A review on measurement techniques of apparent thermal conductivity of nanofluids

Tang Tsz Loong¹, Hamidon Salleh²

Faculty of Mechanical and Manufacturing Engineering, Universiti Tun Hussein Onn Malaysia, 86400 Parit Raja, Batu Pahat, Johor, Malaysia

Corresponding author: gd160030@siswa.uthm.edu.my, hamidon@uthm.edu.my

Abstract. Thermal conductivity of nanofluids has been extensively studied for a number of years because it is a very first evaluation of the heat transfer performance of nanofluids. However, not the single theoretical model predicts thermal conductivity of nanofluids accurately. Hence, different measurement techniques have been used to measure thermal conductivity of nanofluids. This paper focuses on different measurement techniques of thermal conductivity of nanofluids. The working principle, limitation and advantages of different measurement techniques have been discussed. The measurement techniques discussed in this paper included transient hot wire, transient plane source, 3-omega technique, steady-state parallel method, thermal comparator and laser flash method. Eventually, some suggestions have been made for improving the reliability of the measurement of thermal conductivity.

1. Introduction

A nanofluid is a fluid contains suspended nanoparticles typically in size from 1 to 100nm [1, 2]. With the presence of nanoparticles, thermal conductivity of nanofluids is enhanced significantly when compare to fluids without suspended nanoparticles [3]. Application of high thermal conductivity of nanofluids brings promising hope to industry by reducing the energy consumption and enhance heat transfer performance of engineering system [2]. Hence, the worldwide thermofluids enthusiast has launched research on nanofluids as a potential alternative for traditional heat transfer fluids.

Thermal conductivity of nanofluids has been extensively studied for a number of years because it is a very first evaluation of the heat transfer performance of nanofluids [3]. The thermal conductivity of nanofluids is one of the significant parameters which influences convective heat transfer of nanofluids [4]. There are many theoretical models have been proposed to predict thermal conductivity of nanofluids. However, not the single theoretical model predicts thermal conductivity of nanofluids accurately [5, 6]. Hence, different measurement techniques have been used to measure thermal conductivity of nanofluids.

A number of researchers have reported different measurement techniques for study apparent thermal conductivity of nanofluids. The measurement technique included transient hot-wire, transient plane source, 3-omega techniques, steady-state parallel plate, thermal comparator, laser flash method and etc. Experiments reveal anomalous enhancements of thermal conductivity of nanofluids have been observed. The anomalous enhancement of thermal conductivity of nanofluids has been the subject of intense debate within the scientific community. Lee, et al. [7], Choi, et al. [8], Eastman, et al. [9] and Chopkar, et al. [10] have been reported anomalous enhancement with a nonlinear relationship with increases volume fraction of nanoparticles. However, Buongiorno, et al. [11] and Antoniadis, et al. [12]
has pointed out that the no anomalous enhancement is observed in experiment if appropriate practice is strictly followed in experiments. In this regard, careful thermal conductivity measurements have to conduct in order to validate different models proposed to describe thermal conductivity enhancement of nanofluids.

2. Apparent thermal conductivity measurement technique for nanofluids

2.1 Transient hot-wire

Transient hot-wire (THW) determines the thermal conductivity of material sample based on investigation of the transient temperature rise of a thin, vertical, long and resistive wire (Rw) immersed in fluid sample [12]. The wire (Rw) originally in thermal equilibrium to surrounding and a step current is passed through the wire. The wire (Rw) is heated up and time-dependent temperature field inside the wire and material sample is produced. Then, the thermal conductivity of fluid sample can be calculated from the gradient of temperature rise of wire versus natural logarithms of time graph. The temperature rise of wire is normally measured from Wheatstone bridge and an A/D converter is used to convert analog data to digital data then store in computer for further analysis. A schematic diagram of transient hot-wire is shown as Figure 1.

![Schematic diagram of transient hot-wire](image)

**Figure 1.** Schematic diagram of transient hot-wire [7]

Many researchers have employed THW to measure apparent thermal conductivity of nanofluids [7, 13-16]. THW is the most popular measurement technique among other measurement technique because it is well-establish and able to measure nanofluids with low uncertainty [17]. The measurement time for THW is sufficiently short, thus this avoids the experiment results containment by natural convection [13]. Furthermore, THW is simple to use and easy to construct. In addition, THW technique is getting more accurate and reliable due to advancement in electronic device and a full set of theory exist that make absolute measurement of low uncertainty be possible [18]. These reasons have contributed to THW become a widespread measurement technique in the nanofluids research field. However, THW has difficulty in measurement of the thermal conductivity of nanofluids in saturated region and critical region. With the exception of this region THW can achieve absolute uncertainty below 2% for nanofluid [19].

Despite of low uncertainty measurement can be achieved by THW, large discrepancies between published results of nanofluids have been observed. Many researchers have tried to explain this phenomenon based on the physics of nanofluids [20]. In contrast, Tertsinidou, et al. [20] refused this point of view and they pointed out that the cause is mainly due to inappropriate application of THW in an experiment. Antoniadis, et al. [12] has discussed on necessary condition for accurate measurement of THW. They pointed out two wire arrangement (eliminate the end effect), diameter of the wire less than 30mm (to mimic line heat source), insulated wire (avoid current leakage) and small temperature rise (avoid contamination of convection) should be employed to secure low uncertainty of THW while measures thermal conductivity of nanofluids. Furthermore, temperature data range selection is also an
important issue for THW [21]. Hong, et al. [21] did an impact analysis of natural convection on THW measurements of thermal conductivity nanofluids. They discovered the temperature data range is differed depending on type of fluids. The start time should be selected after the heat flux on the wire surface to reach steady state and the end time should be selected before the effect of convection is significant to result. Moreover, the data range should be sufficiently large to avoid the result contaminated by local oscillation of the estimation. Furthermore, Hong, et al. [21] also pointed out that the temperature data range for nanofluids is shorter compared to base fluid may be due to local motion of nanoparticles induces natural convection occurs at early time. In a nutshell, all mentioned precautions have to take care to secure good accuracy of THW measurement of thermal conductivity of nanofluids.

2.2 Transient plane source

Transient plane source (TPS) also can be known as a thermal constant analyzer or Gustafsson probe technique [22]. The experiment setup of transient plane source is schematically shown in Figure 2 (a). The experimental set up comprises thermal constant analyzer, probe, constant temperature bath, sample cell and thermometer. The TPS probe consists of a hot disk sensor in the shape of a plane double spiral embedded in insulating layer and it is shown as Figure 2 (b). The TPS probe acts as both heat source and temperature sensor immersed in a fluid sample. A step voltage is applied to the sensor and at the same time the resistance rise of double spiral is measured by a thermal constant analyzer. Then, a set of data on the average temperature rise of the double spiral versus time is obtained and stored in the computer via thermal constant analyzer. This set of data on the average temperature rise can be used to measure thermal conductivity and thermal diffusivity of material sample incorporated with principle of Fourier Law of heat conduction [22, 23].

![Figure 2. Schematic diagram of TPS device: (a) Experiment setup for TPS (b) TPS probe [24]](image)

The TPS has been used by Zhu, et al. [25], Jiang, et al. [24], Zhi, et al. [26], Wan, et al. [27] and Nikkam, et al. [28] for measuring apparent thermal conductivity of nanofluids. The TPS able detects occurrence of natural convection by examining experiment data. If natural convection is occurring, the experiment data would not fit in the graph, hence, the measurement is not accurate. In this particular case, the thermal analyzer would give an alarm to prevent using the inaccurate data. Furthermore, TPS can use to measure a wide range of thermal conductivity typically from 0.02W/mK to 200W/mK and the sample size is flexible whereby no need sample preparation [25]. However, TPS cannot use to measure thermal conductivity of fluid which undergoes the boiling process. Because the temperature maintains constant at this process whereby not temperature rises can be detected.

Performance of TPS can be improved if two factors have taken into account where there are heat capacity and resistance change of the TPS probe. In this regard, Li, et al. [29] has proposed correction on these two factors. They have used the improved model to measure acrylic standard materials and found improvement about 1.8 to 2.3% as evaluated by the relative standard deviation.
2.3 3-Omega technique

For 3-omega technique, an insulated metal wire is immersed into the material sample acting as both heat source and temperature sensor as shown in Figure 3. A sinusoidal current at frequency $\omega$ is applied to the metal wire, and then a heat wave at frequency $2\omega$ is generated in the material sample, hence, temperature rise of frequency $2\omega$ also has been produced in the wire. The temperature oscillation can be deduced by the voltage component at frequency $3\omega$. Eventually, the liquid thermal conductivity can be obtained from the slope of the straight line of the graph, because the thermal conductivity of the liquid is inversely proportional to the slope of the $2\omega$ temperature rise of the wire as a function of the driven frequency $\omega$ [30]. The test cell is placed in a circulating thermal bath to control the temperature of the sample nanofluids. This technique has been used to measure nanofluids by Oh, et al. [31], Han, et al. [32], Karthik, et al. [30], Tavman, et al. [33] and Wang, et al. [34].

Based on Oh, et al. [31], the thermal conductivity of the nanofluids can be measured by $3\omega$ technique even though, in single droplet volume size. Besides that, the gravitational effect on nanofluids also can be studied by altering the orientation of the device. Furthermore, the stability of nanofluids also can study by this device observe the thermal conductivity enhancement due to sedimentation of nanoparticles. However, $3\omega$ technique has a significant drawback when measure nanofluids with lower thermal conductivity and heat capacity. In this regard, less heat is flowing from metal strip to fluid as compared to the solid substrate with high thermal conductivity and heat capacity. This cause the $3\omega$ signal from solid substrate more significant than fluid, hence reduce the precision of the device.

![Figure 3](image)

**Figure 3.** Schematic of an experimental set up for 3-omega method: (a) top view of the device and (b) side view of the device (not to scale) [31]

2.4 Steady state parallel plate

The steady-state parallel method use simple heat transfer concept to measure thermal conductivity of material sample by using one dimensional heat conduction equation and concept of thermal resistance. The schematic experimental setup for the steady state parallel plate is shown as Figure 4. The fluid sample is placed between upper copper plate and the lower plate. A glass spacer is used to make a space between upper copper plate and the lower plate to fill in a fluid sample. The heat flux flows in the direction from heater 1 to the lower copper plate. Heater 2 and 3 is operated to avoid any heat loss from upper copper plate to the environment by raise temperature of aluminium cell. Heater 4 is used to maintain temperature uniformity of the lower copper plate. After steady temperature difference between the lower surface of upper copper plate and upper surface of lower copper plate is attained, the thermal conductivity of material sample can be calculated from one-dimensional heat conduction equation.
Figure 4. Schematic experimental setup for steady state parallel plate [35]

Basically, Steady-state parallel method is categorized under steady state measurement method. For steady measurement technique the measurement process is done when the temperature of the testing sample does not change with time. However, this type of measurement method is often claimed that take long measurement time to determine the thermal conductivity of nanofluids. Thus, natural convection in nanofluids is unavoidable, especially at elevated temperatures. However, Steady–state parallel method is still being chosen to measure thermal conductivity of nanofluid because of its simplicity of design and the governing equation of this method is simple and reliable. Due to the mentioned benefit, Wang, et al. [35] and Li and Peterson [36] had used this method to measure thermal conductivity of nanofluids.

2.5 Thermal comparator

Thermal comparator method (TC) is used by Paul, et al. [37] and Chopkar, et al. [10] to measure thermal conductivity of zirconium oxide and titanium oxide based nanofluids. The thermal conductivity of material sample can be obtained instantly by use a probe make point contact on the liquid surface of the sample. The schematic diagram of thermal comparator is shown as Figure 5. The probe had heated over a period till the constant temperature difference between the probe and material sample was attained. Then, the sample which has placed in the container was raised up by screw jack until a point contact is made between the probe and the liquid surface of the sample. An instant temperature is attained at this point contact and it is dependent on thermal conductivity of probe and material medium. The temperature at this point was measured by proportional comparator reading or voltage output and a calibration curve is used to convert the comparator reading to the corresponding thermal conductivity of nanofluids.

Figure 5. Schematic of an experimental setup for thermal comparator [37]
TC is a very sensitive device to measure thermal conductivity of nanofluids. This technique can measure thermal conductivity at the instant just by making a point contact between probe and testing sample. Thus, convection of fluid during the experiment can be avoided and improved the precision of the device. The drawback of this technique is required to do a lot work to calibrate the device. Difference liquids with known thermal conductivity have been used to obtain their comparator reading respectively. With this set of data, a calibration curve can be obtained and thermal conductivity of testing sample can be obtained by comparing the comparator in the calibration curve. However, once the calibration curve is plotted out, the thermal conductivity of testing sample can be obtained just by referring to the comparator reading.

2.6 Laser flash method

The laser flash method (LF) is first designed by Parker, et al. [38] used to measure the thermal diffusivity of solid material. Bazan [39] used LF to measure both thermal diffusivity and thermal of poly-alpha-olefin oil based nanofluid. The model of the laser flash apparatus used by Bazan [39] is LFA 457 and the schematic of the apparatus is shown as Figure 6. The sample was filled inside a sample holder which bottom coated with graphite. Then, this sample holder was placed inside of furnace of the device. A laser beam is produced then directed to the sample by a 45° reflecting mirror. The temperature rise of sample is then measured by the detector. This process is monitored by software which is developed for LFA 457. Before the experiment is started, the software required the information of density and specific heat of the liquid sample. With this information, the thermal conductivity and thermal diffusivity of the liquid sample is determined. Besides Bazan [39], investigator such as Shaikh, et al. [40], Li, et al. [41] and Wang, et al. [42] has used LF to measure thermal conductivity of nanofluid.

LF is suitably used to measure thermal conductivity of electrically conducting liquid because laser beam is used instead of electrical current as a heat source of the sample. Nanofluids are electric conducting in nature whereby LF can be used to measure thermal conductivity of nanofluids. Furthermore, the measurement is done in a very short time, thus convection can be avoided. However, laser flash method is not suitable measure nanofluids with low thermal conductivity due to their thermal conductivity will be approximately same as most of the material that serve as the liquid container [5]. Hence, the heat flux passes through the container and cannot be neglected during the experiment. This has made the heat flow in sample be higher-dimensional flow rather than one-dimensional. Therefore, appropriate sample geometries have to choose so that mathematical complexity can be avoided [43].

![Figure 6. Schematic diagram of LFA457 [39]](image-url)
3. Discussion

A literature survey has been done on the six measurement techniques which have discussed in this review paper. Based on table 1, THW is the most frequently used measurement technique for nanofluids compared to other techniques due to its well known reputation. On the other hand, steady-state parallel method is the least popular among measurement techniques, although the design of this method is simple and easy to use. This is because steady-state parallel method natural has high tendency occurs natural convection during the measurement process, thus make the measurement result less accurate.

| Measurement technique          | Published literature (%) |
|-------------------------------|--------------------------|
| Transient hot-wire            | 51.72                    |
| Transient plane source        | 20.69                    |
| 3-omega technique             | 8.62                     |
| Steady-state parallel method  | 5.17                     |
| Thermal Comparator            | 6.90                     |
| Laser flash method            | 6.90                     |

There are two aspects have been concerned when come into thermal conductivity measurement for nanofluids. Firstly, the required time range of measurement is one of the important aspects have been concerned especially for thermal conductivity measurement of nanofluids because long measurement time range will induce natural convection and eventually affect the measurement result. Among these six measurement techniques, laser flash method is the fastest measurement technique since the measurement time is in several microseconds, which is much shorter than THW measurement time in 2 to 8s [5]. Nevertheless, THW and TPS have longer measured time compare to LF, but their measurement time is considered fast and natural convection can be avoided by select measurement time range which without significant deviation from linearity of the graph. Furthermore, thermal comparator is also another measurement technique with fast response as this measurement technique can determine thermal conductivity of nanofluids just by contacting on nanofluids surface with a probe at an instant rate. In contrast, steady-state parallel method is relatively slow compared to other measuring technique due to the sample used in this technique is large, hence, it is required sufficiently amount of time to heat up the sample.

Secondly, degrees of disturbance of measurement techniques bring on nano fluids also have to be considered because the nanoparticles in nanofluids will be agglomerated easily if intense disturbance is applied to it. For example, a hot wire is immersed into the nanofluids sample at initial of measuring process for THW. This action may cause the agglomeration of nanoparticles in nanofluids hence affect the measurement result. As it can be seen, the same things are happening on TPS and 3 omega technique. Therefore, this aspect has to be taken into consideration during the design process of each measuring technique device. However, there are some measuring techniques have done excellent work with minimal disturbance on nanofluids. For instance, TC has minimized the disturbance by making a point contact with the surface of nanofluids only while taking measurements. Besides that, LF have the least disturbance since nothing makes contact with nanofluids due to the only a laser beam applied on the nanofluids and the detector is observed the changes at outside of the sample.

In a nutshell, nanofluids are a kind of challenge fluids to be measured due to its unknown mechanism for thermal conductivity enhancement. Therefore, there are many restrictions have to be aware when one is employing any type of measuring technique to measure thermal conductivity of nanofluids especially on the two aspects which have been discussed in this section. Based on literature review, the validity of measurement technique other than THW has been questioned because lack of reported result measured by a same measuring technique to support their measurement data validity
[6]. This has shown that why THW is more commonly used by investigator to study the thermal behavior of nanofluids due to its wide recognition on the validity of THW.

4. Conclusion

A brief review of different techniques for the measurement of thermal conductivity of nanofluids available in the literature has been made in this paper. The review shows that the transient hot-wire technique is the most frequently used thermal conductivity measurement technique of nanofluids due to the good reputation of THW. From this review activity a few key findings may be pointed out.

- Thermal conductivity of nanofluids could be influenced by various parameters such as volume fraction, temperature, material type of nanoparticles, pH value, stability of nanofluids and etc. However, most of the researchers focused on determining thermal conductivity of nanofluids for difference material type of nanoparticles and volume fraction.
- There is a high possibility of anomalous thermal conductivity enhancement of nanofluids is mainly due to inappropriate practice in the experiment. Proper procedures have to be formulated whereby assure the consistence measurement results.
- More benchmarking activity of a single type of nanofluids with various measuring techniques by strictly following standardizes procedure is preferable to validate anomalous thermal conductivity enhancement phenomenon of nanofluids.
- Although THW is the most recognizing measuring technique used to measure thermal conductivity of nanofluids. However, several conditions have to follow strictly when come into thermal conductivity measurement of nanofluids. These condition are using two wire arrangement (eliminate the end effect), diameter of the wire less than 30mm (to mimic line heat source), insulated wire (avoid current leakage) and small temperature rise (avoid contamination of convection).
- Furthermore, two aspects have been discussed in the discussion where they are measuring time range and degree of disturbance. Based on these two aspects, it can be seen LF is the best methods since it can measure nanofluids at an instant rate without applied any disturbance on nanofluids. However, this method is still no a popular choice compared to THW. This may be due to the high maintenance cost and complex design.

As a conclusion, the thermal conductivity enhancement mechanism of nanofluids is still a mystery, thus measurement technique has played a significant role to study the thermal behavior of nanofluids.

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References

[1] N. A. C. Sidik, H. Mohammed, O. A. Alawi, and S. Samion, "A review on preparation methods and challenges of nanofluids," International Communications in Heat and Mass Transfer, vol. 54, pp. 115-125, 2014.

[2] S. Jana, A. Salehi-Khojin, and W.-H. Zhong, "Enhancement of fluid thermal conductivity by the addition of single and hybrid nano-additives," Thermochimica acta, vol. 462, pp. 45-55, 2007.

[3] W. Yu, D. M. France, J. L. Routbort, and S. U. Choi, "Review and comparison of nanofluid thermal conductivity and heat transfer enhancements," Heat Transfer Engineering, vol. 29, pp. 432-460, 2008.

[4] M. Raja, R. Vijayan, P. Dineshkumar, and M. Venkatesan, "Review on nanofluids characterization, heat transfer characteristics and applications," Renewable and Sustainable Energy Reviews, vol. 64, pp. 163-173, 2016.

[5] C. Kleinstreuer and Y. Feng, "Experimental and theoretical studies of nanofluid thermal conductivity enhancement: a review," Nanoscale Research Letters, vol. 6, p. 229, 2011.

[6] S. Aberoumand, A. Jafarimoghadam, M. Moravej, H. Aberoumand, and K. Javaherdeh, "Experimental study on the rheological behavior of silver-heat transfer oil nanofluid and suggesting two empirical based correlations for thermal conductivity and viscosity of oil based nanofluids," Applied Thermal Engineering, 2016.

[7] S. Lee, S.-S. Choi, S. Li, and, and J. Eastman, "Measuring thermal conductivity of fluids containing oxide nanoparticles," Journal of Heat transfer, vol. 121, pp. 280-289, 1999.

[8] S. Choi, Z. Zhang, W. Yu, F. Lockwood, and E. Grulke, "Anomalous thermal conductivity enhancement in nanotube suspensions," Applied physics letters, vol. 79, pp. 2252-2254, 2001.

[9] J. A. Eastman, S. Choi, S. Li, W. Yu, and L. Thompson, "Anomalously increased effective thermal conductivities of ethylene glycol-based nanofluids containing copper nanoparticles," Applied physics letters, vol. 78, pp. 718-720, 2001.

[10] M. Chopkar, P. K. Das, and I. Manna, "Synthesis and characterization of nanofluid for advanced heat transfer applications," Scripta Materialia, vol. 55, pp. 549-552, 2006.

[11] J. Buongiorno, D. C. Venerus, N. Prabhat, T. McKrell, J. Townsend, R. Christianson, et al., "A benchmark study on the thermal conductivity of nanofluids," Journal of Applied Physics, vol. 106, p. 094312, 2009.

[12] K. D. Antoniadis, G. J. Tertsinidou, M. J. Assael, and W. A. Wakeham, "Necessary Conditions for Accurate, Transient Hot-Wire Measurements of the Apparent Thermal Conductivity of Nanofluids are Seldom Satisfied," International Journal of Thermophysics, vol. 37, pp. 1-22, 2016.

[13] S. Murshed, K. Leong, and C. Yang, "Enhanced thermal conductivity of TiO2—water based nanofluids," International Journal of thermal sciences, vol. 44, pp. 367-373, 2005.

[14] H. Masuda, A. Ebata, and K. Teramae, "Alteration of thermal conductivity and viscosity of liquid by dispersing ultra-fine particles. Dispersion of Al2O3, SiO2 and TiO2 ultra-fine particles," 1993.

[15] J. Eastman, U. Choi, S. Li, L. Thompson, and S. Lee, "Enhanced thermal conductivity through the development of nanofluids," in MRS proceedings, 1996, p. 3.

[16] Y. Xuan and Q. Li, "Heat transfer enhancement of nanofluids," International Journal of heat and fluid flow, vol. 21, pp. 58-64, 2000.

[17] W. A. Wakeham, A. Nagashima, and J. Sengers, Measurement of the transport properties of fluids vol. 3: Blackwell Science Inc, 1991.

[18] M. J. Assael, K. D. Antoniadis, and W. A. Wakeham, "Historical evolution of the transient hot-wire technique," International journal of thermophysics, vol. 31, pp. 1051-1072, 2010.

[19] K. A. Gillis, A. Froeba, S. Will, Y. Nagasaka, J. Winkelmann, S. Wiegand, et al., Experimental Thermodynamics: Advances in Transport Properties of Fluids vol. 9: Royal society of Chemistry, 2014.
[20] G. Tertsinidou, M. J. Assael, and W. A. Wakeham, "The apparent thermal conductivity of liquids containing solid particles of nanometer dimensions: a critique," *International Journal of Thermophysics*, vol. 36, pp. 1367-1395, 2015.

[21] S. W. Hong, Y.-T. Kang, C. Kleinstreuer, and J. Koo, "Impact analysis of natural convection on thermal conductivity measurements of nanofluids using the transient hot-wire method," *International Journal of Heat and Mass Transfer*, vol. 54, pp. 3448-3456, 2011.

[22] V. Bohac, M. K. Gustavsson, L. Kubicar, and S. E. Gustafsson, "Parameter estimations for measurements of thermal transport properties with the hot disk thermal constants analyzer," *Review of Scientific Instruments*, vol. 71, pp. 2452-2455, 2000.

[23] X. Li, D. Zhu, X. Wang, N. Wang, J. Gao, and H. Li, "Thermal conductivity enhancement dependent pH and chemical surfactant for Cu-H 2 O nanofluids," *Thermochimica Acta*, vol. 469, pp. 98-103, 2008.

[24] W. Jiang, G. Ding, and H. Peng, "Measurement and model on thermal conductivities of carbon nanotube nanorefrigerants," *International Journal of Thermal Sciences*, vol. 48, pp. 1108-1115, 2009.

[25] D. Zhu, X. Li, N. Wang, X. Wang, J. Gao, and H. Li, "Dispersion behavior and thermal conductivity characteristics of Al 2 O 3–H 2 O nanofluids," *Current Applied Physics*, vol. 9, pp. 131-139, 2009.

[26] C. Zhi, Y. Xu, Y. Bando, and D. Golberg, "Highly thermo-conductive fluid with boron nitride nanofillers," *ACS nano*, vol. 5, pp. 6571-6577, 2011.

[27] M. Wan, R. Yadav, K. Yadav, and S. Yadav, "Synthesis and experimental investigation on thermal conductivity of nanofluids containing functionalized Polyaniline nanofibers," *Experimental Thermal and Fluid Science*, vol. 41, pp. 6201-6206, 2013.
[38] W. Parker, R. Jenkins, C. Butler, and G. Abbott, "Flash method of determining thermal diffusivity, heat capacity, and thermal conductivity," *Journal of Applied Physics*, vol. 32, pp. 1679-1684, 1961.

[39] J. A. N. Bazan, "Thermal conductivity of poly-alpha-olefin (pao)-based nanofluids," University of Dayton, 2010.

[40] S. Shaikh, K. Lafdi, and R. Ponnappan, "Thermal conductivity improvement in carbon nanoparticle doped PAO oil: An experimental study," *Journal of Applied Physics*, vol. 101, p. 064302, 2007.

[41] N. Li, Y.-X. Zeng, Z.-Q. Liu, X.-W. Zhong, and S. Chen, "Nanofluids containing stearic acid-modified CuO nanorods and their thermal conductivity enhancements," *Nanoscience and Nanotechnology Letters*, vol. 7, pp. 314-317, 2015.

[42] T. Wang, Z.-y. Luo, S.-s. Guo, and K.-f. CEN, "Preparation of controllable nanofluids and research on thermal conductivity," *Journal-Zhejiang University Engineering Science*, vol. 41, p. 514, 2007.

[43] Y. Tada, M. Harada, M. Tanigaki, and W. Eguchi, "Laser flash method for measuring thermal conductivity of liquids—application to low thermal conductivity liquids," *Review of Scientific Instruments*, vol. 49, pp. 1305-1314, 1978.