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Experimental study on thermal conductivity of kerosene-based nanofluids

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ABSTRACT

Thermal conductivity of kerosene-based nanofluids is experimentally studied in the paper. Aluminum (Al), alumina (Al_2O_3) and titanium dioxide (TiO_2) nanoparticles were dispersed respectively in RP3 aviation kerosene, and thermal conductivity of those nanofluids was measured in a wide range of fluid temperature and particle mass fraction. The increase rate of thermal conductivity of kerosene-based nanofluids reached 60% at a temperature of 403 K. The thermal conductivity of nanofluids changes with different particles, particle size, particle concentration and temperature et al. The change rules are given in this paper in detail. Meanwhile, the experimental results of thermal conductivity are compared with the theoretical model proposed in our previous work originally for water-based nanofluids, and the comparison results are found to be good.

1. Introduction

Aviation kerosene is becoming a reliable coolant candidate for active thermal protections of aerospace engines [1,2]. For the purpose of enhancing active cooling property, increasing heat transfer efficiency of aviation kerosene will be the key. Thermophysical properties of fuel especially thermal conductivity has a significant effect on the convective heat transfer efficiency, so that enhancing thermal conductivity is an effective way to improve the cooling performance. The concept of nanofluids which is a kind of nanoparticle-laden colloids was first proposed by Choi in 1995 [3], and in this literature, Choi presented that nanofluids improve thermal conductivity as well as heat transfer coefficient compared to base fluid. Until now, suspension stability [4–6], thermophysical properties [7,8] and flowing properties [9,10] of nanofluids of water or ethylene glycol have been studied in many literatures. A lot of studies indicated that addition of nanoparticles could improve thermal conductivity and convective heat transfer coefficient of simple fluid medium like water of ethylene glycol. However, up to now, studies that applied complex liquid medium especially hydrocarbon fuel such as kerosene as base fluid have been very few. Wu et al. [11] focused on the preparation method of stable nanofluids with JP-10 kerosene as base fluid, and prepared a new kind of macromolecular long-chain modifier, Span-65, for the modification of nanoparticles. Fu et al. [12] studied the effect of mass concentration on specific heat capacity of TiO_2-heat conducting oil nanofluids, and presented that there is a linear relationship between the specific heat capacity of nanofluids and mass concentration. Li et al. [13] conducted heat transfer experiment using copper-aviation cooling medium nanofluids with a Reynolds number range of 500 to 4000, and the conclusions indicated that nanofluids can improve heat transfer coefficient significantly with negligible increase of flow resistance.

The unique heat-conducting property that nanofluids revealed brings a lot of interests to researchers. Hence, a part of studies about mechanisms of nanofluids thermal conductivity increasing were presented. There is a dominant view that Brownian motion causes the increase of nanofluids thermal conductivity. Jang and Choi [14] analyzed the modes of energy transport in nanofluids and presented that Brownian motion played an important role in energy transport. And based on this theory, a theoretical model was constructed. Similarly, Prasher [15] proposed that Brownian motion was the main reason for the increase of thermal conductivity as well. Koo and Kleinstreuer [16], Xu et al. [17] also respectively constructed a theoretical model based on Brownian motion as the main mechanism. Besides, interfacial nanolayer as a significant factor affected nanofluids thermal conductivity is proved by many researchers. Yu and Choi [18], Leong et al. [19], Xie et al. [20] and Tso et al. [21] separately presented theoretical models with nanolayer as major factor. Those theoretical models mentioned before are all applicable to polar media as base fluid. And there is no certain model which is appropriate for aviation kerosene, a non-polar fluid.

In this paper, thermal conductivity of aluminum-kerosene, alumina-kerosene and titanium dioxide-kerosene nanofluids are researched. It is worth mentioning that the thermal conductivity of kerosene-based

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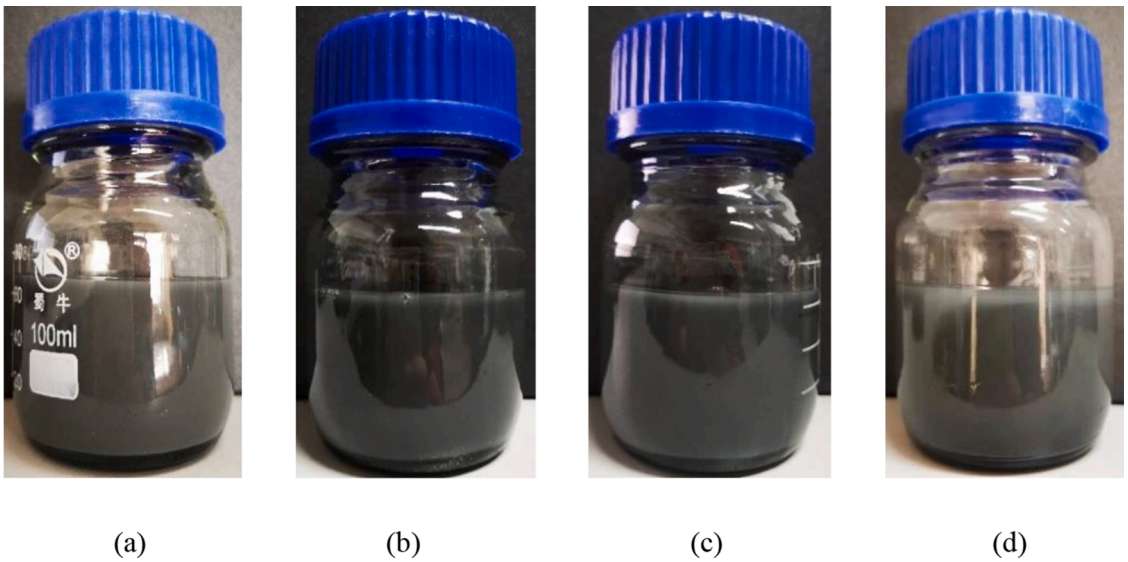

Fig. 1. Results of sedimentation observations of Al-kerosene nanofluids with mass fraction of 0.0128 (a. After preparation; b. 2 days later; c. 6 days later; d. 7 days later).

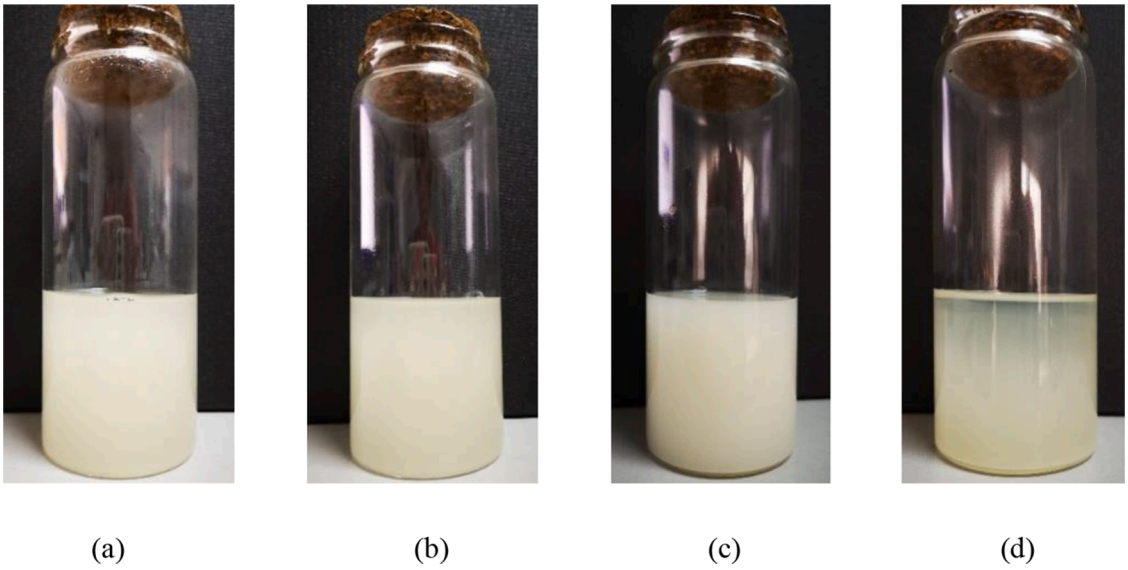

Fig. 2. Results of sedimentation observations of Al_2O_3-kerosene nanofluids with mass fraction of 0.0128 (a. After preparation; b. 2 days later; c. 7 days later; d. 8 days later).

nanofluids is studied in a wide temperature range of 298 K to 403 K, which is different from most of other studies. And the major factors that affect thermal conductivity are discussed. In addition, the measurement results of thermal conductivity of different kinds of nanofluids were compared with a theoretical model which was proposed in our previous work [22], and the comparison results indicated that the theoretical model could be applied to kerosene-based nanofluids with good accuracy.

1.1. Experiment methods

Aluminum nanoparticles (50nm ± 7 nm) with CAS number of 7429–90–5 which is made by CW-NANO Technology, alumina nanoparticles (30nm ± 5 nm or 50nm ± 7 nm) with CAS number of 1344–28–1 and anatase titanium dioxide nanoparticles (30nm ± 5 nm or 50nm ± 7 nm) with CAS number of 13,463–67–7 which are made by Aladdin Bio-Chem Technology are used in this study and the base fluid used is RP3 aviation kerosene. All kind of nanofluids are prepared with a mass concentration between 0.0064 to 0.0385, and the volume fractions of different nanofluids are converted from the mass fractions with known particle density and kerosene density.

Two-step method is applied to prepare nanofluids. Kerosene is prepared by volume with measuring cylinder, and nanoparticles are prepared by mass with electronic balance which was manufactured by BKHX Scientific Instrument. To make sure the stability of the colloids is reliable, an appropriate amount (four times the volume of the particle) of oleic acid is added to the nanofluids. Besides, magnetic force agitation with speed of 1200 rpm for 1 h, and ultra-sonication with ultrasonic frequency of 40 kHz and power of 800 W for 2 h are used to ensure a sufficient dispersion of particles in kerosene. And in order to ensure that the temperature of water bath will not increase, ice cubes are continuously added to the water bath during the ultra-sonication. The magnetic agitator was manufactured by Tianmei Electromechanical Instrument, and the ultrasonator was manufactured by Kunshan Ultrasonic

Fig. 3. Results of sedimentation observations of TiO_2-kerosene nanofluids with mass fraction of 0.0128 (a. After preparation; b. 2 days later; c. 7days later; d. 8 days later).

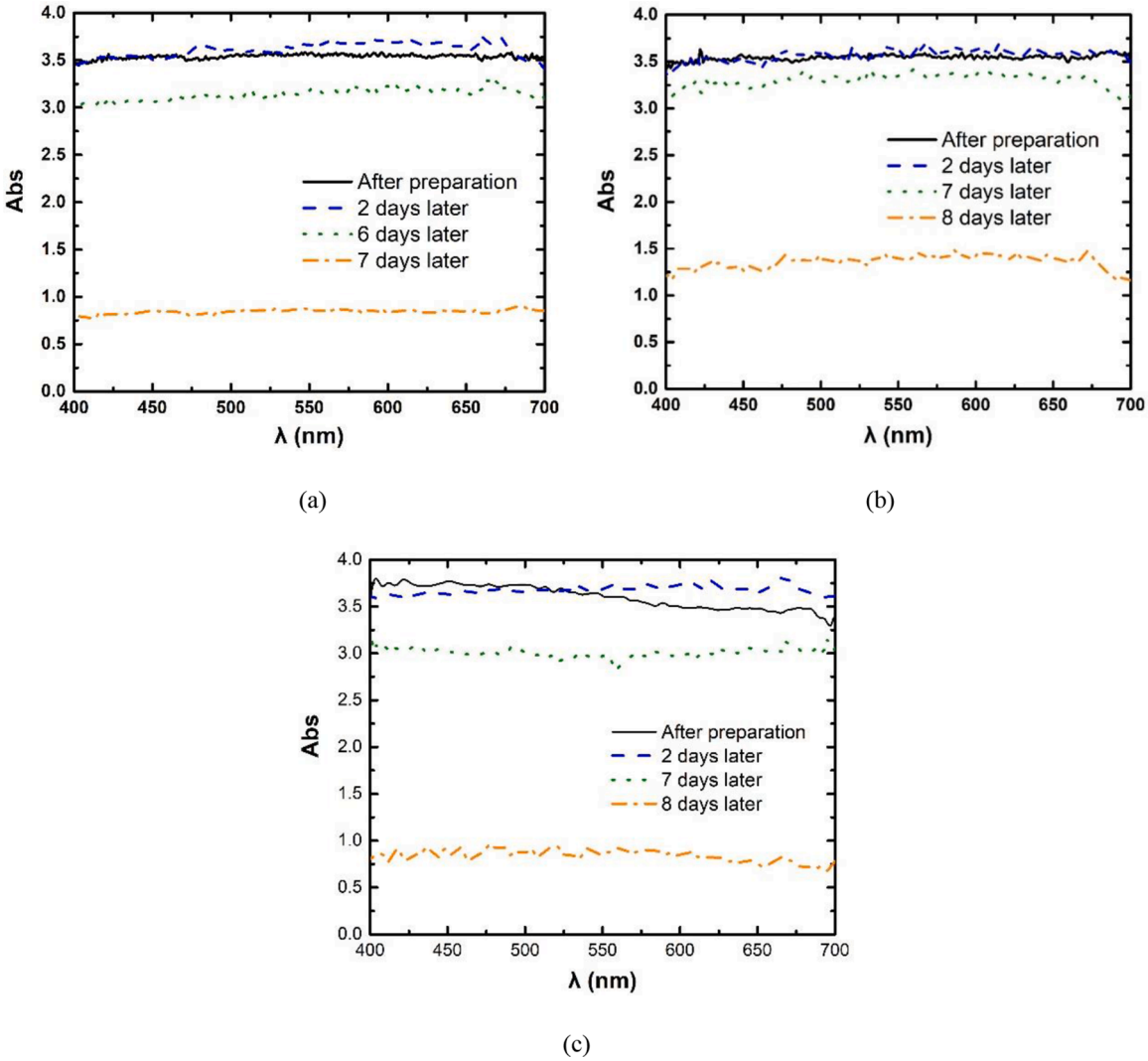

Fig. 4. Measurement results of absorbance of nanofluids with mass fraction of 0.0128
(Note: Uncertainty of measurement is 0.5%)
(a. Al-kerosene nanofluids; b. Al_2O_3-kerosene nanofluids; c. TiO_2-kerosene nanofluids).

Table 1
The repetitive experiment results of thermal conductivity of kerosene.

Count	1	2	3	4
Thermal conductivity (W/(m·K))	0.1425	0.1432	0.1434	0.1419

Insturment. Sedimentation observations results of nanofluids with mass fraction of 0.0128 are shown in Figs. 1-3 and measurement results of absorbance are shown in Fig. 4. These four figures indicate that the kerosene-based nanofluids can maintain dispersion stability for about 7 days without any trace of visible particle sedimentation.

Transient hot wire method is applied in this paper to measure thermal conductivity of nanofluids and the accuracy of measurement has been discussed in previous work [22]. The model of thermal conductivity measurement equipment with measurement accuracy of ± 1% is DRE-2A, which was manufactured by Shuangxi Instrument. The data repeatability is examined and the results of thermal conductivity of kerosene at room temperature are given in Table 1, it is shown that the maximum deviation of repeatability measurement is 2.5%.

2. Results and discussions

In this paper, kerosene-based nanofluids with aluminum particles, alumina particles and titanium dioxide particles of different size as dispersion are prepared, the mass fraction of nanoparticles is all in range of 0.0064 to 0.0385. And the measurement of nanofluids thermal conductivity is in a wide temperature range (298 K to 403 K).

Fig. 5(a)-(c) present thermal conductivity of three kinds of nanofluids. As known, thermal conductivity of kerosene, like most of liquid, decreases with the increase of temperature. However, due to the addition of nanoparticles, thermal conductivity of colloids increases obviously with the increase of temperature. Similar properties of thermal conductivity with temperature have been mentioned in other literature with nonpolar liquid as base fluids [23]. This phenomenon may be explained by the fact that nanoparticles move randomly in the liquid (Brownian motion), and the movement speed is larger for particles at higher liquid temperature, thus the energy transportation is more efficient, and the enhancement of energy transportation significantly exceeds the energy consumption caused by the thermal motion of particles and molecules. Above all, the increase of thermal conductivity can reach

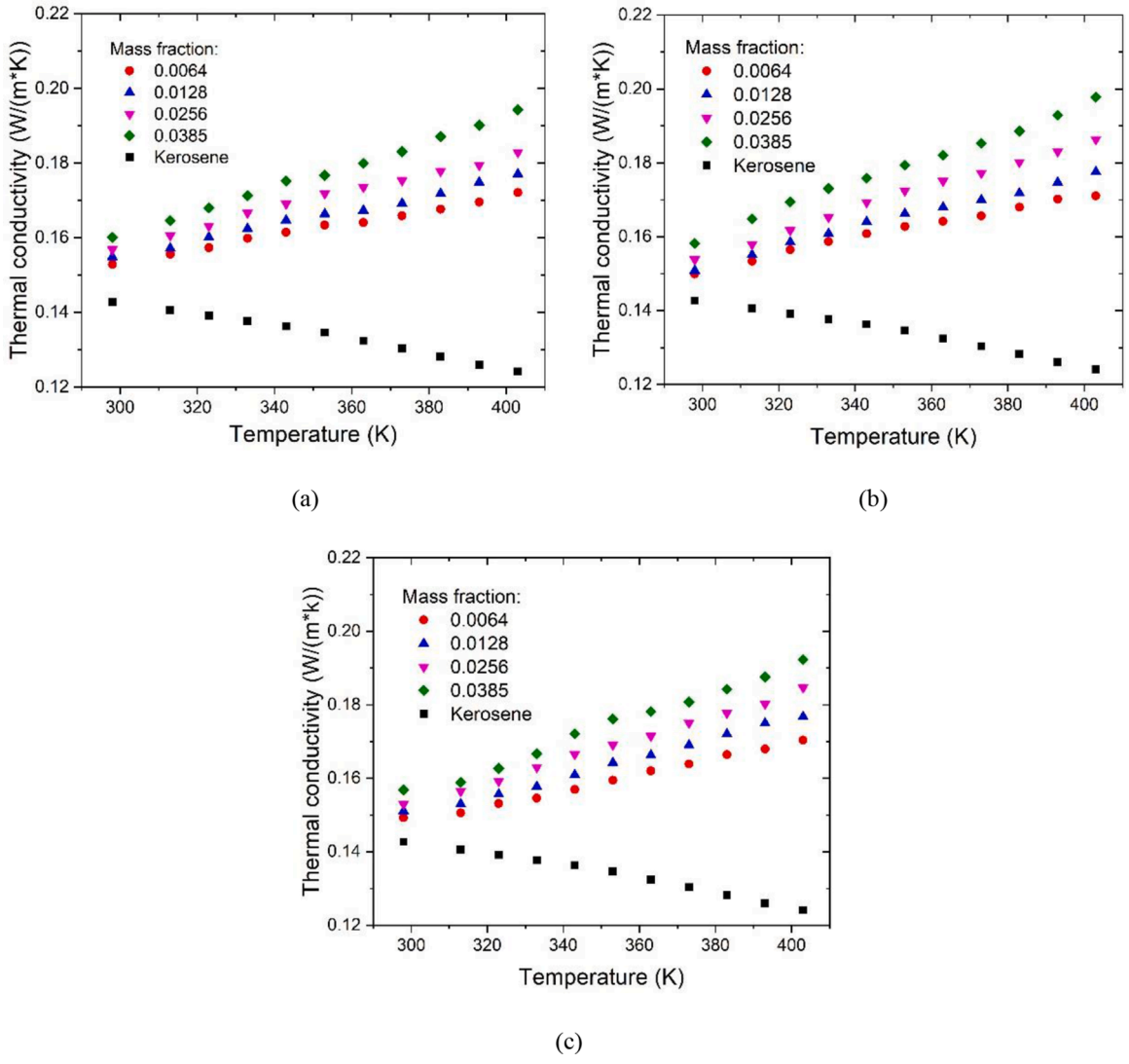

Fig. 5. Thermal conductivity at varied particle mass fractions and temperatures (Note: Uncertainty of measurement is 1%).

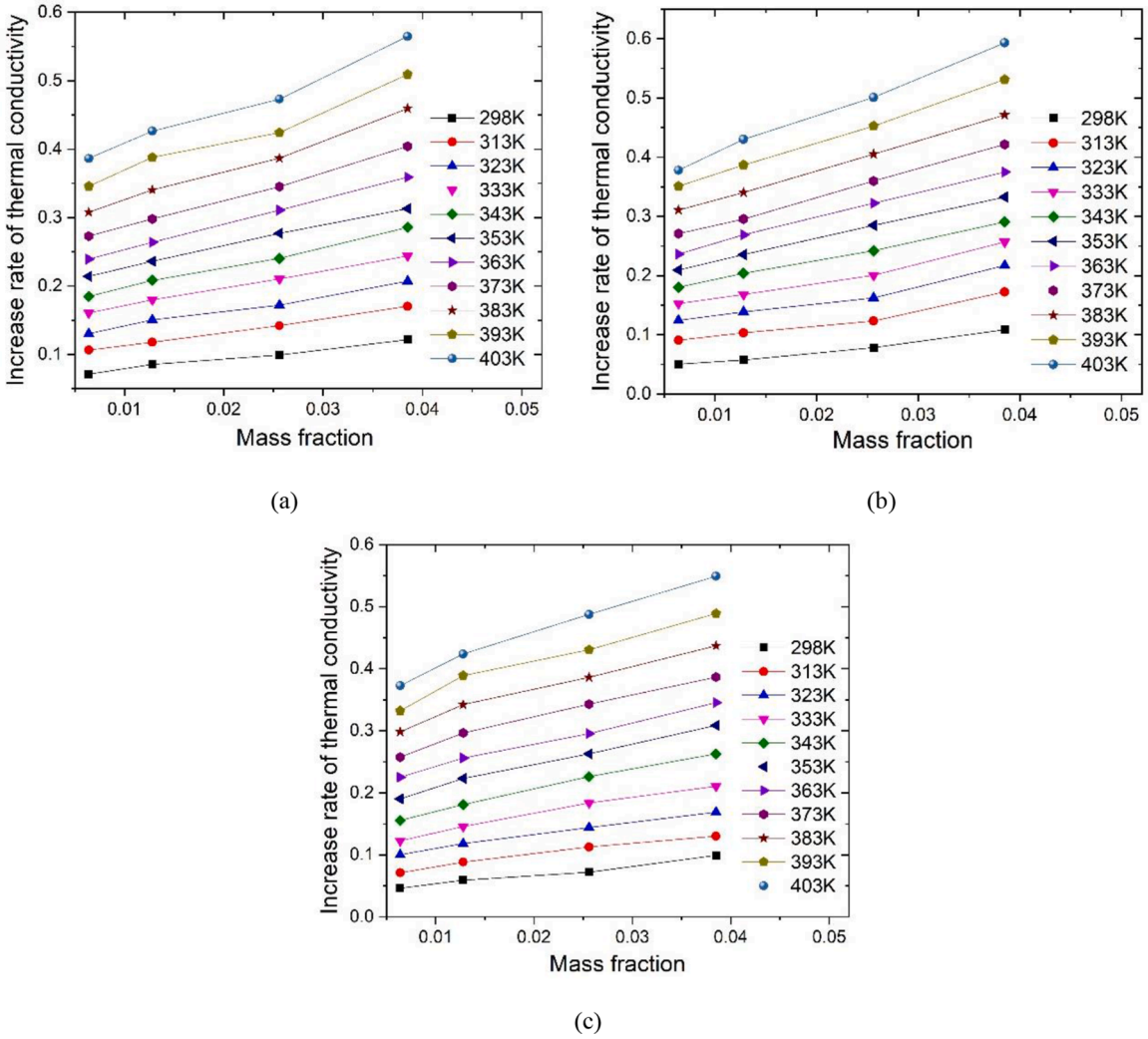

Fig. 6. Increase rate of nanofluids thermal conductivity varied with mass concentration
(Note: Uncertainty of measurement is 1%)
(a. Al-kerosene nanofluids; b. Al_2O_3-kerosene nanofluid; c. TiO_2-kerosene nanofluids).

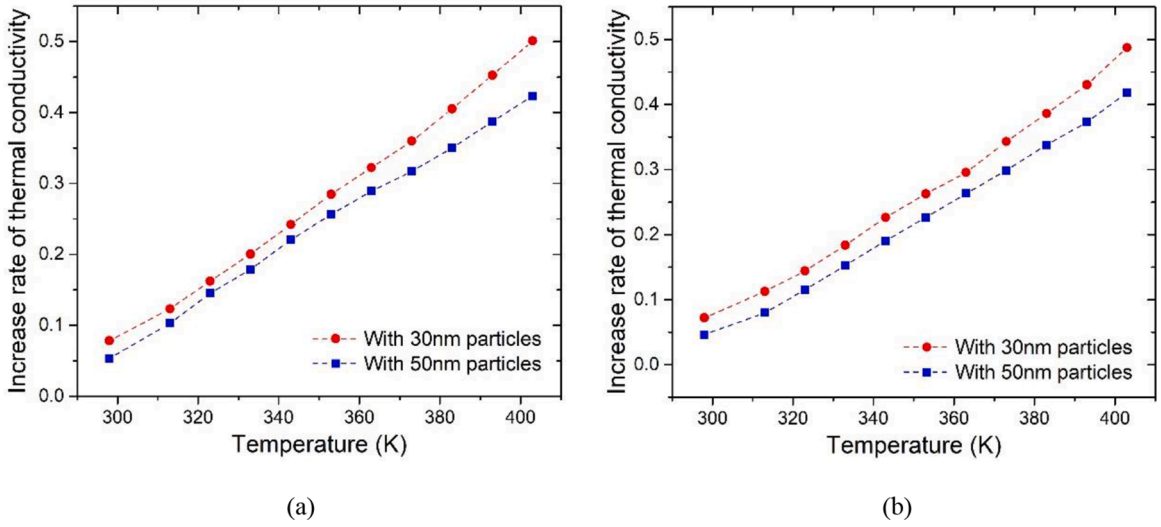

Fig. 7. Effect of particle size on thermal conductivity of nanofluids
(Note: Uncertainty of measurement is 1%)
(a. Al2O3-kerosene nanofluids; b. TiO2-kerosenen nanofluids).

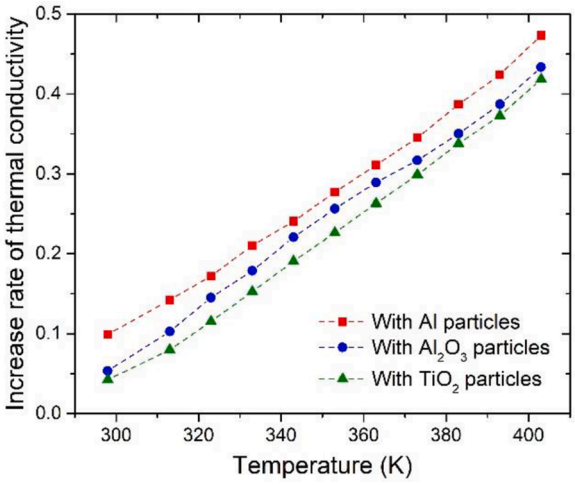

Fig. 8. Effect of particle material on thermal conductivity of nanofluids (Note: Uncertainty of measurement is 1%).

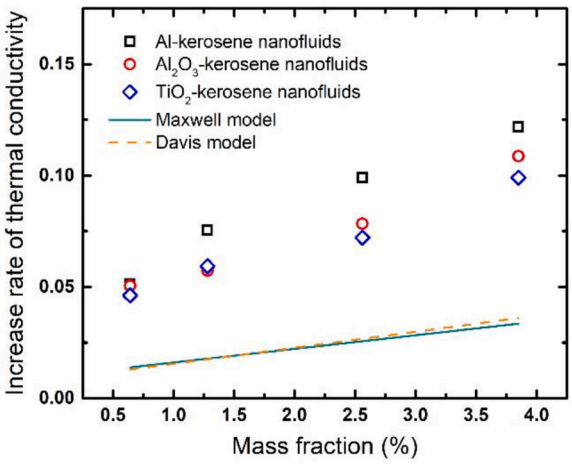

Fig. 9. Comparison between experimental data and classical theoretical models.

almost 60% of three kinds of nanofluids with mass fraction of 0.0385 and at a temperature of 403 K. And a conclusion can be gotten that addition of nanoparticles can significantly increase the thermal conductivity of colloids. It is worth noting that the trends of thermal conductivity with temperature are similar for those nanofluids. The increase of thermal conductivity is almost linear with increasing temperature.

Fig. 5 also shows that the thermal conductivity increases with particle mass fraction for the three nanofluids. For a clearer demonstration of mass fraction effect, increase rates of thermal conductivity as a function of mass fraction are shown in Fig. 6(a)-(c). The increase rate is defined as $r = \frac{k_{nf}-k_f}{k_f}$, in which, r is the increase rate, k_{nf} is the thermal conductivity of nanofluids and k_f is the thermal conductivity of kerosene. Obviously, the growth of increase rate of thermal conductivity is almost linear with the increasing mass fraction, and the slope of increase rate as a function of mass fraction seems larger at higher temperatures.

In order to find the factors that have influences on thermal conductivity of nanofluids, some comparisons at varied particles and particle diameters are presented. Fig. 7 show the effect of different particle sizes on thermal conductivity of nanofluids, which indicate that the smaller the particle diameter is, the higher the thermal conductivity is. The comparison between different particles is presented in Fig. 8. The thermal conductivity of aluminum-kerosene nanofluids is distinctly higher than that of the other two kinds of nanofluids. And the thermal conductivity of alumina-kerosene nanofluids is a bit higher than titanium dioxide -kerosene nanofluids as well. It is considered that the thermal conductivity of nanofluids is significantly related to thermal properties of particles. The thermal conductivity of aluminum particles is much higher than metallic oxide particles and that of aluminum particles is a little higher than titanium dioxide particles as well.

Fig. 9 gives the comparison between experimental data at room temperature and classical models of Maxwell [24] and Davis [25]. At present, classical theoretical models of thermal conductivity of solid-liquid two-phase mixture cannot accurately predict the thermal conductivity of nanofluids, Meanwhile, almost all theoretical models of nanofluids thermal conductivity are focused on water-based nanofluids, and those models can hardly be appropriate for other nanofluids, especially non-polar fluids. In our previous work [22], a theoretical model constructed with classical solid-liquid two-phase theory, Brownian motion theory and interfacial nanolayer theory has been proposed for analysis of water-based nanofluids, and the expression of the model can be written as:

$$k_{eff} = (1 + aRe^m Pr^n)\frac{k_{pe} + 2k_f + 2(1+\beta)^3\Phi(k_{pe} - k_f)}{k_{pe} + 2k_f - (1+\beta)^3\Phi(k_{pe} - k_f)}k_f \quad (1)$$

In which, k_{eff} is the effective thermal conductivity of nanofluids, Re is the Reynolds number of particle motion, Pr is the Prandtl number of base fluid, k_{pe} is the thermal conductivity of equivalent particle, k_f is the thermal conductivity of base fluid, β is the ratio between nanolayer thickness and particle radius, and Φ is the volume fraction of nanoparticles. Besides, a, m and n are coefficients, the value of m indicates the influence of particle motion on thermal conductivity, the value of n indicates the influence of the base fluid properties on thermal conductivity, and a is an empirical coefficient. This theoretical model has a good applicability to experimental data as described in the literature [22]. And it is found that this model can be applied to kerosene-based nanofluids as well.

The formula applied to aluminum-kerosene nanofluids is written as:

$$k_{eff} = \left(1 + 52Re^{1.7}Pr^{0.5}\right)\frac{k_{pe} + 2k_f + 2(1+\beta)^3\Phi(k_{pe} - k_f)}{k_{pe} + 2k_f - (1+\beta)^3\Phi(k_{pe} - k_f)}k_f \quad (2)$$

Fig. 10 show the comparison results of aluminum-kerosene nanofluids between theoretical model and the measurement results. It is found the predicted thermal conductivity agree well with the experimental data with a standard deviation of 0.038. The results of comparison indicate that Eq. (2) is able to predict the thermal conductivity of aluminum-kerosene nanofluids.

Figs. 11 and 12 respectively give the comparison results of alumina-kerosene nanofluids and titanium-kerosene nanofluids which both show good agreement between the value calculated by theoretical model and experimental data. The prediction formula applied to alumina-kerosene nanofluids is written as

$$k_{eff} = \left(1 + 40Re^{1.8}Pr^{0.7}\right)\frac{k_{pe} + 2k_f + 2(1+\beta)^3\Phi(k_{pe} - k_f)}{k_{pe} + 2k_f - (1+\beta)^3\Phi(k_{pe} - k_f)}k_f \quad (3)$$

And the formula applied to titanium-kerosene nanofluids is written as

$$k_{eff} = \left(1 + 75Re^{1.8}Pr^{0.5}\right)\frac{k_{pe} + 2k_f + 2(1+\beta)^3\Phi(k_{pe} - k_f)}{k_{pe} + 2k_f - (1+\beta)^3\Phi(k_{pe} - k_f)}k_f \quad (4)$$

It is found that for different kerosene-based nanofluids, Eqs. (2), (3) and (4) have the same formula and different values of coefficient a, m and n.

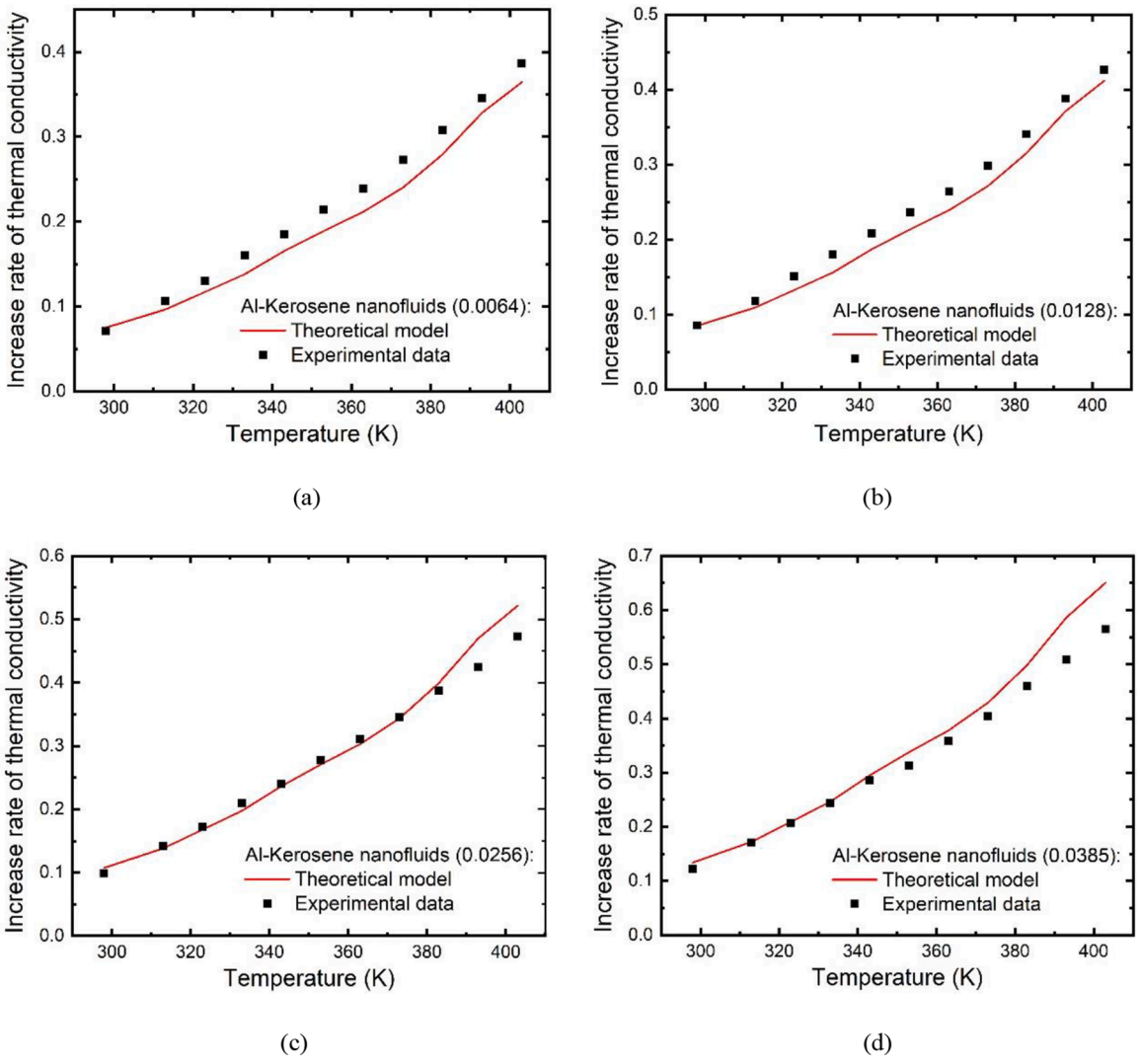

Fig. 10. Comparison between theoretical model and measurement results of Al-kerosene nanofluids (a. Mass frction 0.0064 b. Mass frction 0.0128; c. Mass frction 0.0256; d. Mass frction 0.0385).

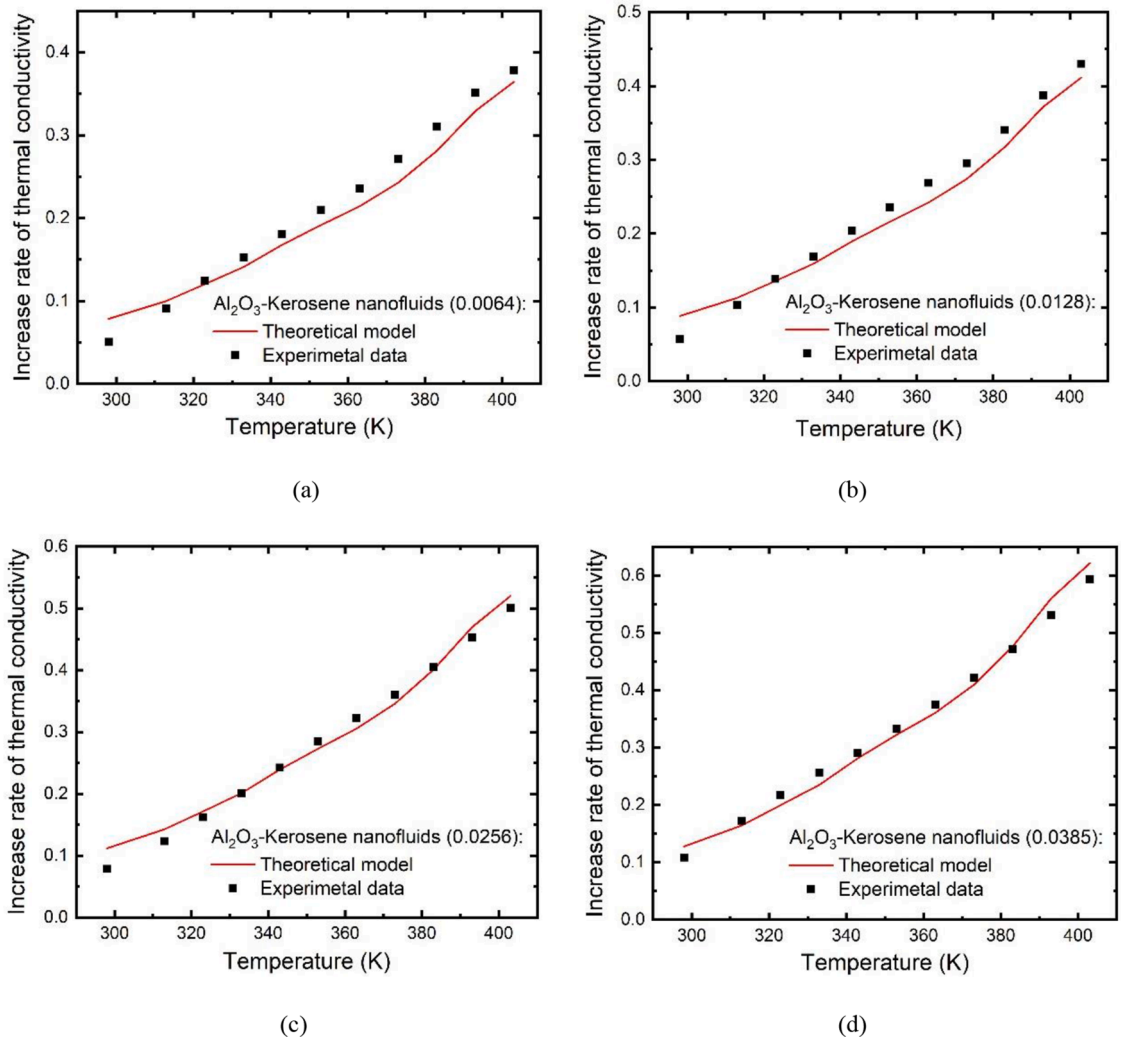

Fig. 11. Comparison between theoretical model and measurement results of Al_2O_3-kerosene nanofluids (a. Mass frction 0.0064 b. Mass frction 0.0128; c. Mass frction 0.0256; d. Mass frction 0.0385).

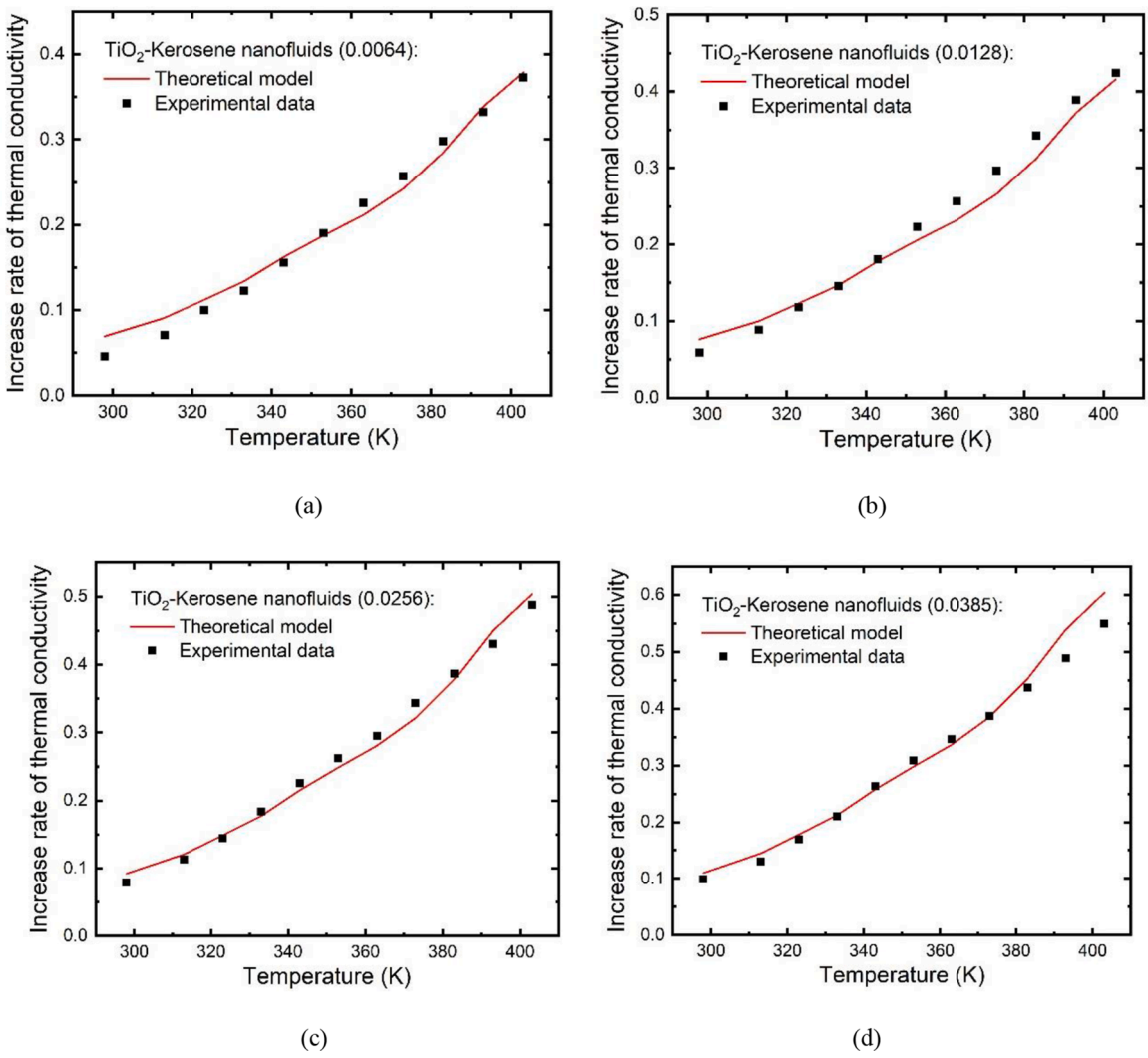

Fig. 12. Comparison between theoretical model and measurement results of TiO_2-kerosene nanofluids (a. Mass frction 0.0064 b. Mass frction 0.0128; c. Mass frction 0.0256; d. Mass frction 0.0385).

3. Conclusions

In this paper, thermal conductivity of kerosene-based nanofluids is researched. Experimental results of thermal conductivity with different nanoparticles and particle sizes, different mass fractions and different temperature conditions are presented and discussed. It is found that nanofluids could improve thermal conductivity greatly compared to kerosene and the increase rate could reach 60% when the mass fraction is 0.0385and the temperature is 403 K. The mass fraction of nanoparticles and temperature are the main factors that have influence on thermal conductivity of nanofluids. Thermal conductivity of nanofluids will increase with higher mass fraction and higher temperature respectively. Besides, it is found that different particles and particle sizes also affect thermal conductivity of nanofluids. The present results indicate that the smaller the particle size is, the higher the thermal conductivity is. In addition, thermal conductivity of metal-kerosene nanofluids is higher than that of metallic oxide-kerosene nanofluids with same conditions which is related to the thermophysical properties of particles. Besides, the theoretical model of thermal conductivity of nanofluids proposed in our previous work [22] is proved to be able to predict the thermal conductivity of kerosene-based nanofluids as well, and the predicted values are found to be in good agreement with the experimental data.

CRediT authorship contribution statement

Wenhui Fan: Conceptualization, Methodology, Validation, Formal analysis, Investigation, Data curation, Writing – original draft, Visualization. **Fengquan Zhong:** Methodology, Resources, Writing – review & editing, Supervision, Project administration, Funding acquisition.

Declaration of Competing Interest

We wish to confirm that there are no known conflicts of interest associated with this publication and there has been no significant financial support for this work that could have influenced its outcome.

We confirm that the manuscript has been read and approved by all named authors and that there are no other persons who satisfied the criteria for authorship but are not listed. We further confirm that the order of authors listed in the manuscript has been approved by all of us.

We confirm that we have given due consideration to the protection of intellectual property associated with this work and that there are no impediments to publication, including the timing of publication, with respect to intellectual property. In so doing we confirm that we have followed the regulations of our institutions concerning intellectual property.

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