Temperature Dependence of Thermal Conductivity of Water Based TiO_2 Nanofluids

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ABSTRACT
This paper deals with the determination of thermal conductivity of water based TiO_2 nanofluids as a function of temperature in the range of 30ºC to 70ºC with different volume concentration of TiO_2 nanoparticles. In the present experimental investigation, nanofluids are prepared with TiO_2 nanoparticles of average size of 21 nm and measurements are made using test setup, specifically designed by namely PA Hilton, UK [17]. Nanofluids with different volume concentrations in the range of 0.2% to 1.0 % (by weight) of TiO_2 are used. Based on the experimental results it is found that the thermal conductivity of nanofluids increases with the percentage of volume concentration and temperature. Experimental results are compared with the models available in the open literature. The experimental results of thermal conductivity of nanofluids of the present investigation closely compare with the predictions of the model proposed by Murshed et al [8]. All other models have under-predicted the thermal conductivity of TiO_2 nanofluids by as much as 20 to 40%. The experimental results in the present investigations are highly encouraging in terms of enhancement of thermal conductivity.

Keywords: TiO_2 nanofluids, Thermal Conductivity.

NOMENCLATURE

d	=	Diameter, m
k	=	Thermal conductivity, W/m K
L	=	Length, meters
n	=	Empirical shape factor
Q	=	Rate of heat transfer, Watts
R	=	Resistance, ohms
T	=	Temperature, °C
V	=	Voltage, volts
W	=	Weight in grams

Subscripts

Air	=	Air
Ele	=	Electrical
f	=	Fluid

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m = Mean
$n.f$ = Nanofluids
p = Particle
w = Water

Symbols
ρ = Density
ψ = Sphericity
ϕ = Volume fraction
β = Nano-layer thickness to the original particle radius

1. INTRODUCTION

Use of single phase heat transfer fluids such as water and ethylene glycol is very common in a variety of industrial heating and cooling equipment. Convective heat transfer coefficient plays an important role and influences the rate of heat transfer in typical industrial equipment such as heat exchangers. Generally the heat transfer rate will be very high whenever there is a change of phase of the working fluid. However, in some applications, change of phase in working fluid is not allowed. Under these circumstances the designer has severe limitations to work with single phase heat transfer fluids. In the recent past nanofluids were developed that are having much better thermal and thermo-physical properties when compared to the corresponding base fluids. It is advantageous to use such heat transfer fluids in cooling and heating equipment. It is mandatory to characterize and establish the properties of such nanofluids before they are put to use in critical applications.

1.1. Litrature review

A critical literature survey has been conducted and a number of important research papers on the heat transfer in nanofluids have been reviewed. Numerous theoretical and experimental studies, on thermal conductivities of suspensions that contain millimeter or micrometer size solid particles, have been conducted since the theoretical work of Maxwell [1]. The problems with the use of these conventional large particles include rapid settling in fluids, abrasion, clogging and fouling. Nanofluids are suspensions consisting solid nanoparticles with sizes generally less than 100 nm. Nanofluid technology is a new challenge and also an opportunity for heat transfer community. It has been reported by Choi[2] that the thermal conductivity of nanofluid increases substantially even with a very low volume fraction of nanofluids. He observed an increase up to approximately two times in the thermal conductivity of the fluid by the addition of nanoparticles less than 1% volumetric concentration. Hence nanofluids can be used as effective heat transfer fluid if the particles can be dispersed uniformly and made to sustain in that state for longer duration.

Das et al. [3], Masuda et al [4], Murshed et al [5], Zhang et al [6], Timofeeva et al. [7], Murshed et al. [8], Prasher et al [9] all have investigated thermo-physical properties of nanofluids prepared with a variety of nanoparticles of different sizes and shapes dispersed in a number of base fluids.

From the above literature, it is evident that nanofluids show substantially higher thermal conductivity than base fluids. However, the thermal conductivity data of nanofluids still differ in different studies leading to a sort of discrepancy on this subject under consideration from research publications. For example, some researchers report that the existing model can be used to predict the thermal conductivity of nanofluids, whereas many other researchers have indicated that these models fail to estimate the thermo-physical property of nanofluids. Although the enhancements of the thermo physical property of nanofluids have been explained by several mechanisms and models, no agreement has been reached yet. This may be because the thermo physical properties of nanofluids depend on various factors such as particle shape, particle size, material such as metallic or non-metallic (oxide), solution chemistry (pH value) and even the solution-ageing. The thermo-physical property model used for computing the thermal conductivity of nanofluids, may have led to these errors in the result. This review leads to the identification of lacuna in the literature with reference to the method of determination of thermal conductivity of nanofluids

In the present work an attempt has been made to prepare a suitable nanofluid using TiO_2 nanoparticles with average size of 21nm *and* water as base fluid with varying concentrations, and determine thermal conductivity experimentally as a function of temperature and volume concentrations utilizing equipment supplied by PA Hilton, UK [17].

2. EXPERIMENTAL INVESTIGATION

2.1. Estimation of requirement of TiO_2 nanoparticles

The TiO_2 nanoparticles with an average particle diameter of 21 nm are purchased from Sigma Aldrich Chemicals Ltd., USA and these are dispersed in water for the preparation nanofluid. The quantity of TiO_2 nanoparticles required for different volume concentrations can be calculated by using the standard formula.

$$\text{Percentage of volume concentration} = \frac{\textit{Volume of } \mathrm{TiO_2}}{\textit{Volume of } \mathrm{TiO_2} + \textit{Volume of water}} \quad (1)$$

$$\text{Percentage of volume concentration} = \frac{\frac{W_p}{\rho_p}}{\frac{W_p}{\rho_p} + \frac{W_w}{\rho_w}} \quad (2)$$

2.2. Preparation of TiO_2 nanofluids

TiO_2 nanofluids samples are prepared by mixing 0.5 ml of oleic acid and $1/10^{th}$ (of weight of TiO_2) CTAB (Cetyl Trimethyl Ammonium Bromide) is added to the base fluid prior to adding TiO_2 nanoparticles. The nanofluid thus prepared is kept in an ultrasonic bath for 6–8 hour in order to avoid any sedimentation. Using the above procedure five different samples with 0.2%, 0.4%, 0.6%, 0.8% and 1.0% nanoparticles concentration are prepared and these are used for the estimation of thermal conductivity.

2.3. Measurement of thermal conductivity of TiO_2 nanofluids

The thermal conductivity of nanofluids is estimated using the thermal conductivity apparatus supplied by P.A. Hilton, U.K shown in **Fig.** 1**a.** The setup consists of a bench top unit for the determination of thermal conductivity of liquids and gases and a console to control heat input and display of temperature.

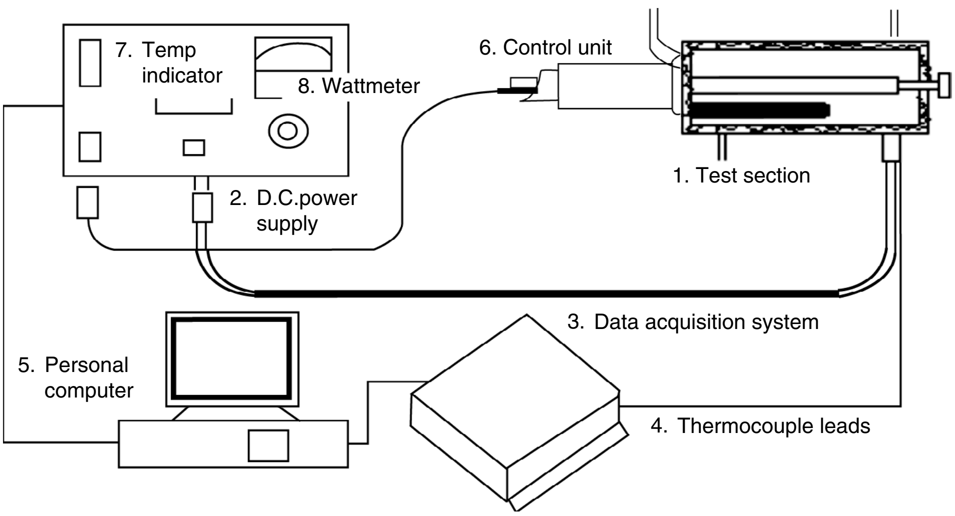

Figure 1a. Schematic representation of the experimental set up.

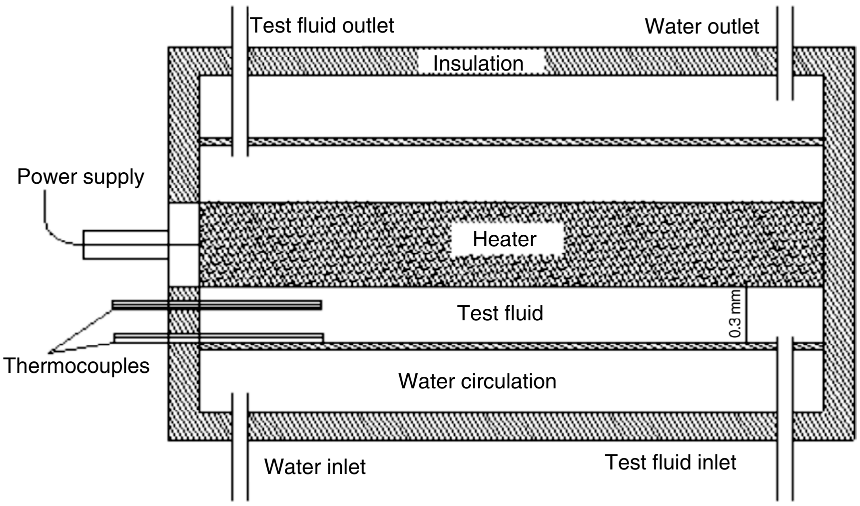

Figure 1b. Details of the test section.

The schematic diagram of the test setup shows test section, D.C. power supply, data acquisition system, thermocouple sensors, personal computer, control unit with on-off switch, temperature indicator, wattmeter, dimmerstat, etc.

Nanofluid samples are filled in the small radial clearance shown in **Fig. 1b.** between a heated plug and water cooled jacket. The clearance is small enough to prevent natural convection in the fluid and the fluid is presented as a lamina of face area $\pi\, d_m\, L$ and thickness r transferring heat from the plug to the jacket. The plug is machined from aluminium and contains a cylindrical heating element whose resistance at the working temperature is accurately measured. A thermocouple is inserted into the heater plug close to its external surface and the plug has ports for the introduction and venting of the test fluid. The jacket is constructed from brass and has a water inlet and drain connections and the thermocouple is carefully fitted to the inner sleeve. Due to the positioning of the thermocouples and the high thermal conductivities of the materials involved, the temperatures measured are essentially the temperatures of the hot and cold surfaces of the fluid lamina. An analog voltmeter enables the power input to be determined and digital temperature indicators with 0.1°C resolution display the temperatures of the heater plug and jacket surfaces.

2.4. Calibration of the test section

Atmospheric air is taken as the fluid in the radial space for calibration and standardization. Once calibrated, the data is used as reference in the determination of thermal conductivity of other fluids subsequently. Cooling water is passed through the jacket and the heater input is varied to maintain a small temperature difference across the ‘air lamina’. Under steady state conditions, the voltage applied to the heater and the temperatures are noted. The rate of heat transfer Q through the air lamina is then estimated from Eq. (3) with the known value of k_{air}

$$Q = \frac{k_{air}\, \pi\, d_m\, L\, \Delta t}{\Delta r} \tag{3}$$

The difference between the electrical power input $Q_{Elec} = V^2/R$ and that estimated with Eq. (3) is the incidental heat transfer at any given temperature. The above procedure is repeated at other plug and jacket temperatures and a calibration curve showing incidental heat transfer against plug or jacket temperature difference is drawn for reference.

2.5. Estimation of thermal conductivity

The fluid to be tested is introduced into clean test section in the radial space. Water is then passed through the jacket and the heater adjusted to give a reasonable temperature difference and heat transfer rate. The thermal conductivity of the nanofluids samples is estimated once the test section reaches steady state condition and using *Eq*. (3) by replacing k_{air} with k_{fluid}.

2.6. THEORETICAL MODELS FOR THERMAL CONDUCTIVITY

The effective thermal conductivity of a two-phase mixture can be theoretically estimated by H.C. model [11]

$$k_{n.f} = k_f \left[\frac{k_p + (n-1)\,k_f - \phi\,(n-1)\left(k_f - k_p\right)}{k_p + (n-1)\,k_f + \phi\left(k_f - k_p\right)} \right] \tag{4}$$

Where $n = 3/\psi$, in which n is the empirical shape factor and ψ is the sphericity, defined as the ratio of the surface area of a sphere (with the same volume as the given particle) to the surface area of the particle. The sphericity is 1 and 0.5 for the spherical and cylindrical shapes, respectively.

Murshed et al [8], modified Bruggeman model and developed the following expression for computing the thermal conductivities of nanofluids.

$$k_{n.f} = \frac{1}{4}\left[(3\phi - 1)\,k_p + (2 - 3\phi)k_f \right] + \frac{k_f}{4}\sqrt{\Delta} \tag{5}$$

Where $$\Delta = \left[(3\phi - 1)^2 (k_p/k_f)^2 + (2 - 3\phi)^2 + 2(2 + 9\phi - 9\phi^2)(k_p/k_f) \right]$$

Wasp [12] derived an equation for calculating the thermal conductivity of nanofluids, which is expressed as follows:

$$k_{n.f} = k_f \left[\frac{k_p + 2k_f - 2\phi\left(k_f - k_p\right)}{k_p + 2k_f + \phi\left(k_f - k_p\right)} \right] \tag{6}$$

For spherical particles, the results given by the Wasp model concur with those of the H–C model.

An alternative formula for calculating thermal conductivity was introduced by Yu et al [13], which is expressed in the following form:

$$k_{n.f} = k_f \left[\frac{k_p + 2k_f - 2\left(k_f - k_p\right)(1+\beta)^3 \phi}{k_p + 2k_f + \left(k_f - k_p\right)(1+\beta)^3 \phi} \right] \tag{7}$$

Where β is the ratio of the nano-layer thickness to the original particle radius. Normally β = 0.1 is used to calculate the thermal conductivity of nanofluid.

Timofeeva et al [7] suggested the effective medium theory to calculate thermal conductivity of nanofluids, which is expressed as follows:

$$k_{n.f} = k_f\,[1 + 3\phi] \tag{8}$$

3. RESULTS AND DISCUSSIONS

Thermal conductivity of water at atmospheric temperature (30ºC) and at different temperatures is estimated experimentally by using the thermal conductivity measuring instrument of P.A. Hilton., U.K[17] and the results are shown in Fig. 2. From the figure it is observed that the results are in very good agreement with the ASHARE hand book fundamentals [10]. From the calibration results the deviation of the measured value from the reference value is less than 2.5% which indicates that the experimental setup is well calibrated. Fig.3 shows the thermal conductivity of TiO_2-water nanofluids as a function of particle volume concentration and temperature. The results show that the thermal conductivity of nanofluids significantly increases with increase in nanofluid temperature and particle

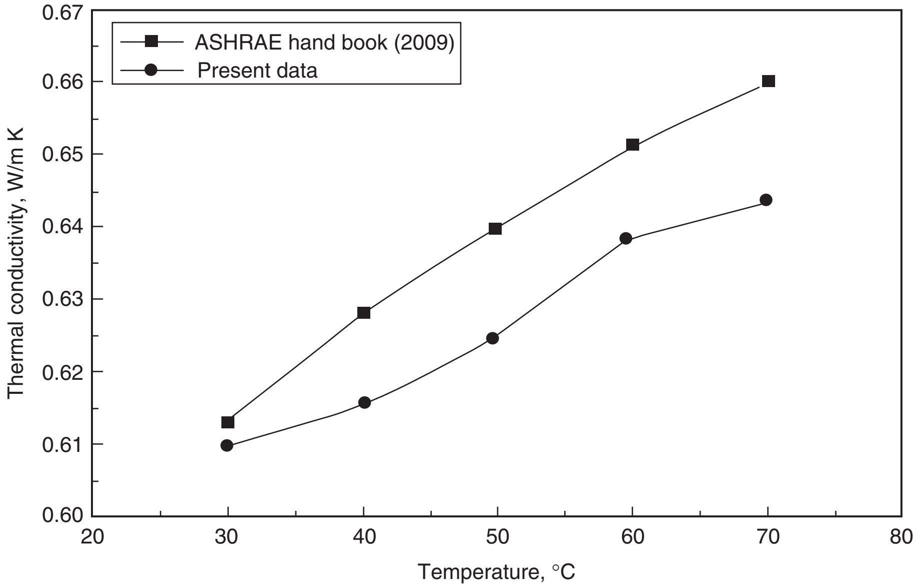

Figure 2. Comparison of the measured thermal conductivity with reference data.

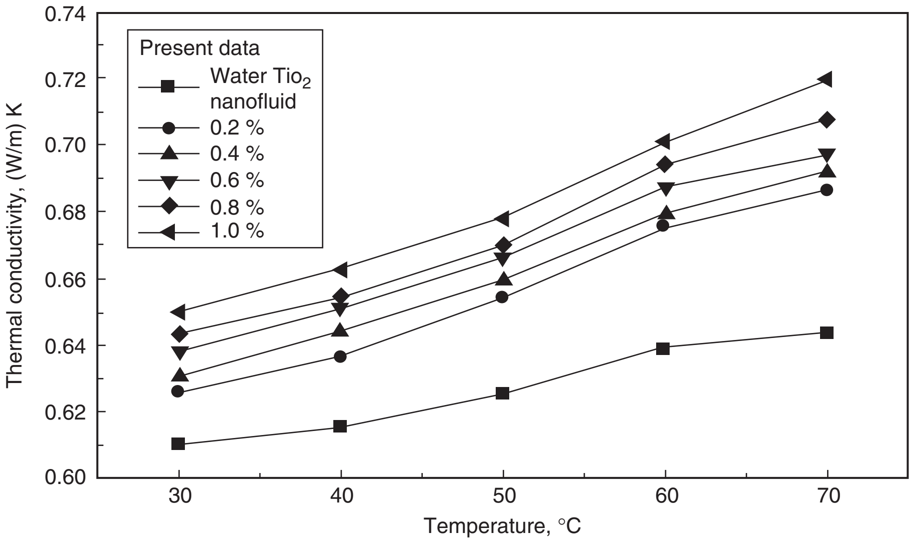

Figure 3. Thermal conductivity of TiO_2-water nanofluids as a function of temperature and volume concentration.

volume concentration. Fig. 4. shows a comparison of measured values of thermal conductivity of nano fluids with the predicted values correlations available in literature. As shown in Fig. 4. The measured thermal conductivity of nanofluids is much higher than the predicted value of the H-C model [11], Wasp model [14], Bruggeman model, Yu and Choi model [13] and effective medium theory [7]. The results also show that the measured values are in close agreement with the Murshed et al [14]. Values than that of the other correlations. Fig. 5. shows the thermal conductivity as a function of volume concentration and temperature. It can be clearly seen that the use of nanoparticles dispersed in base liquid gave greater thermal conductivity than the base fluid by about 2.6 to 6.5% for the volume concentration range between 0.2 vol % and 1.0 vol % at room temperature (30ºC). Furthermore, the results demonstrated that the measured thermal conductivity from the present study at room temperature was greater than that of Weerapun Dungthongsuk[13] and good agreement with Murshed et al. [5].

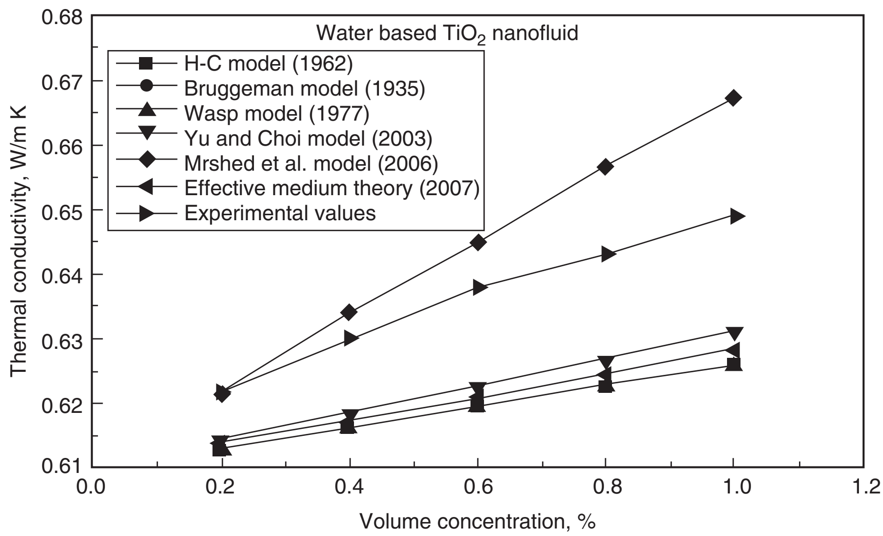

Figure 4. Comparison of measured thermal conductivities with those obtained from various correlations.

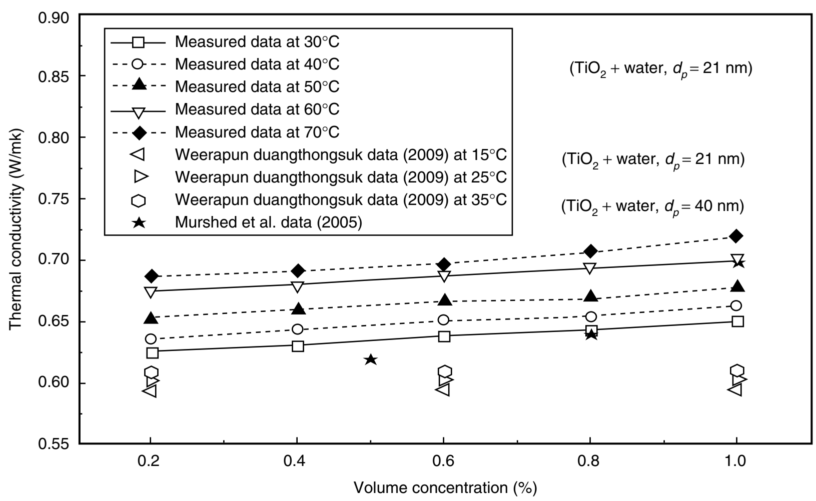

Figure 5. Comparison of the measured thermal conductivity enhancement with those obtained various researchers.

Fig. 6. shows the measured thermal conductivity of nanofluids as a function of particle volume concentration, and also shows the comparison between the present data and the measured data from other researchers. The experimental results show good agreement with the measured values of Murshed et al [5] and differ from the measured data of Weerapun Dungthongsuk [13]. From Figs. 5 and 6, it is clear that the data observed by other researchers are quite different from those of the present study. This difference could have been due to several factors such as difference in the particle size, particle preparation, particle source, or even the measurement technique. Therefore, more experimental work is required before concrete conclusions can be inferred on the thermal behavior of nanofluids. As described above, it is evident that thermal conductivity is a function of temperature and particle volume concentration. It is also seen that the existing well-known correlations gave inconsistent predictions of the thermal conductivity of nano fluids. A regression equation has been developed in the following form.

$$\frac{k_{nanofluid}}{k_{water}} = a + b\phi \tag{9}$$

Where 'a' and 'b' are constants which are given in Table-I.

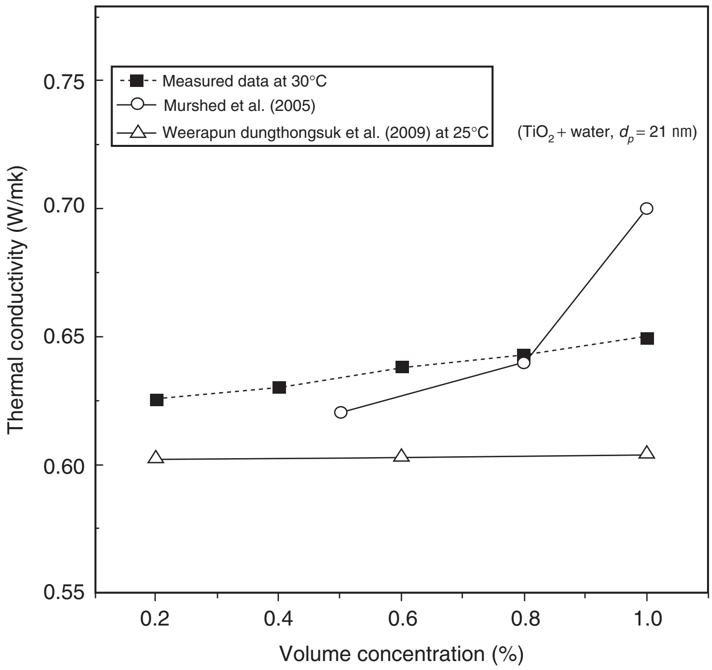

Figure 6. Comparison of the measured thermal conductivity at room temperature with those reported by various researchers.

Table – I

Temp (^{0}C)	A	b
30	1.0152	0.04990
40	1.0255	0.05055
50	1.0361	0.04725
60	1.0452	0.05120
70	1.0502	0.06405

The above equation is derived through the use of the data on TiO_2-water nanofluids which is applicable for: (1) temperature range between 30°C and 70°C and (2) particle volume concentration range between 0.2 vol. % and 1.0 vol. %.

CONCLUSIONS

- The effective thermal conductivity of TiO_2-water nanofluid system with particle volume concentrations of 0.2, 0.4, 0.6, 0.8 and 1.0 vol. % were measured experimentally.
- Thermal conductivity of nanofluids is determined in the temperatures range of 30°C to 70°C. It is established that thermal conductivity of nanofluids is higher when compared to the corresponding base fluid. It is found that the thermal conductivity increases with temperature and percentage of TiO_2 nanoparticles concentration.
- Except the model proposed by Murshed et al, all other existing correlations under predicted thermal conductivity of nanofluids. The disagreement between experimental results is attributed to several reasons such as particle size, method of preparation (solution chemistry), the type of measurement technique or even different particle sources.
- In this work a new correlation is developed for predicting the thermal conductivity of nanofluids from the present experimental results. The thermal conductivity enhancement for 0.2% TiO_2 nanofluids is 2.59% and for 1.0 % TiO_2 nanofluids is 6.54% at 30°C.
- It is concluded that, the temperature and volume concentration of nanoparticles have dominant influence on the enhancement of thermal conductivity of TiO_2 nanofluids.

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