

University of Dayton eCommons

Chemical and Materials Engineering Faculty
Publications

Department of Chemical and Materials Engineering

2007

Thermal Conductivity Improvement in Carbon Nanoparticle Doped PAO Oil: An Experimental Study

Shadab Shaikh
University of Dayton

Khalid Lafdi
University of Dayton, klafdi1@udayton.edu

Rengasamy Ponnappan
Air Force Research Laboratory

Follow this and additional works at: https://ecommons.udayton.edu/cme_fac_pub

 Part of the [Other Chemical Engineering Commons](#), [Other Materials Science and Engineering Commons](#), and the [Polymer and Organic Materials Commons](#)

eCommons Citation

Shaikh, Shadab; Lafdi, Khalid; and Ponnappan, Rengasamy, "Thermal Conductivity Improvement in Carbon Nanoparticle Doped PAO Oil: An Experimental Study" (2007). *Chemical and Materials Engineering Faculty Publications*. 16.
https://ecommons.udayton.edu/cme_fac_pub/16

This Article is brought to you for free and open access by the Department of Chemical and Materials Engineering at eCommons. It has been accepted for inclusion in Chemical and Materials Engineering Faculty Publications by an authorized administrator of eCommons. For more information, please contact frice1@udayton.edu, mschlange1@udayton.edu.

Thermal conductivity improvement in carbon nanoparticle doped PAO oil: An experimental study

S. Shaikh^{a)} and K. Lafdi

University of Dayton, 300 College Park, Dayton, Ohio 45469

R. Ponnappan

AFRL/PRPS, Power Division, Wright Patterson AFB, Ohio 45433

(Received 7 December 2006; accepted 13 January 2007; published online 16 March 2007)

The present work involves a study on the thermal conductivity of nanoparticle-oil suspensions for three types of nanoparticles, namely, carbon nanotubes (CNTs), exfoliated graphite (EXG), and heat treated nanofibers (HTT) with PAO oil as the base fluid. To accomplish the above task, an experimental analysis is performed using a modern light flash technique (LFA 447) for measuring the thermal conductivity of the three types of nanofluids, for different loading of nanoparticles. The experimental results show a similar trend as observed in literature for nanofluids with a maximum enhancement of approximately 161% obtained for the CNT-PAO oil suspension. The overall percent enhancements for different volume fractions of the nanoparticles are highest for the CNT-based nanofluid, followed by the EXG and the HTT. The findings from this study for the three different types of carbon nanoparticles can have great potential in the field of thermal management. © 2007 American Institute of Physics. [DOI: [10.1063/1.2710337](https://doi.org/10.1063/1.2710337)]

I. INTRODUCTION

Low thermal conductivity is a primary limitation in the development of energy efficient heat transfer fluids required in many industrial and commercial applications. The heat rejection requirements are continually increasing due to trends toward faster speeds (in the multigigahertz range) and smaller features (to <100 nm) for microelectronic devices, more power output for engines, and brighter beams for optical devices. Cooling becomes one of the top technical challenges facing high-tech industries such as microelectronics, transportation, manufacturing, and metrology. Conventional methods to increase heat flux rates include extended surfaces such as fins and microchannels and/or increasing flow rates by increasing pumping power.

However, current design solutions already push the available technology to its limits. Conventional heat transfer fluids have inherently poor thermal conductivity compared to solids (see Fig. 1). Conventional fluids that contain millimeter- or micrometer-sized particles do not work with the emerging miniaturized technologies because they can clog the tiny channels of these devices.

New technologies and new advanced fluids with the potential to improve flow and thermal characteristics are of critical importance. Inclusion of high thermal conductivity particles inside the fluid is a promising way toward enhancing thermal properties of fluids. The idea of increasing heat transfer in fluids by suspending conductive particles was first addressed by Maxwell.¹ These fluids are termed as *nanofluids* when suspensions of nanometer-sized particles are used inside the parent fluid. Nanoparticles stay suspended much longer than microparticles and, if below a threshold

level and/or enhanced with surfactants/stabilizers, remain in suspension almost indefinitely. Furthermore, the surface area per unit volume of nanoparticles is much larger (a million times) than that of microparticles (the number of surface atoms per unit of interior atoms of nanoparticles is very large). These properties can be utilized to develop stable suspensions with enhanced flow, heat transfer, and other characteristics. Examples of nanofluids are the addition of materials such as carbon, copper, or copper oxide in liquids such as oil, water, and ethylene glycol. Before detailing the experimental and theoretical analyses carried out through this study a comprehensive review on nanofluids is described in the next section.

II. LITERATURE REVIEW

A. Role of nanofluids in thermal management

As mentioned before, cooling is one of the most important technical challenges facing many diverse industries, including microelectronics, transportation, solid-state lighting, and manufacturing. The novel concept of “nanofluids”—heat transfer fluids containing suspensions of nanoparticles—has been proposed as a means of meeting these challenges,² which cannot be resolved by the conventional fluids and most of the traditional methods used to increase the heat flux rate.

Modern nanotechnology provides opportunities to produce nanoparticles. Argonne National Laboratory developed the novel concept of nanofluids.³ The main factor that has intrigued many researchers in the development of nanofluids is the significant improvement in the heat transfer performance as compared to conventional fluids. Some of the main reasons⁴ are listed as follows: (i) the suspended nanoparticles increase the surface area and the heat capacity of the fluid; (ii) the suspended nanoparticles increase the effective (or ap-

^{a)}Author to whom correspondence should be addressed; electronic mail: shaikhsa@notes.udayton.edu

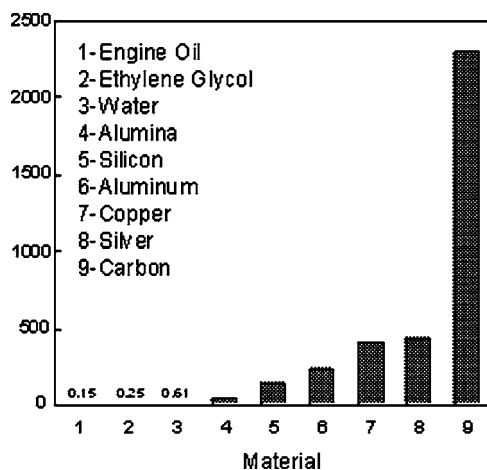


FIG. 1. Thermal conductivity of typical materials.

parent) thermal conductivity of the fluid; (iii) the interaction and collision among particles, fluid, and the flow passage surface are intensified; (iv) the mixing fluctuation and the turbulence of the fluid are intensified; and (v) the dispersion of nanoparticles flattens the transverse temperature gradient of the fluid.

Nanofluids are solid-liquid composite materials consisting of solid nanoparticles or nanofibers with sizes typically of 1–100 nm suspended in liquid. Nanofluids have attracted great interest recently because of reports of greatly enhanced thermal properties. For example, a small amount ($<1\%$ volume fraction) of Cu nanoparticles or carbon nanotubes dispersed in ethylene glycol or oil is reported to increase the inherently poor thermal conductivity of the liquid by 40% and 150%, respectively.⁵ Conventional particle-liquid suspensions require high concentrations ($>10\%$) of particles to achieve such enhancement. Other perplexing results in this rapidly evolving field include a surprisingly strong temperature dependence of the thermal conductivity^{6,7} and a three-fold higher critical heat flux compared with the base fluids.^{8,9} These enhanced thermal properties are not merely of academic interest. If confirmed and found consistent, they would make nanofluids promising for applications in thermal management. The interdisciplinary nature of nanofluid research presents a great opportunity for exploration and discovery at the frontiers of nanotechnology.^{10,11}

Early experimental studies of the thermal transport properties of nanofluids focused on changes in properties created by high concentrations of oxide nanoparticles. Masuda *et al.*¹² reported a 30% increase in the thermal conductivity of water with the addition of 4.3 vol % of Al_2O_3 nanoparticles. A subsequent study by Lee *et al.*¹³ also examined the behavior of Al_2O_3 nanoparticles in water, but observed only a 15% enhancement in thermal conductivity at the same nanoparticle loading. Xie *et al.*¹⁴ found an intermediate result, i.e., the thermal conductivity of water is enhanced by approximately 20% by a nanoparticle loading of 5 vol %. Wang *et al.*¹⁵ reported a surprising 17% increase in thermal conductivity for a loading of just 0.4 vol % CuO nanoparticles in water. The anomalously large increases in thermal conductivity observed for CuO, Au, and Ag nanofluids have not been confirmed independently. In fact, a recent attempt at

duplicating the Cu nanofluid results appears to have failed: In this case, the Cu nanoparticles were larger (50 nm) but no significant enhancement in thermal conductivity was observed with Cu nanoparticle loadings of up to 0.5 vol %.¹⁶

The largest increases in thermal conductivity have been observed in suspensions of carbon nanotubes, which, in addition to high thermal conductivity, have a very high aspect ratio. The first reported work on a single-walled carbon nanotube-polymer epoxy composite¹⁷ demonstrated a 125% increase in thermal conductivity at a 1 wt % nanotube loading at room temperature. Choi *et al.*¹⁸ measured thermal conductivities of oil suspensions containing multiwalled carbon nanotubes up to 1 vol % loading and found similar behavior, in this case a 160% enhancement. Interestingly, the conductivity enhancement increased more rapidly than a linear dependence on nanotube loading. Thus interactions of thermal fields associated with different fibers may become important as the loading approaches 1 vol %. Several studies of carbon nanotube suspensions have shown smaller enhancements in thermal conductivity: Xie *et al.*¹⁹ measured carbon nanotube-organic liquid and water suspensions and found only 10%–20% increases in thermal conductivity at 1 vol %; Wen and Ding²⁰ found a $\sim 25\%$ enhancement in the conductivity at ~ 0.8 vol % carbon nanotubes in water; and Assael and co-workers found a maximum enhancement of 38% with 0.6 vol % nanotubes in water. In the work of Wen and Ding, the enhancement in the conductivity of the suspension increases rapidly with loading up to 0.2 vol % and then begins to saturate.

Nanofluids can thus play a vital role in the field of thermal management right from applications related with cooling of microelectronics to operation of fuel cells in the automotive industry. Thermal conductivity has hence received the most attention but several groups have recently initiated studies of other heat transfer properties. However, a number of factors need to be considered before these nanofluids can be brought into practice at the industrial level. Some of them can be listed as the lack of agreement between results obtained in different laboratories, the often poor characterization of the suspensions; and the lack of theoretical understanding of the mechanisms responsible for the observed changes in properties.

B. Synthesis of nanofluids

The optimization of nanofluid thermal properties requires successful synthesis procedures for creating stable suspensions of nanoparticles in liquids. Depending on the requirements of a particular application, many combinations of particle materials and fluids are of potential interest. For example, nanoparticles of oxides, nitrides, metals, metal carbides, and nonmetals with or without surfactant molecules can be dispersed into fluids such as water, ethylene glycol, or oils. Studies to date have used one or more of several possible methods for nanoparticle production and dispersion. Here, we briefly mention the techniques that, so far, have been most commonly used.

Several studies, including the earliest investigations of nanofluids, used a two-step process in which nanoparticles or

nanotubes are first produced as a dry powder, often by inert gas condensation. Chemical vapor deposition has also been used to produce materials for use in nanofluids, particularly multiwalled carbon nanotubes. The nanoparticles or nanotubes are then dispersed into a fluid in a second processing step. Simple techniques such as ultrasonic agitation or the addition of surfactants to the fluids are sometimes used to minimize particle aggregation and improve dispersion behavior. Such a two-step process works well in some cases, such as nanofluids consisting of oxide nanoparticles dispersed in de-ionized water. Less success has been found when producing nanofluids containing heavier metallic nanoparticles. Since nanopowder synthesis techniques have already been scaled up to industrial production levels by several companies, there are potential economic advantages in using two-step synthesis methods that rely on the use of such powders.

Single-step nanofluid processing methods have also been developed. For example, nanofluids containing dispersed metal nanoparticles have been produced by a direct evaporation technique.²¹ As with the inert gas condensation technique, this involves the vaporization of a source material under vacuum conditions. An advantage of this technique is that nanoparticle agglomeration is minimized, while a disadvantage is that only low vapor pressure fluids are compatible with the process. Various single-step chemical synthesis techniques can also be employed to produce nanofluids. For example, a technique for producing metallic nanoparticles²² by the reduction of metal salts has been used widely to produce colloidal suspensions in various solvents for a wide range of applications; including studies of thermal transport.^{23,24} Excellent control of size and very narrow size distributions can be obtained by using such methods.

C. Methods for measuring thermal conductivity of nanofluids

Experimental studies of the thermophysical properties of liquids are exceedingly difficult. The main problems are connected with elimination of convective heat transfer in the liquid and monitoring of the temperature fields and gradients in the course of an experimental run. In spite of many methods being reported for the determination of thermal conductivity,^{25,26} reliable data for these classes of materials are still lacking. The increased interest in different commercial composite materials used in the casting industry and demands for engine oils and coolants with greater heat transfer capabilities in the auto industry claims to improve direct measurement methods for thermal conductivity.

The different techniques for determining the thermal conductivity of liquid can be classified into the various hot wire methods under the category of steady-state and transient methods. Both these methods have certain advantages and disadvantages. The steady-state methods have certain merits in relation to the simplicity of the equipment design and use of simple and reliable equations. The transient hot wire (THW) method has been well developed and widely used for measurements of the thermal conductivities and, in some cases, the thermal diffusivities of fluids with a high degree of accuracy.²⁷⁻³¹ Modified transient hot wire apparatuses have

also been reported for different measurement situations and purposes.³²⁻³⁶ The most attractive advantage of this method for application to fluids is its capacity for experimentally eliminating convective error and the data obtained are more reliable than those obtained using the steady-state method. Although the THW can be considered as an absolute technique and instruments based on its principle are considered capable of providing the highest accuracy possible, at present the melt density and specific heat capacity needed for calculations are often unknown. Finally, there should be no chemical reactions between the electrically conducting melt and the wire; thus it is necessary to apply a coating. The application of the THW may be restricted to high temperatures since with increasing temperatures the coatings become progressively more conducting, more vulnerable to chemical attack, and the mismatch in thermal expansions of metal and coating becomes more pronounced and can lead to spalling.

Sklyarchuk and Plevachuk³⁷ described an experimental arrangement based on the steady-state concentric cylinder method for the measurement of the thermal conductivity of liquid metals over a wide temperature range (up to 1700 K) under ambient pressures of argon gas (up to 1 MPa). In this method particular attention was paid to the minimization of heat leakage and convection heat flows. The authors obtained the results for thermal conductivity of molten Pb and Sn in this investigation and found that they were in good agreement with the values obtained in other THW investigations. This steady-state method is capable of measuring the thermal conductivity of liquids to an accuracy of 7%, as reported by the authors.

Hung *et al.*³⁸ described a device based on THW methodology for measuring conductivity of nanofluids. The THW technique is widely employed to measure thermal conductivity of nanofluids. The approach adopted by the authors consisted of using sensing wires made of nickel-chromium alloy and covered with Teflon. Nickel-chromium alloy wire was used as it is less expensive compared to platinum wire, can be changed easily at any time, and can avoid errors when measuring electric conductivity of fluid. The authors compared the results for the enhanced thermal conductivity ratio from their measurements with two different approaches from the literature and found that the difference was within $\pm 5\%$.

Shawn *et al.*³⁹ described an optical beam deflection technique for measurements of the thermal diffusivity of fluid mixtures and suspensions of nanoparticles. Solutions of C₆₀-C₇₀ fullerenes in toluene and suspensions of alkanethiolate protected Au nanoparticles were measured to maximum volume fractions of 0.6% and 0.35 vol %, respectively. The approach was based upon the deflection of a laser beam created by a gradient in the index of refraction in the fluid. The index of the refraction gradient was created by alternately heating a pair of parallel Au thin-film lines fabricated by photolithography on a fused silica (FS) substrate. The Au line heaters were separated by 50 μm and have a width of 6 μm . The fluid cell was mounted on a two-axis tilt stage and heated from above. The laser beam first passed between the metal line heaters on the FS substrate and then through

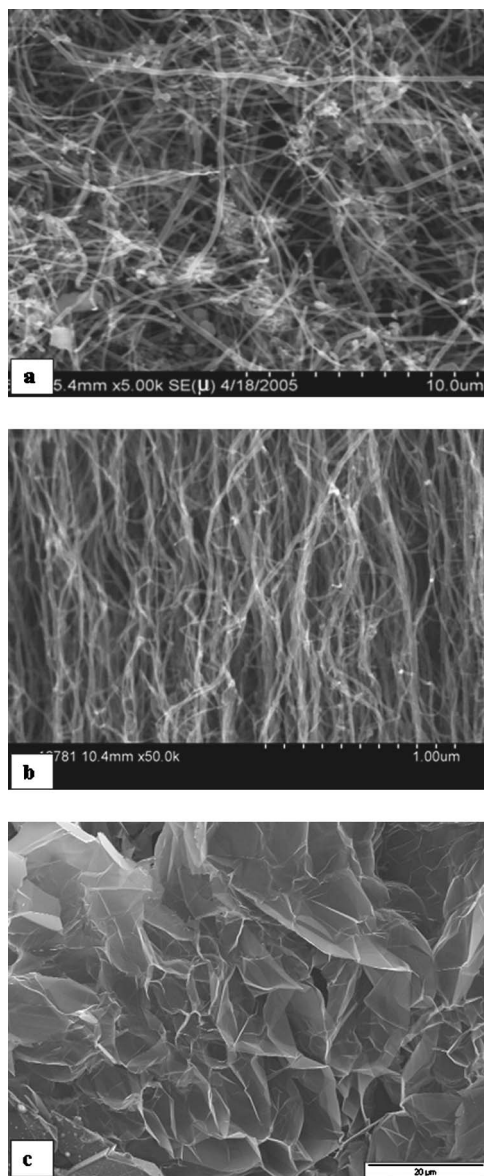


FIG. 2. (a) Scanning electron microscopy images of heat treated carbon nanofibers (HTTs). (b) Scanning electron microscopy images of carbon nanotubes (CNTs). (c) Scanning electron microscopy images of exfoliated graphite (EXG).

the fluid under study. The periodic beam deflections exiting the fluid cell were measured with a position-sensitive detector and lock-in amplifier. The authors concluded that they did not observe a significant enhancement in the thermal conductivity of fluids that was loaded by small volume fractions of nanoparticles. Within the context of effective medium theory, these findings were expected. The experimental results were, however, in direct conflict with the anomalous results of theoretical models in literature that attempt to explain the anomalous experimental results. The authors further stated that since they were unable to synthesize and study well-dispersed nanoparticle suspensions with greater concentrations, they cannot exclude the possibility that higher loadings of nanoparticles greater than (1 vol %) could enhance the thermal conductivity of fluids to an extent significantly larger than the predictions of effective medium theory.

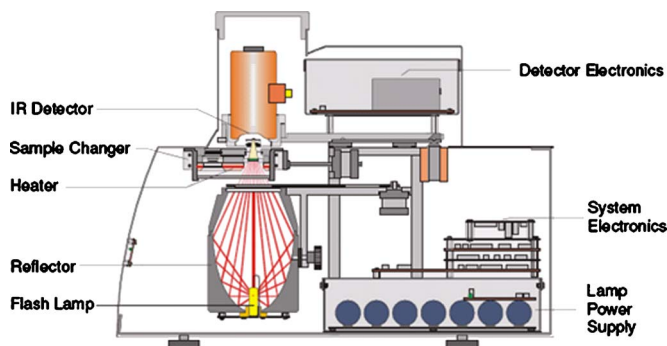


FIG. 3. Detailed view of the laser flash apparatus (LFA 447).

III. EXPERIMENTAL METHOD

A. Fabrication of materials

The present experimental investigation involves the thermal diffusivity analysis of PAO (poly-alpha-olefin) oil due to the inclusion of three different types of additives: carbon nanotubes (CNTs), heat treated nanofibers (HTTs), and exfoliated graphite powder (EXG). As shown in Fig. 2 these nanoparticles are distinct in shape and dimension. Carbon nanofibers (NF) were produced through the pyrolysis of carbon-containing gases (methane, ethylene, acetylene, carbon monoxide, etc.) on a metal (most often iron) catalyst at 500–1100 °C and then heat treated to 3000 °C. The average diameter is about 100 nm [Fig. 2(a)]. CNTs consist of a multiple cylinders of graphite sheets and are approximately 10–15 nm in diameter [Fig. 2(b)] and were produced by chemical vapor deposition using carbon monoxide and an iron cobalt catalyst at a temperature between 600 and 800 °C. However, the expanded or exfoliated graphite (EXG) was prepared as follows: A mixture containing sulfuric acid and natural graphite was prepared. After 24 h of reaction, the acid was absorbed by the graphite flakes and then the mixture was filtered, washed with water, and dried. The graphite intercalation compound thus formed was put in an oven at 900 °C where rapid expansion occurred. The expansion ratio was as high as 300 times [Fig. 2(c)]. All nanoparticles were functionalized by adding phenyl and carboxylic groups to facilitate their dispersion in the oil. Then the suspension was shear mixed and sonicated for a period of 1 h to obtain a well-dispersed and stable suspension.

B. Thermal measurement

A schematic arrangement of the laser flash (LFA-447) apparatus is shown in Fig. 3.

The LFA 447 is a modern contact-free laser flash method used for the measurement of thermal diffusivity of both solids and liquids. As shown in Fig. 3, the light pulse is produced by means of a high-performance xenon flash lamp placed within a parabolic mirror. A homogeneous illumination of the entire sample surface is achieved. Both the released energy of the flash lamp and the length of the heating pulse can be adjusted via the 32-bit Microsoft Windows software nanoflash. The flash lamp, sample, and infrared detector are vertically arranged. The samples are located in an automatic sample changer, with which up to four samples can be

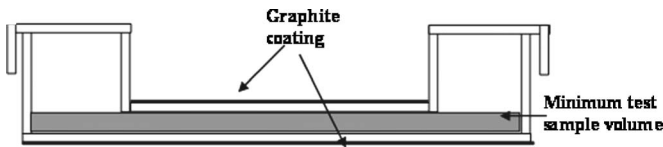


FIG. 4. Sample holder for nanofluid thermal diffusivity measurement.

measured in one measuring cycle. There are standard sample holders for testing round and square samples from 8 to 25.4 mm width (see Fig. 4). The furnace (room temperature to 300 °C) is directly integrated into the sample changer, creating a small thermal mass and therefore fast heating and cooling times are possible. The sample thermocouple, which accurately measures the temperature, is positioned in the sample carrier. The measurement of the temperature rise, after the light pulse, is carried out with liquid nitrogen cooled in Sb infrared detector. The noncontact measurement of the temperature rise guarantees an easy sample change and a short response time for the signal acquisition system. There are 15 different evaluation models, with and without correction, which can take into consideration heat losses from the side and from the front surfaces. Also, the analysis of two- and three-layer component systems, using nonlinear regression, with or without pulse length correction, is possible. All the data gathered from the measurements taken using NANOFLASH software is loaded in another software, LFA analysis. This software does the calculation of the thermal properties and makes plots for all the measured values. The thermal diffusivity measuring range is 0.01 to 0.01–1000 mm²/s with reproducibility of approximately $\pm 3\%$. In addition to the thermal diffusivity, by employing a comparative method, the specific heat can also be determined with this apparatus by using a known sample as the reference. For the specific heat, a reproducibility of $\pm 5\%$ is achieved. If the bulk density is known, a direct determination of the thermal conductivity is possible. The thermal conductivity range is 0.1–2000 W/mK.

The analysis procedure for measuring liquid samples using LFA-447 is slightly different from that followed for a solid sample. The main difference is in the type of sample holder used and the corresponding input data entered in NANOFLASH software.

To prepare the holder for testing, a thin coating of graphite is sprayed on the bottom of the container and on the top of the lower surface of lid. For the lid a mask is used to prevent coating other surfaces. Accurate values of the density and specific heat of the liquid sample are needed to measure the thermal conductivity of the liquid sample. Now the target sample mass is calculated from the target sample volume and sample density. This target sample mass is now accurately weighed out and poured into the container using a syringe or dropper (see Fig. 5). Now, by using the recommended measurement settings in Nanoflash software, around eight to ten measurements are taken for the liquid sample. After measurements are complete, the data is loaded into LFA analysis software, which calculates the thermal diffusivity of the liquid sample. By using a reference liquid sample with known values of thermal diffusivity, and specific heat the specific heat of the tested sample can be measured.

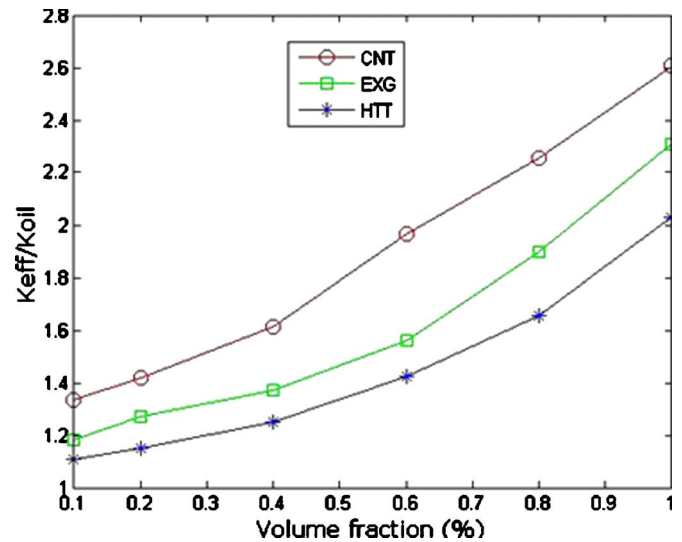


FIG. 5. Trend for measured values of thermal conductivity with different nanoparticle loadings for the three types of nanoparticle-oil suspensions.

C. Experimental results and discussions

Before starting with the measurements for the nanofluid samples, verification of the accuracy of the measurement procedure was carried out by measuring thermal diffusivity of liquid samples like distilled water, ethylene glycol, and olive oil and the results were compared with literature.

Using the procedure adopted above thermal diffusivity measurements were carried out for the above liquid samples. For all the three samples ten readings were taken and the average value of the thermal diffusivity (α_s) was obtained in mm²/s. From Table I it can be seen that a good agreement was observed between the measured values and the values from literature for the three liquid samples. The reproducibility in the thermal diffusivity values for all the three samples was around $\pm 2.5\%$. All the values for thermal diffusivity were measured around 25 ± 0.5 °C.

After comparison of the LFA technique with literature, the three types of nanofluid samples were then analyzed for their thermal diffusivity and thermal conductivity. As described before, all three nanofluid samples CNT, HTT, and EXG were prepared for different loadings of the nanoparticles from 0.1% to 1%. The density of the nanofluid samples corresponding to different loadings were calculated from the rule of mixture. In order to keep the samples well dispersed all three nanofluid samples were kept continuously in the sonic-bath. The three nanofluid samples each with different loading percentage were then analyzed for their thermal diffusivity on the LFA device. For each type of sample total eight readings were taken and the average value of the ther-

TABLE I. Data comparison between measured and published diffusivities for various liquids.

Liquid sample	Present LFA method α_s (mm ² /s)	Literature α_s (mm ² /s)	Reference No.
Distilled water	0.1442 \pm 0.002	0.1456	45
Ethylene glycol	0.0918 \pm 0.001	0.0939	46
Olive oil	0.0881 \pm 0.001	0.0799	44,47

TABLE II. Percent thermal property enhancement for measured nanofluids.

Sample type	Thermal diff. (α_{av}) (mm ² /s)	Percent increase in α	Thermal cond. (K) (W/mK)	Percent increase in K
PAO Oil	0.2671	–	0.1166	–
CNT PAO-oil suspensions				
PAO/CNT (0.1%)	0.3230	20.97	0.1558	33.62
PAO/CNT (0.2%)	0.3425	28.27	0.1652	41.69
PAO/CNT (0.4%)	0.3901	46.10	0.1882	61.38
PAO/CNT (0.6%)	0.4750	77.90	0.2291	96.51
PAO/CNT (0.8%)	0.5449	104.08	0.2629	125.43
PAO/CNT (1%)	0.6300	135.95	0.3039	160.63
EXG PAO-oil suspensions				
PAO/EXG (0.1%)	0.2890	8.23	0.1377	18.12
PAO/EXG (0.2%)	0.3010	12.73	0.1435	23.02
PAO/EXG (0.4%)	0.3359	25.80	0.1601	37.29
PAO/EXG (0.6%)	0.3820	43.07	0.1821	56.13
PAO/EXG (0.8%)	0.4640	73.78	0.2211	89.65
PAO/EXG (1%)	0.5650	111.61	0.2693	130.93
HTT PAO-oil suspensions				
PAO/HTT (0.1%)	0.2740	2.62	0.1290	10.63
PAO/HTT (0.2%)	0.2850	6.74	0.1342	15.07
PAO/HTT (0.4%)	0.3101	16.10	0.1459	25.16
PAO/HTT (0.6%)	0.3519	31.83	0.1657	42.12
PAO/HTT (0.8%)	0.4113	53.93	0.1935	65.94
PAO/HTT (1%)	0.5031	88.38	0.2368	103.09

mal diffusivity (α_{av}) was obtained in mm²/s. The specific heat of the nanofluid samples was then measured using distilled water as the reference sample. The measured specific heat value was approximately similar to the one calculated from the rule of mixture with an error of $\pm 4\%$. The calculated value of density and the measured values of the specific heat and thermal diffusivity were then used to estimate the thermal conductivity of all the nanofluid samples. Table II gives the results for the thermal diffusivity and thermal conductivity for the CNT, HTT, and EXG nanofluid samples, respectively, for loading between 0.1% and 1% as compared to the base fluid, which is the PAO oil. Also Fig. 5 gives the plots showing the trend for the change in ratio of effective thermal conductivity to thermal conductivity of oil for all three types of nanofluids with the increase in loading of nanoparticles.

From Table II it can be seen that as the percentage of volume of nanoparticles was increased for all three types of nanofluids, effective thermal conductivity showed an increase. The maximum value of percentage enhancements for the CNT, EXG, and HTT nanoparticle-oil suspensions were 160.63%, 130.93%, and 103.09%, respectively, corresponding to 1% volume of the nanoparticles. Among all three types of nanofluids, the CNT based nanoparticle-oil suspension had the greatest enhancement (160.63%). This result for the CNT-oil suspension is similar to that observed by Choi *et al.*¹⁸ They noted an enhancement of 160% for the CNT-oil suspension for oil with thermal conductivity of 0.1448 W/mK.

Figure 5 gives the trend for change in the thermal conductivity ratio with the volume fraction for the three types of nanoparticle-oil suspensions. It was observed that the trend for all three nanofluids was nonlinear, which is once again

similar to the observation of Choi *et al.*¹⁸ It was interpreted that the maximum percentage enhancement obtained for the CNT based nanofluid was due to the better mixing of the carbon nanotubes in the PAO oil. The visual of all three types of nanofluids clearly revealed that the carbon nanotubes were well dispersed in the oil as compared to the exfoliated graphite and heat-treated nanofiber particles. Also the other important reason can be the higher thermal conductivity of the CNT as compared to EXG and HTT nanoparticles.

IV. CONCLUSIONS

A detailed experimental study was carried out to analyze the effective thermal conductivity of nanoparticle-PAO-oil suspensions with three types of nanoparticles, namely, CNT, EXG, and HTT. The study included the use of a modern light flash technique to measure the thermal conductivity of the three nanofluids with different nanoparticle loadings. The results obtained were similar to that observed in literature for experimentally measured thermal conductivity values of nanofluids. The percent enhancement in the thermal conductivity of the three nanofluids over the PAO oil was maximum for the CNT based nanoparticle suspension followed by the EXG and HTT. From the experimental results it was concluded that the high thermal conductivity possessed by the carbon nanoparticles and their good dispersion ability contributed to the significant improvement in the effective thermal conductivity of the three nanofluids analyzed.

- ¹J. C. Maxwell, *A Treatise on Electricity and Magnetism* (Clarendon, Oxford, 1891).
- ²P. Keblinski, J. A. Eastman, and D. G. Cahill, *Mater. Today* **8**, 36 (2005).
- ³S. U. S. Choi, *Proceedings of the American Society of Mechanical Engineers* **66**, 99 (1995).
- ⁴Y. Xuan and Q. Li, *Int. J. Heat Fluid Flow* **21**, 58 (2000).
- ⁵S. U. S. Choi, Z. G. Zhang, W. Yu, F. E. Lockwood, and E. A. Grulke, *Appl. Phys. Lett.* **79**, 2252 (2001).
- ⁶S. K. Das, N. Putra, P. Thiesen, and W. Roetzel, *J. Heat Transfer* **125**, 567 (2003).
- ⁷H. E. Patel, S. K. Das, T. Sundararajan, N. A. Sreekumaran, and B. George, *Appl. Phys. Lett.* **83**, 2931 (2003).
- ⁸S. M. You, J. H. Kim, and K. H. Kim, *Appl. Phys. Lett.* **83**, 3374 (2003).
- ⁹P. Vassallo, K. Ranganathan, and S. D'Amico, *Int. J. Heat Mass Transfer* **47**, 407 (2004).
- ¹⁰P. M. Ajayan, M. Terrones, A. de la Guardia, V. Huc, N. Grobert, B. Q. Wei, H. Lezec, G. Ramaneth, and T. W. Ebbesen, *Science* **296**, 705 (2002).
- ¹¹S. K. Das, N. Putra, and W. Roetzel, *Int. J. Heat Mass Transfer* **46**, 851 (2003).
- ¹²H. Masuda, A. Ebata, K. Teramae, and N. Hishinuma, *Netsu Bussei* **4**, 227 (1993).
- ¹³S. Lee, S. U. S. Choi, S. Li, and J. A. Eastman, *J. Heat Transfer* **121**, 280 (1999).
- ¹⁴H. J. Xie, J. Wang, T. Xi, Y. Liu, and F. Ai, *J. Appl. Phys.* **91**, 4568 (2002).
- ¹⁵H. Xie, J. Wang, T. Xi, and Y. Liu, *Int. J. Thermophys.* **23**, 571 (2002).
- ¹⁶M. J. Assael, C. R. Chen, I. N. Metaxa, and W. A. Wakeam, *Proceedings of the 27th International Thermal Conductivity Conference and 15th International Thermal Expansion Symposium*, edited by H. Wang and W. D. Porter (DES Tech Publications, Lancaster, PA, 2005), Vol. 153.
- ¹⁷M. J. Biercuk, M. C. Llaguno, M. C. Radosavljevic, J. K. Hyun, A. T. Johnson, and J. E. Fischer, *Appl. Phys. Lett.* **80**, 2767 (2002).
- ¹⁸J. A. Eastman, S. U. S. Choi, S. Li, W. Yu, and L. J. Thompson, *Appl. Phys. Lett.* **78**, 718 (2001).
- ¹⁹H. Xie, H. Lee, W. Youn, and M. Choi, *J. Appl. Phys.* **94**, 4967 (2003).
- ²⁰D. S. Wen and Y. L. Ding, *J. Thermophys. Heat Transfer* **18**, 481 (2004).
- ²¹S. Kasukabe, S. Yatsuya, and R. Uyeda, *J. Cryst. Growth* **24-25**, 315 (1974).

- ²²M. Brust, M. Walker, D. Bethel, and D. J. Schiffrin, *J. Chem. Soc., Chem. Commun.* **7**, 801 (1994).
- ²³O. M. Wilson, H. Xiaoyuan, G. C. David, and V. B. Paul, *Phys. Rev. B* **66**, 224301 (2002).
- ²⁴L. P. Filippov, *Int. J. Heat Mass Transfer* **11**, 331 (1968).
- ²⁵Y. Nagasaka and A. Nagashima, *J. Phys. E: J. Sci. Instrum.* **14**, 1435 (1981).
- ²⁶J. S. Powell, *Meas. Sci. Technol.* **2**, 111 (1991).
- ²⁷C. A. N. Castro, J. C. G. Calado, M. Dix, and W. A. Wakeham, *J. Phys. E: J. Sci. Instrum.* **9**, 1073 (1976).
- ²⁸Y. Nagasaka and A. Nagashima, *Rev. Sci. Instrum.* **52**, 229 (1981).
- ²⁹A. N. Gurova and C. A. N. Castro, *Proceedings of the 4th Asian Thermophysical Properties Conference*, Tokyo, edited by A. Nagashima (Tokyo, 1995), Vol. 129.
- ³⁰M. J. Assael, E. Charitidou, C. A. N. Castro, and W. A. Wakeham, *Int. J. Thermophys.* **19**, 379 (1998).
- ³¹H. Xie, J. Wang, T. Xi, Y. Liu, F. Ai, and Q. Wu, *J. Appl. Phys.* **91**, 4568 (2002).
- ³²S. E. Gustafsson, *Rev. Sci. Instrum.* **62**, 797 (1991).
- ³³T. Log, *J. Am. Ceram. Soc.* **74**, 650 (1991).
- ³⁴N. Mathis, *High Temp. - High Press.* **32**, 321 (2000).
- ³⁵X. G. Liang, Y. Zhang, and X. Ge, *Phys. Med. Biol.* **36**, 1599 (1991).
- ³⁶H. Xie and S. X. Cheng, *Meas. Sci. Technol.* **12**, 58 (2001).
- ³⁷V. Sklyarchuk and Y. Plevachuk, *J. Mater. Sci. Technol.* **16**, 467 (2005).
- ³⁸C. S. Jwo, T. P. Teng, C. J. Hung, and Y. T. Guo, *J. Phys.: Conf. Ser.* **13**, 55 (2005).
- ³⁹S. A. Putnam, D. G. Cahill, P. V. Braun, Z. Ge, and R. G. Shimmin, *J. Appl. Phys.* **99**, 084308 (2006).