with CNT.
Step 3: Vibrating the vessel containing the mixture of refrigerant and CNT with an ultrasonic processor for 30 minutes.

The volume fractions of CNTs in each kind of CNT nanorefrigerant are 0.2, 0.4, 0.6, 0.8 and 1.0 vol%, respectively. The test temperature and pressure of CNT nanorefrigerant are 303 K and 101 kPa. The thermal conductivity of pure R113 is 0.06726 $W\,m^{-1}\,K^{-1}$ at 303 K and 101 kPa.

3. Experiments on thermal conductivity of CNT nanorefrigerant

3.1. Experimental setup

In order to measure the thermal conductivity of the CNT nanorefrigerant, a thermal constants analyzer produced by Hot Disk Company is employed. The thermal constants analyzer uses the transient plane source (TPS) method to measure the thermal conductivity of a nanofluid [24]. The TPS method use the Fourier Law of heat conduction as its fundamental principle for measuring the thermal conductivity, just like the transient hot wire (THW) method. As the uncertainties of the TPS and THW methods [25] are about 5%, and the most enhancements of nanofluids' thermal conductivities to pure fluids' thermal conductivities in experiments are higher than 10%, the majority of nanofluids' thermal conductivities are measured by the TPS method [26–31] or THW method [1,2,4,6,8,9,21]. Some researchers pointed out that the TPS and THW methods ignored the influence of thermal wave effects via hyperbolic heat conduction so the two methods might be not fit for heterogeneous suspensions, such as nanofluids [32]. However, the TPS and THW method are commonly used for measuring nanofluids' thermal conductivities [1,2,4,6,8,9,21,26–31]. So in research here, the thermal conductivities of CNT nanorefrigerants are also measured by the thermal constants analyzer.

The experimental setup is schematically shown in Fig. 2. The setup includes a thermal constants analyzer, a vessel, a constant temperature bath and a thermometer. The thermal constants analyzer has a probe and the probe is immersed in the nanorefrigerant vertically. The nanorefrigerant is put in the vessel. The vessel is placed in the constant temperature bath and the thermometer is immersed in the vessel to measure the temperature of the nanorefrigerant.

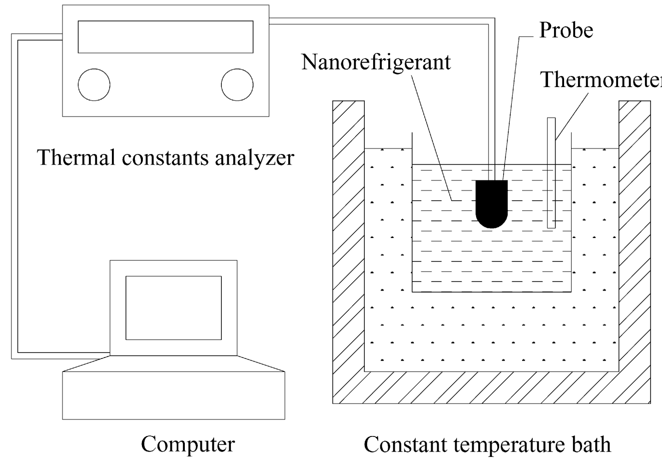

Fig. 2. Schematic diagram of the experimental setup.

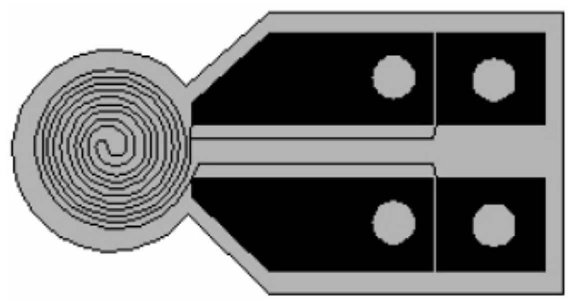

Fig. 3. Schematic diagram of TPS probe.

3.2. The probe

According to the TPS method, the fluid's thermal conductivity is yielded by measuring the resistance of the probe which is immersed into the fluid [24]. The probe consists of an electrical conducting pattern of thin foil and an insulating layer, just as Fig. 3 shows.

When a constant electric power is supplied to the probe, the temperature rise of the probe, $\Delta T(\tau)$, can be measured by the probe resistance with time, $R_p(\tau)$:

$$\Delta T(\tau) = \frac{1}{\alpha}\left[\frac{R_p(\tau)}{R_0} - 1\right] \tag{1}$$

where α is the temperature coefficient of the electric resistance; R_0 is the electric resistance of the probe when $\tau = 0$; τ is the variable on the time of electrification and be defined as:

$$\tau = \sqrt{\frac{t\kappa}{r_p^2}} \tag{2}$$

where t is the measuring time; κ is the thermal diffusivity of fluid; r_p is the radius of the probe.

According to Fourier Law of heat conduction, if no natural convection of a fluid occurs, $\Delta T(\tau)$ can also be calculated as [24]:

$$\Delta T(\tau) = \frac{W}{\pi^{1.5} r_p k} D(\tau) \tag{3}$$

$$D(\tau) = \int_0^\tau d\sigma\,\sigma^{-2}\int_0^1 v\,dv\int_0^1 u\,du \times \exp\left(\frac{-u^2 - v^2}{4\sigma^2}\right) I_0\left(\frac{uv}{2\sigma^2}\right) \tag{4}$$

where W is the electric power supplied to the probe; k is the thermal conductivity of fluid; I_0 is a modified Bessel function.

Table 2
Parameters of the thermal constants analyzer.

Amount of probe	Power	Measurement time	Probe radius	Temperature coefficient of resistance	Disk type	Temperature rise of probe
1	0.01W	5 s	2.001 mm	0.471 K^{-1}	Kapton	1.4 K

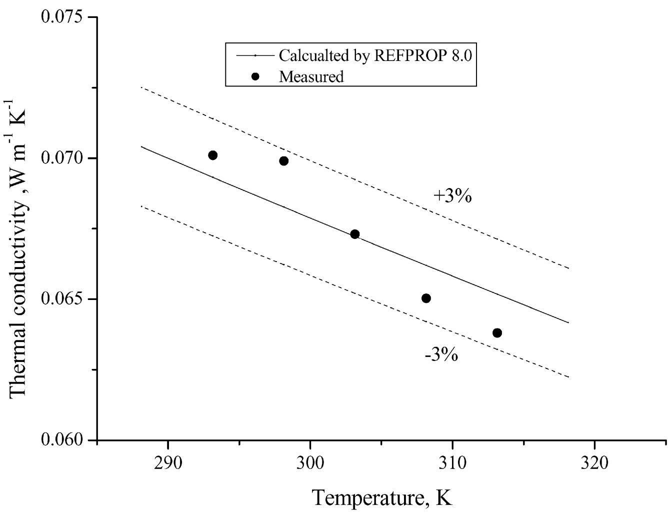

Fig. 4. Validation of the thermal constants analyzer with R113.

If no natural convection of a fluid occurs, by fitting the experimental data to the straight line given by Eq. (3), the thermal conductivity of fluid can be obtained by calculating the value of slope for the fitting line $W/(\pi^{1.5} r_p k)$. If natural convection of fluid occurs, the thermal conductivity calculated by Eq. (3) will vary with $D(\tau)$, and the result is not correct. In this case, the thermal constants analyzer can automatically give an alarm to avoid using the unbelievable result.

In order to avoid the happening of natural convection, the parameters of the analyzer should be controlled properly. In the experiment, the parameters of the thermal constants analyzer are shown in Table 2.

3.3. Validation of the thermal constants analyzer

In order to test the thermal constants analyzer in this research, the thermal conductivities of pure R113 in different temperature are measured directly on an absolute basis. The deviation of the measured data from those calculated by REFPROP 8.0 [33] is less than 3%, as shown in Fig. 4.

3.4. Experimental procedure

Following shows the experimental procedure.

Step 1: Putting the CNT nanorefrigerant into a vessel placed in a constant temperature bath.
Step 2: Immersing the probe of thermal constants analyzer and a thermometer into the nanorefrigerant vertically.
Step 3: Adjusting the temperature of CNT nanorefrigerant to 303 K.
Step 4: Measuring the thermal conductivity of nanorefrigerant by the thermal constants analyzer for three times to get the average.

4. Measuring results and discussion

Fig. 5 shows the experimental k_{nf}/k_f of CNT-R113 nanorefrigerants, where k_{nf} and k_f mean the thermal conductivities of nanorefrigerant and pure refrigerant, respectively. It can be seen that the thermal conductivities of CNT nanorefrigerants increase significantly with the increase of the CNT volume fraction. When the CNT volume fraction is 1.0 vol%, the experimental thermal conductivities of No.1-CNT-, No.2-CNT-, No.3-CNT- and No.4-CNT-R113 nanorefrigerants increase 82%, 104%, 43% and 50%, respectively.

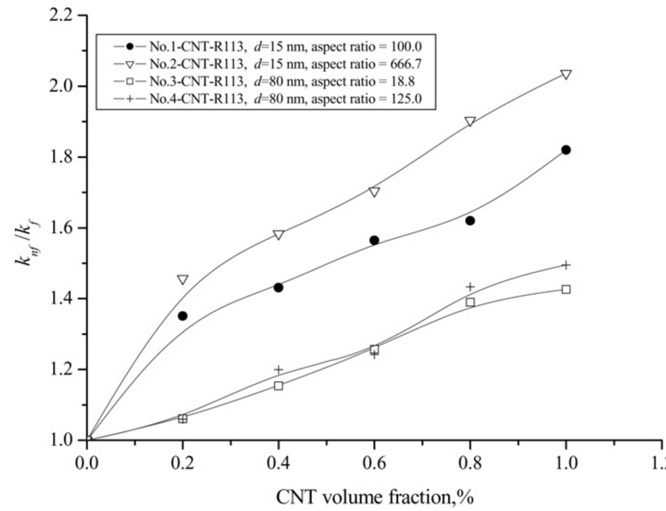

Fig. 5. k_{nf}/k_f of four kinds of CNT-R113 nanorefrigerants.

The experimental results in Fig. 5 show that the thermal conductivities of nanorefrigerants with different kinds of CNTs are different. For the No.3-CNT whose diameter is 80 nm and aspect ratio is 18.8, k_{nf}/k_f is 1.43 when φ is 1.0 vol%. The enhancement of the No.3-CNT-nanorefrigerant's thermal conductivity to pure refrigerant's thermal conductivity is close to the experimental results of CNT-decene [18], in which k_{nf}/k_f is 1.20 when φ is 1.0 vol%. For the No.2-CNT whose diameter is 15 nm and aspect ratio is 666.7, k_{nf}/k_f is 2.04 when φ is 1.0 vol%. The enhancement is close to the experimental results of CNT-Oil [15], in which k_{nf}/k_f is 2.60 when φ is 1.0 vol%. Since the CNTs in this research were prepared by the same method and the purities of CNTs are the same, it indicates that the influences of CNT's diameter and aspect ratio on the thermal conductivity of nanorefrigerants are obvious. So the influences of CNT's diameter and aspect ratio should be analyzed.

4.1. Influence of diameter of CNT on thermal conductivity

As Fig. 5 shows, the thermal conductivities of nanorefrigerants with No.1-CNT and No.2-CNT whose diameters are 15 nm are much higher than those of nanorefrigerants with No.3-CNT and No.4-CNT whose diameters are 80 nm. The smaller diameter means the larger specific surface of CNTs and the larger specific surface means more obvious Brownian movement which is regarded as an important factor to increase the thermal conductivity of nanofluid [4,7,10]. Moreover, larger specific surface means that there are more liquid molecules close to the surface of CNT if the volume fractions of CNTs are the same. These liquid molecules can form a layer structure, called interfacial layer [34]. The interfacial layer on the nanoparticle surface can increase the thermal conductivity of nanofluids [3,19,35]. So the smaller diameter means the thicker interfacial layer and the greater thermal conductivity enhancement.

4.2. Influence of aspect ratio of CNT on thermal conductivity

As Fig. 5 shows, for the CNTs with the same diameter, the larger the aspect ratio of CNT is, the higher the thermal conductivity of nanorefrigerant is. The reason may be that the CNT can build up high thermal conductivity percolation paths to enhance the thermal conductivity of the refrigerant. The longer the percolation path is, the greater the enhancement of thermal conductivity is. Higher aspect ratio means longer percolation path and the greater thermal conductivity enhancement. So the CNT with high aspect ratio could be used to enhance the thermal conductivity of nanorefrigerant.

Fig. 5 also shows the thermal conductivity of No.1-CNT-nanorefrigerant is higher than that of No.4-CNT-nanorefrigerant though the aspect ratio of No.4-CNT is larger than that of No.1-CNT. The reason may be that No.1-CNT's diameter is less than No.4-CNT's. It means that the influence of aspect ratio of CNT on nanorefrigerant's thermal conductivity is less than that of diameter.

4.3. Comparison of thermal conductivities among CNT nanorefrigerants, CNT–water nanofluids and spherical-particle nanorefrigerants

The thermal conductivities of four kinds of CNT–water nanofluids and five kinds of spherical-nanoparticle-R113 nanorefrigerants were measured and then compared with the experimental results of thermal conductivities of CNT-R113 nanorefrigerants. The spherical nanoparticles in the experiments include copper, aluminum, nickel, copper oxide and aluminum oxide nanoparticles. The volume fractions of CNT and nanoparticles in above nanorefrigerants and nanofluids are 0.2 vol%. The comparison is shown in Fig. 6. It can be seen that the thermal conductivities of CNT nanorefrigerants are higher than the thermal conductivities of CNT–water nanofluids and spherical-nanoparticle-nanorefrigerants. The results show that the CNT is better than other nano-scale materials in improving thermal conductivities of nanorefrigerants.

Experimental results in Fig. 6 show that k_{nf}/k_f of CNT-R113 nanorefrigerant is larger than that of CNT–water nanofluid with the same CNT volume fraction. The reason may be that k_{CNT}/k_f for CNT-R113 nanorefrigerant is one order of magnitude larger than that of CNT–water nanofluid. Therefore, the enhancement on thermal conductivity of CNT-R113 nanorefrigerant is more obvious than that of CNT–water nanofluid.

Experimental results show that the smaller the diameter of CNT is or the larger the aspect ratio of CNT is, the higher the thermal conductivity of CNT–water nanofluid is. The influences of CNT's diameter and aspect ratio on thermal conductivities of CNT–water nanofluids are as the same as those on CNT nanorefrigerants. It proves that the analysis of influences of CNT's diameter and aspect ratio in Sections 3.1 and 3.2 is fit for other CNT nanofluids.

5. On modeling the thermal conductivity of CNT nanorefrigerants

Yu–Choi model, Xue model and Hamilton–Crosser model are the existing models for predicting thermal conductivities of CNT nanofluids. In order to find the model for predicting thermal conductivities of CNT nanorefrigerants, it is better to validate the possibility of using these existing models for nanorefrigerants.

In Yu–Choi model [19], k_{nf} can be calculated by Eqs. (5) and (6):

$$k_{nf} = \left(1 + \frac{3\psi^{-\alpha}\varphi A}{1-\varphi A}\right)k_f \tag{5}$$

$$\alpha = 1.55 \tag{6}$$

where k_{nf} and k_f are thermal conductivities of nanofluid and pure fluid respectively; ψ is the parameter on sphericity; φ is volume fraction of CNT in fluid; A is the parameter on thermal conductivity of CNT.

In Xue model [20], k_{nf} can be calculated from Eq. (7):

$$9(1-\varphi)\frac{k_{nf}-k_f}{2k_{nf}+k_f} + \varphi\left[\frac{k_{nf} - \frac{Lk_{\mathrm{CNT}}}{L+2R_k k_{\mathrm{CNT}}}}{k_{nf} + 0.14d\left(\frac{k_{\mathrm{CNT}}}{L+2R_k k_{\mathrm{CNT}}} - \frac{k_{nf}}{L}\right)} + 4\frac{k_{nf} - \frac{dk_{\mathrm{CNT}}}{d+2R_k k_{\mathrm{CNT}}}}{2k_{nf} + 0.5\left(\frac{dk_{\mathrm{CNT}}}{d+2R_k k_{\mathrm{CNT}}} - k_{nf}\right)}\right] = 0 \tag{7}$$

where k_{nf}, k_f and k_{CNT} are thermal conductivities of nanofluid, pure fluid and CNT, respectively; φ is volume fraction of CNT in fluid; L and d are length and diameter of CNT, respectively; and R_k is an empirical constant. The value of R_k is $13.9 \times 10^{-7}\ \mathrm{m^2\,K\,W^{-1}}$ as Xue recommended.

In Hamilton–Crosser model [22], if the particles in fluid are cylindrical, just like CNTs, k_{nf} can be calculated as:

$$k_{nf} = \frac{k_{\mathrm{CNT}} + 5k_f - 5(k_f - k_{\mathrm{CNT}})\varphi}{k_{\mathrm{CNT}} + 5k_f + (k_f - k_{\mathrm{CNT}})\varphi}k_f \tag{8}$$

where k_{nf}, k_f and k_{CNT} are thermal conductivities of nanofluid, pure fluid and CNT, respectively; φ is volume fraction of CNT in fluid.

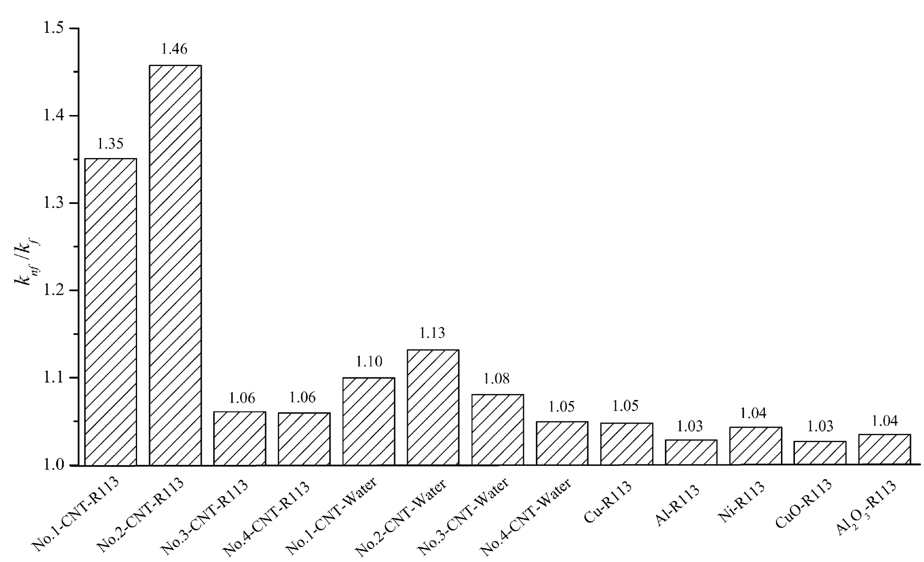

Fig. 6. Comparison of k_{nf}/k_f among CNT-R113, CNT–water and spherical-particle-R113, for $\varphi = 0.2$ vol%.

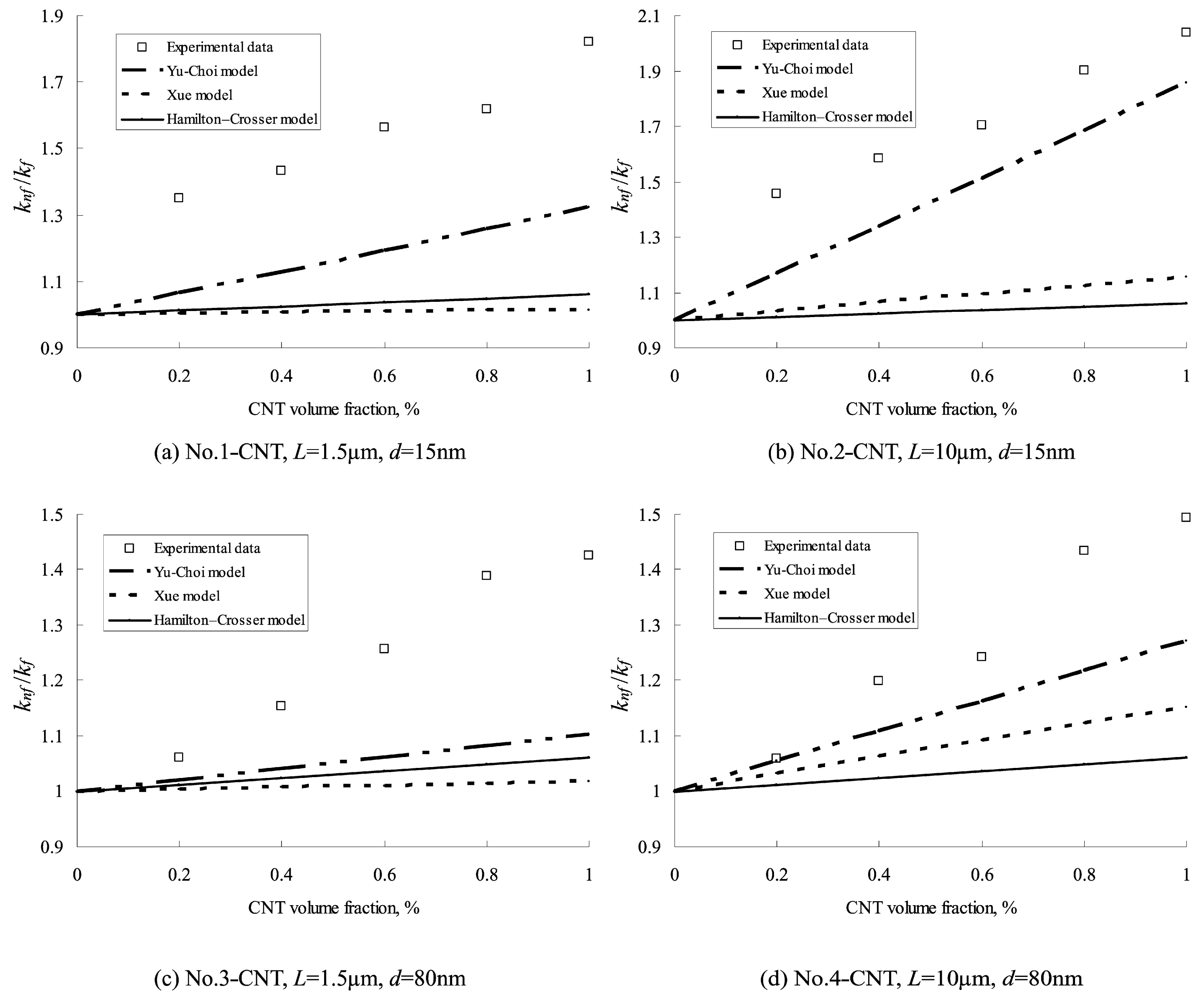

Fig. 7. Experimental data vs. predicted data of Yu–Choi model, Xue model and Hamilton–Crosser model.

Yu–Choi model, Xue model and Hamilton–Crosser model are validated by experiments on CNT-R113 nanorefrigerants, as shown in Fig. 7. The mean and maximum deviations of Yu–Choi model are 15.1% and 27.4%, respectively. The mean and maximum deviations of Xue model are 31.5% and 61.0%, respectively. The mean and maximum deviations of Hamilton–Crosser model are 26.9% and 47.9%, respectively. Yu–Choi model is more accurate than Xue model and Hamilton–Crosser model, but there is still obvious deviation of the predicted results of Yu–Choi model from the experimental results. It is better to establish a more accurate model by improving Yu–Choi model, for example, modifying Eq. (6), which is used for the calculation of the empirical constant α.

Eq. (6) is yielded by regression analysis on experimental data of CNT–oil's thermal conductivities [19]. In Eq. (6), the influences of CNT's length and diameter on thermal conductivities are not reflected. However, the experimental data in this research show that the influences of length and diameter on thermal conductivities cannot be ignored. So Eq. (9) is presented instead of Eq. (6) by regression analysis on experimental data of CNT-R113 nanorefrigerants' thermal conductivities. In Eq. (9), the non-dimensional parameter, d/L, is used and it reflects the mechanism that the CNT's length and diameter have obvious effect on the thermal conductivity of CNT nanorefrigerant.

$$\alpha = 1.55 + 16.7(d/L)^{0.71} \tag{9}$$

where L and d are length and diameter of CNT, respectively. The modified Yu–Choi model, consisting of Eqs. (5) and (9) is used to predict the thermal conductivities of the CNT-R113 nanorefrigerants. Fig. 8 shows the comparison between the experimental data and the predicted results of the modified Yu–Choi model. The mean and maximum deviations of the modified Yu–Choi model are 5.5% and 15.8%, respectively, which shows that the modified Yu–Choi model is better than the existing models in predicting thermal conductivities of CNT nanorefrigerants.

6. Conclusions

(1) The thermal conductivities of CNT nanorefrigerants increase significantly with the increase of the CNT volume fraction. When the CNT volume fraction is 1.0 vol%, the measured thermal conductivities of four kinds of CNT-R113 nanorefrigerants increase 82%, 104%, 43% and 50%, respectively. The thermal conductivity enhancements of CNT-R113 nanorefrigerants

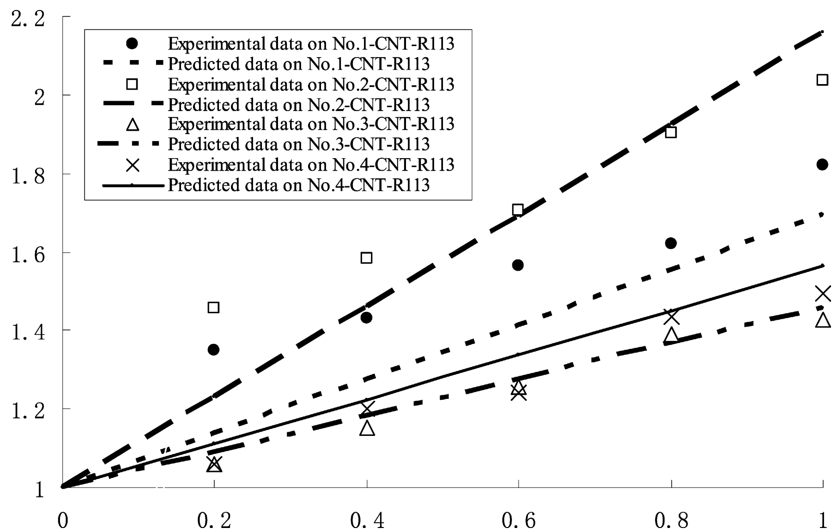

Fig. 8. Experimental data vs. predicted data of the modified Yu–Choi model.

are higher than those of CNT–water nanofluids and spherical-nanoparticles-R113 nanorefrigerants with the same nanoparticle volume fraction.

(2) The diameter and aspect ratio of CNT can influence the thermal conductivities of CNT nanorefrigerants. The smaller the diameter of CNT is or the larger the aspect ratio of CNT is, the higher the thermal conductivity of CNT-R113 nanorefrigerant is. The influence of aspect ratio of CNT on nanorefrigerants' thermal conductivities is less than the influence of diameter of CNT.

(3) The existing models for predicting thermal conductivities of CNT nanofluids, including Hamilton–Crosser model, Yu–Choi model and Xue model, cannot predict the thermal conductivities of CNT nanorefrigerants within a mean deviation of less than 15%. Yu–Choi model is more accurate than the other two models. On the basis of Yu–Choi model, a modified model is proposed and it has a mean deviation of 5.5%. The modified Yu–Choi model is recommended for predicting thermal conductivities of CNT nanorefrigerants.

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