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Temperature-Dependent Thermal Conductivity Measurement System for Various Heat Transfer Fluids

Yunita Anggraini[1], Alfriska O. Silalahi[2], Inge Magdalena Sutjahja[1*], Daniel Kurnia[1], Sparisoma Viridi[1], Surjamanto Wonorahardjo[3]

[1] Department of Physics, Institut Teknologi Bandung, Jl. Ganesha No. 10, Bandung 40132, Indonesia
[2] Department of Electrical Engineering, Institut Teknologi Del, Jl. Sisingamangaraja, Laguboti, Tobasa, Sumatera Utara 22381, Indonesia
[3] Department of Architecture, Planning and Policy Development, Institut Teknologi Bandung, Jl. Ganesha No. 10, Bandung 40132, Indonesia

Corresponding Author Email: inge@fi.itb.ac.id

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ABSTRACT

Accurate measurement of the thermal conductivity of a heat transfer fluid (HTF) is important for optimizing the performance of a thermal energy storage system. Herein, we develop a system to measure the thermal conductivity of an HTF during temperature variation, and the system was checked to measure several samples comprising water, lauric acid, stearic acid, oleic acid, and coconut oil. The thermal conductivity was measured using a KS-1 sensor of a KD2 Pro analyzer. In the study, a static heat conducting medium was used to control the temperature of the fluid, instead of the commonly used flowing water bath. The measured thermal conductivities of water (298 to 318 K) and lauric acid (323 to 373 K), stearic acid (358 to 372 K), oleic acid (334 to 372 K), and coconut oil (298 to 363 K) were compared to data from previous studies and fitted to available models. The accuracy of the data is further analyzed by relating the number of C and H atoms in the fatty acid, and the fatty acid content in coconut oil.

1. INTRODUCTION

A heat transfer fluid (HTF) is a liquid or gas that is used to transfer heat from one system to another [1, 2]. In addition to water and ethylene glycol [3, 4] liquid HTFs include edible oils [5-7] salt solutions or salt hydrates [8, 9], ionic liquids [10, 11], and fatty acid [12, 13]. The liquid thermal conductivity of a HTF, which is a measure of its ability to transfer heat, is an important parameter for the optimization of the performance of a thermal energy storage system. In general, thermal conductivity depends on temperature [14, 15] and type and amount of a nanoparticle dopant, which is directly added to form a stable suspension called a nanofluid [16]. Dopants are commonly categorized as non-magnetic (e.g., various carbon materials [17, 18], Al_2O_3, TiO_2, and CuO [19]), or magnetic (e.g., Fe_2O_3 and Fe_3O_4) [20-23].

Accurate measurement of HTF's thermal conductivity is very important, both from science and for technological applications. However, the effect of convection is a dominant factor in determining the temperature dependency of thermal conductivity, especially as temperature increases. As shown in Table 1, the systems developed in previous studies allow convection, thus potentially reducing the accuracy of the thermal conductivity data. Herein, we describe a simple system for heating a liquid to measure its thermal conductivity as the temperature varies from 298 to 373 K while minimizing the convection effect. The thermal conductivity was measured using a KS-1 sensor of a KD2 Pro, which works on the basis of the hot wire transient method [24-31]. This method is a dynamic transient technique based on measuring the temperature rise at a certain distance from a fine and long wire-shaped heat source embedded in the test material. The hot wire transient method offers several advantages over other measurement methods [32, 33], such as the capability to eliminate errors related to natural convection, quick experimental results, and simple conceptual design. The instrument was tested by measuring the thermal conductivity of water, lauric acid, stearic acid, oleic acid, and coconut oil. The experimental results were compared with the available data from other studies and fitted using available models.

Lauric acid ($C_{12}H_{24}O_2$) and stearic acid ($C_{18}H_{36}O_2$) are saturated fatty acids with a melting point of approximately 316 K [34] and 341 K [35]. Oleic acid ($C_{18}H_{34}O_2$) is a monounsaturated fatty acid with one double bond that occurs naturally in various animal and vegetable fats and oils. It has a melting point of approximately 287 K [36]. Oleic acid has a similar amount of carbon and oxygen to the stearic acid in those chemical compounds. Coconut oil is edible oil and melts at room temperature. Coconut oil contains many kinds of saturated and unsaturated fatty acids, with an enormous amount of saturated fatty acid (90%) with a medium-chain fatty acid, such as lauric acid (50%) [37]. Despite many applications of coconut oil in engineering fields [35, 37-42], no available data for temperature-dependent thermal conductivity. Further analysis will be performed to study the relation between the number of C and H content in the fatty acid, the number of saturated and unsaturated bonding and the composition of fatty acid in the coconut oil with the thermal conductivity values.

This paper is organized as follows. The Method and

Materials section explains the development of the instrumentation system and the material used. The Results and Discussion section presents the experimental results of the temperature-dependent thermal conductivity of various HTFs. The data were fitted using available models and compared with the results of previous studies. We found that the developed apparatus accurately measured the temperature-dependent thermal conductivity of various HTFs.

Literature review of liquid thermal conductivity heating systems

Table 1 summarizes the heating systems used to measure the thermal conductivity of liquids from previous studies, with the samples used and the technical conditions of the system.

Table 1. Heating systems used in liquid thermal conductivity measurement

Heating system	Sample	Technical condition	Ref.
Direct heating	Fe_3O_4-water magnetic nanofluid	This method can cause convection currents in the sample, which reduces the accuracy of thermal conductivity measurement.	Doganay et al. [22]
	Water-based TiO_2 nanofluid		Turgut et al. [43]
Circulating bath	An-oil based nanofluid	Circulating water for sample heating, either using a flowing water bath or storage tank, causes convection currents in the water as these currents aid the heat transfer process.	Jiang et al. [7]
	Six-ionic liquid		Liu et al. [14]
	TiO_2- MWCNTs/ (EG-water hybrid nanofluid		Moradi et al. [44]
	Fe_2O_3 nanofluid		Agarwal et al. [45]
	Magnetic nanofluid		Roszko et al. [46]
	(γ –Fe_2O_3) water- based nanofluids		Nurdin et al. [47]
	Deionized water and ethylene glycol-based nanofluids		Abdullah et al. [48]
Static bath	Water-graphene oxide/aluminum oxide nanoparticles	With the relatively large amount of water used to heat the sample, inhomogeneous temperature is possible.	Taherialekouhi et al. [49]
	Semiclathrate hydrates and aqueous solutions of tetrabutylammonium bromide (TBAB) and tetrabutylammonium chloride (TBAC)		Fujiura et al. [50]
	Graphene oxide/Water nanofluid		Yang et al. [51]
	Edible oil		Turgut et al. [52]
	rGO-Fe_3O_4-TiO_2 hybrid nanofluid		Cakmak et al. [53]
	Deionized water, lauric acid, stearic acid, oleic acid, and coconut oil	Simple instrument, cost-effective, < 1 L liquid medium required to heat a sample.	Present Work

2. METHOD AND MATERIALS

Figure 1 shows the setup of the measuring system, which consists of three main parts: (1) thermal conductivity sensor, (2) heating system, and (3) sample system. The heating system consists of a transformer (2a) to control the voltage output to the heater controller (2b) that is controlled by a PC (2c). The sample system consists of a sample glass (3a) equipped with a circular heater (3b) and a thermocouple data logger (3c) to monitor the temperature readings in the heating medium. The overall sample system was placed in an adiabatic container to inhibit heat loss to the environment (3d).

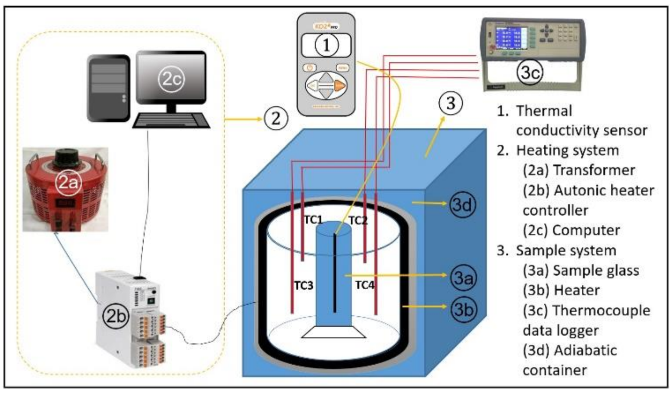

Figure 1. Set up for measuring the thermal conductivity of the liquid material samples during temperature variation

The thermal conductivity was measured using the KS-1 sensor of a KD2 Pro thermal properties analyzer (Decagon, USA) [54]. This is a commonly used analyzer for measuring thermal conductivity [55-58]. The sensor has a diameter and length of 1.3 mm and 6 cm, respectively. The heat flux per unit length (q) and the time-dependent temperature can be used to calculate the thermal conductivity using Eq. (1) [25, 59].

$$k = \frac{q}{4\pi}\left(\frac{d\,ln(t)}{dT}\right) \tag{1}$$

To measure the thermal conductivity with temperature variation, approximately 30 mL samples were placed into sample glasses with an inner diameter of 2.3 cm, outer diameter of 2.5 cm, and height of 9.8 cm. Then, the sample glasses were placed inside a beaker containing approximately 500 mL of a heat conductive liquid medium, which was covered with a circular heating system made of stainless steel. For accurate thermal conductivity measurements, the sensor was placed in a holder system that maintained its vertical position inside the sample glass. The holder system also served as a cover for the sample and heat conduction medium.

The heating system used throughout this experiment had a relatively small thermal mass; hence, the applied input voltage to the heater was small. To achieve the required voltage, the source voltage of a transformer was adjusted. Then, the power drawn by the heater was controlled by an Autonic heater controller, which uses the pulse width modulation (PWM) technique [60]. PWM is a modulating technique, in which the pulse width is varied while maintaining a fixed amplitude and frequency. The PWM duty cycle is the ratio of the 'on' time to the regular interval or 'period' of time. The duty cycle is expressed as a percentage, with 100% being fully on and 0 % being completely off. A low duty cycle corresponds to a low applied heater power [61]. Meanwhile, the heater was set to heat the heat conductive medium and sample up to a user-defined temperature set-point. At least three or four calibrated temperature sensors were used to monitor the temperature distribution in the heat conductive medium. These sensors were placed opposite to each other at two different height position from the upper part of the heating medium (Table 2). In this study, T-type thermocouples with a diameter of approximately 1 mm, connected to an Applent data logger with an accuracy of 0.2% ± 1℃, were used as temperature sensors.

The voltage at each temperature set-point was adjusted to be as low as possible to avoid large heat pulses and allow sufficient time for heat propagation from the heater to the middle of the sample. After the temperature set-point was reached, the heater was turned off to prevent heat pulses and heat waves that could result in convection, that could reduce the accuracy of the measurements. After achieving a uniform temperature distribution as determined from the three or four thermocouple sensors, the thermal conductivity was measured.

Table 2. Relative positions of the thermocouple channels of Applent in the heating medium

No of thermocouples	Height from the upper part of heating medium (cm)
TC1	2
TC2	2
TC3	8
TC4	8

De-ionized water, lauric acid, stearic acid, oleic acid, and coconut oil were used in the temperature ranges from room temperature to 318 K, from 323 to 373 K, from 358 to 372 K, from 334 to 372 K, and from 298 to 363 K, respectively, to calibrate the heating system. During measurements for each sample over all temperature ranges, voltages of 30-35 V and 35-55 V for water and lauric acid, respectively, and 40 V for stearic acid, oleic acid, and coconut oil were used. The voltage value should be constant for a single set of measurement to maintain the overall heating rate. The measurements were repeated two times for water and three times for lauric acid, stearic acid, oleic acid, and coconut oil to ensure that the readings were reproducible. In addition, thermal conductivity measurement for lauric acid and oleic acid was conducted two times to verify its repeatability. The average values are presented here.

For this experiment, technical grade lauric acid and stearic acid with purities of 85−90% from Indonesia were used as the heat conductive media. In contrast, non-technical grade lauric acid and stearic acid were used as the sample for thermal conductivity measurements. For this purpose, lauric acid and stearic acid with purity ≥ 98% and ≥ 95%, respectively, were purchased from Sigma Aldrich. Technical grade oleic acid was purchased from a traditional market in Indonesia. Coconut oil commonly used for household needs was purchased from a traditional market in Indonesia.

3. RESULTS AND DISCUSSION

Figure 2 shows the temperature distributions in samples when they were used as heat conductive media for thermal conductivity measurement.

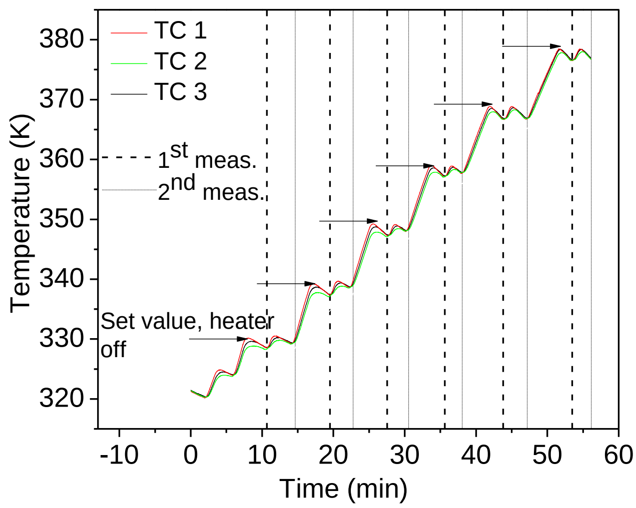

Figure 2. Typical temperature distribution of the heat conductive medium

The experimental results show that at the same height position of Applent thermocouple, the temperature is relatively uniform, with the temperature on the upper thermocouple position being higher (about 0.1 K) than that on the bottom position. These results indicate that convection did not occur at the beginning of the measurement, and temperature differences at different heights were related to the buoyancy convection effect [62]. As shown in Figure 2, after waiting for some time, we switched off the heater, and the temperatures at different heights will become the same, and the thermal conductivity measured under these conditions. The waiting time became shorter as the temperature increased due to the faster Brownian motion of molecules [63].

Figure 3 shows the results of the temperature-dependent thermal conductivity for de-ionized water.

Table 3. Regression coefficients of water thermal conductivity data using Eq. (2) for the present experiment and those from [64] and [65]

Regression coefficient	Present data	Previous studies	
		[64]	[65]
A	1.01	−0.55	−0.90
B	-4.10×10^{-3}	6.25×10^{-3}	8.39×10^{-3}
C	9.13×10^{-6}	-7.93×10^{-6}	-1.12×10^{-5}
χ^2	7.74×10^{-6}	6.30×10^{-5}	2.62×10^{-8}

From Figure 3, one can see that the experimental data were close to the data from the previous studies, with a maximum error value of 1.1% at T = 313 K. The measurement of water at high temperatures above 323 K might cause an increase in the measurement errors because of the drastic change in the viscosity of water [54]. In this study, the appearance of microbubbles might have caused convection, which might have led to inaccurate results.

As shown in Figure 3, the thermal conductivity of water increases with temperature, and the values are close to those reported by [65] but higher than values reported by [66] and lower than those reported by [64]. In the high-temperature range, the increase in the thermal conductivity occurred up to 423 K before decreases as the temperature increased thereon [67], and strongly related to the hydrogen bond strength [68]. Based on [67], the temperature-dependent thermal conductivity of water was analyzed using a second-order polynomial function, as in Eq. (2), which is commonly used for liquid and solid inorganic compounds.

$$k(T) = A + BT + CT^2 \qquad (2)$$

where, k is the thermal conductivity; A, B, and C are the regression coefficients; and T is the absolute temperature. Table 3 shows the results of the fitting of the water thermal conductivity data from the present experiment with those from [69]. The similarity of the regression coefficients for the three sets of data, together with the reduced chi-square values show that the data fitted well.

The liquid thermal conductivity of lauric acid, stearic acid, oleic acid, and coconut oil are shown in Figure 4(a), Figure 4(b), Figure 4(c), and Figure 4(d), respectively. Increasing the temperature invariably decreased the thermal conductivity. This trend is common for organic liquids [70].

Based on [67], the temperature-dependent thermal conductivities of lauric acid, stearic acid, oleic acid, and coconut oil were analyzed using Eq. (3),

$$k = A + B\left(1 - \frac{T}{C}\right)^{\frac{2}{7}} \qquad (3)$$

Table 4 shows the results of the fitting of the thermal conductivity data of lauric acid, stearic acid, oleic acid, and coconut oil, respectively, along with the reference. The regression coefficients and reduced chi-square values listed in the table indicate that the data fitted well.

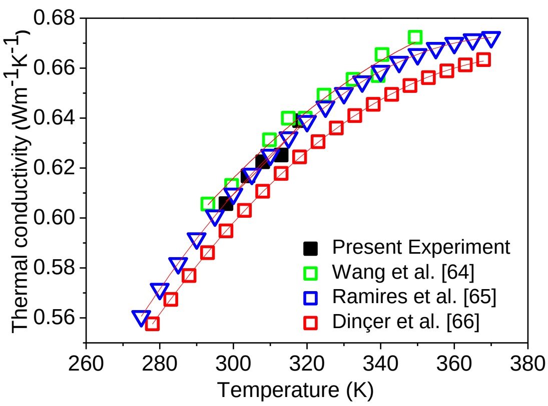

Figure 3. Thermal conductivity data of water. Red lines: fitted curves to Eq. (2) (see text)

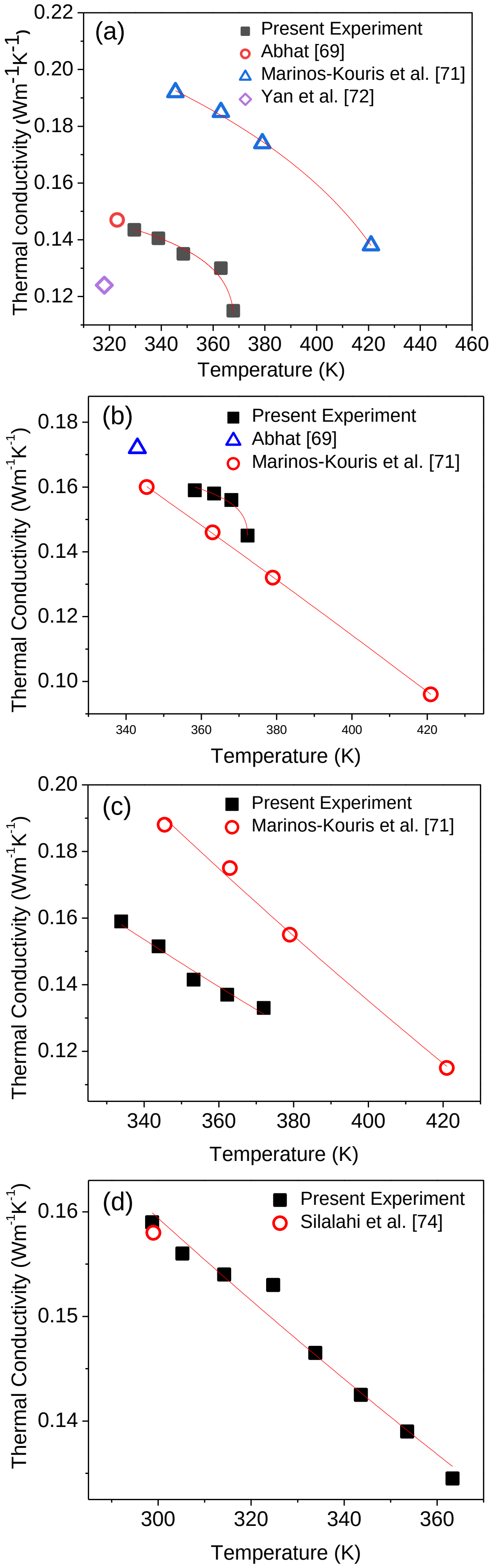

Figure 4. Thermal conductivity data of (a) lauric acid, (b) stearic acid, (c) oleic acid, and (d) coconut oil. Red lines: fitted curves to Eq. (3)

Table 4. The best results for the regression coefficients of lauric acid, stearic acid, oleic acid, and coconut oil thermal conductivity using Eq. (3), for the present data and previous study [71]

Regression coefficient	Present data	Previous study, [71]
	Lauric Acid	
A	0.09	-8.69×10^{-3}
B	0.08	0.28
C	368.49	447.16
χ^2	8.41×10^{-6}	9.85×10^{-7}
	Stearic Acid	
A	0.14	1.27
B	0.04	-8.89×10^{-4}
C	372.31	-4.68×10^{-9}
χ^2	2.06×10^{-6}	8.10×10^{-7}
	Oleic acid	
A	1.02	1.48
B	-8.06×10^{-4}	-6.65×10^{-4}
C	-7.98×10^{-9}	-1.02×10^{-9}
χ^2	3.13×10^{-6}	5.04×10^{-6}
	Coconut oil	
A	0.58	
B	-7.47×10^{-4}	
C	-6.58×10^{-8}	
χ^2	2.10×10^{-6}	

Comparison of the present experimental data with those from previous studies over a temperature from 320 to 420 K, the measured thermal conductivity of lauric acid was close to those reported by [69], but higher than those reported by [72], and lower than those reported by [71]. In the same condition, stearic acid thermal conductivity in the temperature range 358-372 K also close to the reference reported by [71], but lower than those reported by [69]. Oleic acid thermal conductivity value over a temperature of 334-372 K also close to the reference reported by [71]. The results of our study show that the thermal conductivity of stearic acid is higher than lauric acid, in agreement with the close relationship between the number of C and H atoms with thermal conductivity data of saturated fatty acid ethyl ester [64]. We note that the solid thermal conductivity data of fatty acid also shows a similar relationship, although there is no explicit explanation for that [73]. Besides that, the thermal conductivity of stearic acid does not resemble those of oleic acid with the same C number. It is seemingly that the occurrence of unsaturated bonding does not give considerable influence to the thermal conductivity data.

For the coconut oil thermal conductivity, one can see at room temperature, the present value is almost the same with the value reported by Silalahi et al. [74], but lower than those reported in Ref. [75]. The difference due to measuring temperature or phase condition of the sample, namely solid phase of coconut oil that reported in Ref. [75]. Generally, thermal conductivity of coconut oil is close to the values of soybean oil and considerably lower than the values of other vegetable oils [76]. At temperature 320 K the thermal conductivity of coconut oil is close to the value of lauric acid, in agreement with a previous report by Hoffmann et al. [5], that fatty acid composition in the vegetable oil determines the thermal conductivity and other temperature-dependent thermophysical parameters.

4. CONCLUSIONS

We have demonstrated a heating system for measuring the thermal conductivity of liquid HTF during temperature variation. The thermal conductivity was measured using a KS-1 sensor of a KD2 Pro analyzer, which works based on the transient heat line source method. The thermal conductivities of de-ionized water (room temperature to 318 K), lauric acid (323 to 373 K), stearic acid (358 to 372 K), oleic acid (334 to 372 K), and coconut oil (298 to 363 K) are measured and found to be in good agreement with the data reported in previous studies. Available models were used to fit the experimental data. Further analysis show that the thermal conductivity values are comparable to the number of C and H atoms contained in the fatty acid, and minor contribution of unsaturated bonding. At temperature around 320 K, coconut oil thermal conductivity value is close to lauric acid, which corresponds to the character of the fatty acid content in coconut oil.

We note that, although the developed apparatus can be used to measure the thermal conductivity of any HTF, the applied voltage might be different for a specific type of liquid. In addition, it is necessary to maintain a constant voltage during the measurement, as a change in voltage might cause a pulse heat and induce a convection current.

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NOMENCLATURE

k	thermal conductivity, $W.m^{-1}. K^{-1}$
q	heat flux per unit length, $W.m^{-2}$
t	time, s
T	temperature, K
A	regression coefficient, -
B	regression coefficient, -
C	regression coefficient, -
χ^2	residual sum of squares