DETERMINATION AND MEASUREMENT OF SOME THERMOPHYSICAL PROPERTIES OF NANOFLUIDS AND COMPARISON WITH LITERATURE STUDIES

by

Adnan TOPUZ, Beytullah ERDOGAN, and Osman AYCAN *

Department of Mechanical Engineering, Faculty of Engineering,
Zonguldak Bulent Ecevit University, Zonguldak, Turkey

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The thermophysical properties of nanofluids must be determined to evaluate their thermal performances like heat transfer, convection heat transfer coefficient, and Nusselt number. The purpose of this study is to obtain the thermophysical properties of nanofluids. The Al_2O_3, TiO_2, and ZnO are used as a nanoparticle, while deionized water is used as base fluid. The solutions included nanoparticles in a way to be each with 0.5%, 0.7%, and 1.0% volumetric concentration were prepared. The sodium dodecyl sulfate was added to the solutions as a surfactant to prevent instability that occurred due to agglomeration and sedimentation. For thermal conductivity measurement, the device that works by the transient hot-wire method was used between 30-60 °C temperatures. Also, for viscosity measurement, the device that works as based on the vibrating plate method was used between 20-50 °C temperatures. Density and specific heat values are obtained with the help of the well-known equations while thermal conductivity and viscosity are measured. Thanks to this study, it is emphasized how thermophysical properties of nanofluids change according to temperature and volumetric concentration. Moreover, their curve fitting equations are obtained. All of the thermophysical properties compared with the studies in the literature. It is established that the thermal conductivity of nanofluids is proportional to temperature, and viscosity of it is proportional to volumetric concentrations but inversely with temperature. Finally, the effects of the augmentation in dynamic viscosity on pumping power were considered as well as the increase in thermal conductivity, thus, no abnormal heat transfer enhancement was observed.

Key words*: nanofluid, thermal conductivity, viscosity, Al_2O_3, TiO_2, ZnO*

Introduction

Thermophysical properties of nanofluids are required to determine numerous performance types like heat transfer, pumping losses. These properties of nanofluids take different values depending on concentration, temperature, particle size, and shape. For this purpose, information about the studies in the literature is given and thermophysical measurements of nanofluids are done.

Azmi *et al.* [1] have worked on giving a comprehensive review of the research progress and on the enhancement of effective thermal conductivity and effective dynamic viscosity of nanofluids such as Al_2O_3, Cu, CuO, Fe_3O_4, SiC, SiO_2, TiO_2, ZnO, and ZrO_2. The thermal conductivity and dynamic viscosity of TiO_2-SiO_2 nanofluid [2] and only thermal conductivity of

* Corresponding author, e-mail: osman.aycan@beun.edu.tr

water-ethylene glycol-based SWVNT-ZnO hybrid nanofluid [3] have examined experimentally. The studies of Heyhat *et al.* [4] and Sahin *et al.* [5] are related to experimental investigation of laminar convective heat transfer and pressure drop of water-based Al_2O_3 nanofluids in fully developed flow regime. Barzegari *et al.* [6] also have worked effect of Al_2O_3-water nanofluid on convective heat transfer coefficient for helical tube heat exchanger, and Khurana *et al.* [7] experimentally examined with two types of insert (SST and MST). Mert *et al.* [8] experimentally investigated the cooling power of the radiator by using Al_2O_3-ethylene glycol/water nanofluid. Maiga *et al.* [9] examined the heat transfer characteristic of γAl_2O_3-water and ethylene glycol-γAl_2O_3 nanofluid in a heated tube. Turgut *et al.* [10] and Utomo *et al.* [11] focused on thermal conductivity and viscosity measurements of water-based TiO_2 nanofluids. Duangthongsuk and Wongwises [12] worked an experimental study on the heat transfer performance and pressure drop of TiO_2-water nanofluids flowing under a turbulent flow regime, and Arulprakasajothi *et al*. [13] also observed the effect of TiO_2-water nanofluid in tube heat exchanger. Eiamsa-Ard *et al.* [14] also studied TiO_2-water nanofluid in the dimpled tube with twisted tape inserts. Azmi *et al.* [15] investigated the comparison of convective heat transfer coefficient and friction factor of TiO_2 nanofluid-flow in a tube with twisted tape inserts.

Ferrouillat *et al.* [16] and Nguyen *et al.* [17] searched temperature and particle-size dependent viscosity data and influence of nanoparticle shape factor on convective heat transfer and energetic performance of water-based SiO_2 and ZnO nanofluids. Fard *et al.* [18] studied about ZnO-water nanofluid in the concentric tube and plate heat exchangers both numerical and experimental. Manay *et al.* [19] have experimentally investigated convective heat transfer of SiO_2-water nanofluid. In another study, thermophysical properties of Cu-water nanofluid, [20] and ethylene glycol-diethylene glycol mixture based copper nanofluid has worked both experimentally and theoretically by considering the particle size and base fluid [21]. Sharma *et al.* [22] found correlations to predict friction and forced convection heat transfer coefficients of water-based nanofluids for turbulent flow in a tube. Ahmadi *et al.* [23] have studied numerically on the heat transfer effect of flowing water-based Al_2O_3 nanofluid in a square channel. Raei *et al.* [24] have also examined experimentally the heat transfer enhancement with the same nanofluid within a double-tube heat exchanger.

Generally, it is done on the studies between limited temperature ranges for one type of nanofluid. The different sides of this study according to the other studies are more nanoparticle types, wide temperature ranges, and different volumetric concentrations. In this study, water-based Al_2O_3, TiO_2, and ZnO nanofluids with 0.5%, 0.7%, and 1.0% volumetric concentration were prepared. Thermophysical properties, thermal conductivity, and viscosity of these nanofluids were measured between 20-60 °C experimentally. All measurement results are given and compared in graphics.

The literature equations used in this study for thermal conductivity and dynamic viscosity are shown in tabs. 1 and 2.

Materials and method

Properties of nanoparticles

The Al_2O_3, TiO_2, and ZnO nanoparticles are used to prepare nanofluid. The average sizes of Al_2O_3, TiO_2, and ZnO nanoparticles are 13 nm, 10-25 nm, and 18 nm, respectively. The detailed properties of the nanoparticles are given in tab. 3. Sodium dodecyl sulfate (SDS) as a surfactant is used to prevent the nanoparticles to precipitate by agglomerating and keep on the stability of nanofluid. However, SDS is not used in Al_2O_3 nanofluid since the desired stability is obtained even without it. The SDS density is 1.1 g/cm^3, and the pH value is between 6 and 9.

Table 1. The literature equations for thermal conductivity

Literature	Equation	Description
[25]	$\frac{k_{\text{nf}}}{k_{\text{bf}}}=\frac{k_{\text{np}}+2k_{\text{bf}}+2\left(k_{\text{np}}-k_{\text{bf}}\right)\phi}{k_{\text{np}}+2k_{\text{bf}}-\left(k_{\text{np}}-k_{\text{bf}}\right)\phi}$	This equation is the first one given for colloidal suspensions. It is valid for only spherical nanoparticles
[26]	$k_{\text{nf}}=\frac{1}{4}\left[\left(3\phi-1\right)k_{\text{np}}+\left(2-3\phi\right)k_{\text{bf}}\right]+\frac{k_{\text{bf}}}{4}\Delta^{0.5}$	This equation includes interactions between nanoparticles distributed randomly
[27]	$\frac{k_{nf}}{k_{\text{bf}}}=\frac{k_{\text{np}}+\left(n-1\right)k_{\text{bf}}+\left(n-1\right)\left(k_{\text{np}}-k_{\text{bf}}\right)\phi}{k_{\text{np}}+\left(n-1\right)k_{\text{bf}}-\left(k_{\text{np}}-k_{\text{bf}}\right)\phi}$	This equation that includes shape factor of particles is an advanced Maxwell one
[28]	$\frac{k_{\text{nf}}}{k_{\text{bf}}}=\frac{k_{\text{np,eq}}+2k_{\text{bf}}+2\left(k_{\text{np,eq}}-k_{\text{bf}}\right)\phi_{\text{eq}}}{k_{\text{np,eq}}+2k_{\text{bf}}-\left(k_{\text{np,eq}}-k_{\text{bf}}\right)\phi_{\text{eq}}}$	This equation included nanolayer having constant thermal conductivity is an advanced Maxwell one, β = 0.1 [29, 30]
[31]	$\frac{k_{\text{nf}}}{k_{\text{bf}}}=1+3\Theta\phi_{\text{eq}}+\frac{3\Theta^2\phi_{\text{eq}}^2}{1-\Theta\phi_{\text{eq}}},\quad \Theta=\frac{\beta_{\text{lf}}\left[\left(1+\gamma\right)^3-\frac{\beta_{\text{pl}}}{\beta_{\text{fl}}}\right]}{\left(1+\gamma\right)^3+2\beta_{lf}\beta_{\text{pl}}}$ $\beta_{\text{lf}}=\frac{k_{\text{l}}-k_{\text{f}}}{k_{\text{l}}+2k_{\text{f}}},\ \beta_{\text{pl}}=\frac{k_{\text{p}}-k_{\text{l}}}{k_{\text{p}}+2k_{\text{l}}},\ \beta_{\text{fl}}=\frac{k_{\text{f}}-k_{\text{l}}}{k_{\text{f}}+2k_{\text{l}}}$	This equation included nanolayer with changeable thermal conductivity is an advanced [28] one
[22]	$\frac{k_{\text{nf}}}{k_{\text{bf}}}=0.8938\left(1+\phi\right)^{1.37}\left(1+\frac{T_{\text{nf}}}{70}\right)^{0.2777}\cdot$ $\cdot\left(1+\frac{d_{\text{np}}}{150}\right)^{-0.0336}\left(\frac{\alpha_{\text{np}}}{\alpha_{\text{bf}}}\right)^{0.01737}$	This equation is valid for the conditions; (a) Spherical nanoparticles, (b) nanoparticles with diameters 8-150 nm, (c) 20-70 °C temperature range, and (d) nanofluid volumetric concentration less than 4%. max. deviation is 11%

Table 2. The literature equations for viscosity

Literature	Equation	Description
[32]	$\frac{\mu_{\text{nf}}}{\mu_{\text{bf}}}=1+2.5\phi$	This equation is valid for smaller volume concentration than 5% [33]
[34]	$\frac{\mu_{\text{nf}}}{\mu_{\text{bf}}}=\left(1-\phi\right)^{-2.5}$	This equation is valid for bigger volume concentration than 5% as well as smaller than it is
[35]	$\frac{\mu_{\text{nf}}}{\mu_{\text{bf}}}=1+2.5\phi+6.2\phi^2$	This equation includes Brownian moving effect of nanoparticles
[17]	$\frac{\mu_{\text{nf}}}{\mu_{\text{bf}}}=1+7.3\phi+123\phi^2$	Nguyen obtained this equation by curve fitting to the data in three studies [36-38]
[22]	$\frac{\mu_{\text{nf}}}{\mu_{\text{bf}}}=\left(1+\phi\right)^{11.3}\cdot$ $\cdot\left(1+\frac{T_{\text{nf}}}{70}\right)^{-0.038}\left(1+\frac{d_{\text{np}}}{170}\right)^{-0.061}$	This equation is valid for the conditions; (a) spherical nanoparticles, (b) nanoparticles with diameters 20-170 nm, (c) 20-70 °C temperature range, and (d) nanofluid volumetric concentration less than 4%. max. deviation is 13%

Table 3. Properties of nanoparticles, at 300 K, [39, 40]

Nano particle	Purity	Average particle diameter	Specific surface area [m^2g^{-1}]	Shape	Density [kgm^{-3}]	Specific heat [$Jkg^{-1}K^{-1}$]	Thermal conductivity [$Wm^{-1}K^{-1}$]
Al_2O_3	%99.8	13 nm	85-115	Nearly spherical	3890	778	46
TiO_2	%99.5	10-25 nm	200-240	Nearly spherical	3900	710	10
ZnO	%99.9	18 nm	40-70	Nearly spherical	5606	500	54

Preparation of nanofluids

In this study, all nanofluids are prepared by the Step 2 method [41, 42]. Firstly, the nanoparticles are bought by the producers. Then the nanoparticles are dispersed in a base fluid with the help of an ultrasonic homogenizer. A probe-type of the ultrasonic homogenizer is used to disperse the nanoparticles in deionized water (DW) used as base fluid (ultrasonic homogenizer mark/model: Optic Ivymen System / CY-500, Power: 500 W, Frequency: 20 kHz, probe diameter/length: Ø5.6/60 mm). All nanofluids are got at three different volumetric concentrations (0.5%, 0.7%, and 1.0%) at certain conditions [43, 44].

Those conditions are ultrasonic power applied: 500 W, ultrasonic dispersing time: 30 minutes, height of ultrasonic probe from bottom: 1-2 cm, solution temperature: 25 °C, and prepared solution volume: 100 mL.

Mass amounts of nanoparticle, DW, and SDS are calculated by taking into account the desired nanofluid volumetric concentration, volume of nanofluid, and mass concentration of SDS. These values are given in tab. 3. The mass amount is measured by AND GX-600 (max: 610 g, deviation: 0.001 g) with a precision balance. Stability time of Al_2O_3, TiO_2, and ZnO nanofluids are 5, 26, and 21 days, respectively. The equations used in tab. 4 for the nanofluids are the following;

Volume concentration of nanofluid:

$$\phi = \frac{\forall_{\mathrm{np}}}{\forall_{\mathrm{nf}}} = \frac{\rho_{\mathrm{nf}} - \rho_{\mathrm{bf}}}{\rho_{\mathrm{np}} - \rho_{\mathrm{bf}}} \text{ [45]} \tag{1}$$

where ϕ is volumetric concentration of nanofluid, $\forall_{\mathrm{np}}$ and $\forall_{\mathrm{nf}}$ are nanoparticle and nanofluid volume, ρ_{nf}, ρ_{np}, and ρ_{bf} – the densities of nanofluid, nanoparticle, and base fluid, respectively. Also, ϕ_{w} is mass concentration of SDS according to nanoparticle, and it is seen with $\phi_{\mathrm{w}} = m_{\mathrm{SDS}}/m_{\mathrm{np}}$ formula.

Experimental study

Density

Densities of nanofluids are determined by simple density equations and precision balance. As expressed in Azmi *et al.* [46], the nanofluid volumetric concentration equation showed by eq. (2) was used to obtain the density of nanofluid. For each nanofluid, the change of density values according to temperature and volumetric concentration is given, tab. 5:

$$\rho_{\mathrm{nf}} = \rho_{\mathrm{np}}\,\phi + \rho_{\mathrm{bf}}\left(1-\phi\right) \text{ [13]} \tag{2}$$

While the densities of Al_2O_3 and TiO_2 nanofluids are approxitely the same, but the density of ZnO nanoparticle is bigger than that of Al_2O_3 and TiO_2. This can be seen in tab. 1.

Table 4. Calculated mass amounts for definite concentrations and volume of nanofluid at 20 °C

Nano fluid	Volume concentration	Volume of nanofluid	Density of base fluid	Particle density	Volume of particle	SDS – Paritcle weight concentration
	ϕ [%]	$\forall_{nf}$ [mL]	ρ_{bf} [kgm^{-3}]	ρ_{np} [kgm^{-3}]	$\forall_{np}$ [mL]	ϕ [%]
Al_2O_3	0.5	100	998.0	3890	0.50	15.00%
	0.7	100	998.0	3890	0.70	15.00%
	1.0	100	998.0	3890	1.00	15.00%
TiO_2	0.5	100	998.0	3900	0.50	15.00%
	0.7	100	998.0	3900	0.70	15.00%
	1.0	100	998.0	3900	1.00	15.00%
ZnO	0.5	100	998.0	5606	0.50	15.00%
	0.7	100	998.0	5606	0.70	15.00%
	1.0	100	998.0	5606	1.00	15.00%

Table 5. Change of density of nanofluids with temperature

Relative density, ρ_r [–]										
Nanofluid	Concentration	Temperature, T [°C]								
	ϕ [%]	20	25	30	35	40	45	50	55	60
Water	–	0.998	0.996	0.995	0.993	0.992	0.990	0.988	0.986	0.983
Al_2O_3	0.5%	1.012	1.011	1.009	1.008	1.006	1.004	1.002	1.000	0.998
	0.7%	1.018	1.017	1.015	1.014	1.012	1.010	1.008	1.006	1.004
	1.0%	1.027	1.025	1.024	1.022	1.021	1.019	1.017	1.015	1.012
TiO_2	0.5%	1.012	1.011	1.010	1.008	1.006	1.004	1.002	1.000	0.998
	0.7%	1.018	1.017	1.015	1.014	1.012	1.010	1.008	1.006	1.004
	1.0%	1.027	1.025	1.024	1.022	1.021	1.019	1.017	1.015	1.012
ZnO	0.5%	1.021	1.019	1.018	1.016	1.015	1.013	1.011	1.009	1.006
	0.7%	1.030	1.029	1.027	1.026	1.024	1.022	1.020	1.018	1.016
	1.0%	1.044	1.042	1.041	1.040	1.038	1.036	1.034	1.032	1.029

Although eq. (2) does not have a temperature parameter directly, the density values change with temperature. The reason is that it is available indirectly. It is considered the change of the density of the base fluid, which is DW here, according to temperature. If the change of density of the base fluid were not taken into account, densities would have become constant along with the temperature.

Specific heat

Specific heats of nanofluids are determined by using specific heat equation expressed as eq. (3). In the literature, some researchers measured specific heats of nanofluids [47-50] some calculated it by equations [5, 15, 51, 52]. Also, some of them explained that the results obtained by eq. (3) are compatible with ones measured [4, 46, 48, 53].

In this study, the results obtained from the equation are used. For each nanofluid, the change of specific heat values according to temperature and volumetric concentration is given, tab. 6:

$$\rho_{nf} c_{nf} = \rho_{np} c_{np} \phi + \rho_{bf} c_{bf} (1-\phi) \tag{3}$$

Table 6. Change of specific heat of nanofluids with temperature

Specific heat, c_p [Jkg^{-1}K^{-1}]									
Nano-fluid	Concentration	Temperature, T [°C]							
	ϕ [%]	20	25	30	35	40	45	50	60
Water	–	4182	4180	4178	4178	4179	4180	4181	4185
Al_2O_3	0.5%	4124	4121	4119	4117	4116	4116	4116	4118
	0.7%	4099	4096	4094	4092	4091	4091	4091	4093
	1.0%	4063	4060	4057	4056	4054	4054	4054	4055
TiO_2	0.5%	4120	4118	4115	4114	4113	4112	4112	4114
	0.7%	4094	4091	4089	4087	4086	4086	4086	4087
	1.0%	4055	4052	4050	4048	4047	4046	4046	4048
ZnO	0.5%	4087	4084	4081	4080	4079	4078	4078	4080
	0.7%	4047	4044	4042	4040	4039	4039	4038	4041
	1.0%	3990	3987	3984	3983	3981	3981	3981	3982

Thermal conductivity

For the thermal conductivity measurement of nanofluids, it is used as a device that works by the transient hot-wire method [54] (mark/model: Decagon/KD2 Pro, KS-1 probe thermal cond. Measurement range: 0.02-2 W/mK, KS-1 Probe accuracy: ±0.01 W/mK between 0.02-0.2 W/mK and ±5% between 0.2-2 W/mK, temperature measurement range: –50~+150 °C). Each thermal conductivity measurement takes 90 seconds totally, which consists of 30 seconds of thermal balance, 30 seconds heating, and 30 seconds waiting.

This method and the device were used to measure thermal conductivity at a lot of works widely [4, 5, 11, 46, 50, 55-59]. Besides, it is used eqs. (4)-(6) obtained from experimental results of thermal conductivity measurement of Al_2O_3, TiO_2, and ZnO nanofluids to calculate thermal conductivity ratios depending on volumetric concentration, ϕ, and temperature, T.

For Al_2O_3 nanofluid:

$$\frac{k_{\mathrm{nf}}}{k_{\mathrm{bf}}} = 0.76 + (36.15\phi) + (0.003T) + \left(-187.27\phi^2\right) + \left(2.58 \cdot 10^{-5} T^2\right) + (-0.46\phi T) \tag{4}$$

For TiO_2 nanofluid:

$$\frac{k_{\mathrm{nf}}}{k_{\mathrm{bf}}} = 0.83 + (23.58\phi) + (0.005T) + \left(-550.03\phi^2\right) + \left(-3.42 \cdot 10^{-5} T^2\right) + (-0.20\phi T) \tag{5}$$

For ZnO nanofluid:

$$\frac{k_{\mathrm{nf}}}{k_{\mathrm{bf}}} = 0.97 + (15.17\phi) + (-0.0012T) + \left(294.23\phi^2\right) + \left(4.14 \cdot 10^{-5} T^2\right) + (-0.23\phi * T) \tag{6}$$

For calibration of the KS-1 probe of the device used, the calibration sample (glycerin, k = 0.285 W/mK, at 20 °C), which comes with the device, was used. When the thermal conductivity of glycerin was measured, it was found as 0.277 W/mK at 22 °C. This means about a 3% deviation that is in the 5% range. However, since change with temperature on values measured is more important, the measurements were done with DW. The calibration results according to temperature for DW are given in fig. 1. In addition, ±5% accuracy range on the measurement values is showed at the same figure. The table values were taken from reference [60].

As seen in fig. 3, it is found that the measurement results are at a 5% deviation. This is compatible with the deviation indicated in the device specification [54].

Thermal conductivity measurements of nanofluids are done just after they are prepared as. Since thermal conductivity is dependent on temperature, it was necessary for measurements to be done at a constant temperature.

Viscosity

For viscosity measurement of nanofluids, it is used a device that works by tuning-fork vibration method [61] (mark/model: AND/SV-10, viscosity measurement range: 0.3 mPa·s – 10 Pa·s, accuracy: ±3% between 0.3-1000 mPa·s, temperature measurement range: 0 ~ +160 °C). Each viscosity measurement takes about 15 seconds. The device was used with a heat bath (Cole-Parmer, Digital, Heating: 1 kW, Cooling: 200 W) that controls the temperature of the fluid.

Also, it is used eqs. (7)-(9) obtained from experimental results of thermal conductivity measurement of Al_2O_3, TiO_2, and ZnO nanofluids to calculate dynamic viscosity ratios depending on volumetric concentration, ϕ, and temperature, T.

For Al_2O_3 nanofluid:

$$\frac{\mu}{\mu_{\mathrm{bf}}} = 0.89 + \left(2.84\phi\right) + \left(0.008T\right) + \left(-195.67\phi^2\right) + \left(-9.28\cdot 10^{-5}T^2\right) + \left(0.116\phi T\right) \tag{7}$$

For TiO_2 nanofluid:

$$\frac{\mu}{\mu_{\mathrm{bf}}} = 1.26 + \left(-42.48\phi\right) + \left(-0.007T\right) + \left(1342.3\phi^2\right) + \left(-1.32\cdot 10^{-5}T^2\right) + \left(1.25\phi T\right) \tag{8}$$

For ZnO nanofluid:

$$\frac{\mu}{\mu_{\mathrm{bf}}} = 0.78 + \left(-22.92\phi\right) + \left(0.021T\right) + \left(1564.13\phi^2\right) + \left(-2.96\cdot 10^{-4}T^2\right) + \left(0.2\phi T\right) \tag{9}$$

For calibration of the device, pure water was used. The calibration results according to temperature for pure water are given in fig. 2. The table values and measurement values of pure water were compared with error bars in fig. 2. Also, ±3% between 20-30 °C and ±5% (estimated) for higher than 30 °C accuracy range on the measurement values are shown at the same figure. The table values were taken from reference [60].

As seen in fig. 4, it is found that the measurement results are at a 5% deviation (accepted value over 30 °C). This is compatible with the deviation indicated in the device specification [61].

Dynamic viscosity measurements of nanofluids are done just like thermal conductivity ones similarly. Since viscosity is dependent on temperature, it is necessary to do the measurement at constant temperatures. A heat bath was used to increase the nanofluid temperature to the desired values.

In the experimental studies, thermal conductivity and dynamic viscosity of nanofluids were measured with appropriate instruments. During the measurements of the parameters, uncertainties occurring are presented in tab. 7. When the measurement of dynamic viscosity and thermal conductivity of nanofluids were performed, the range of the results and measurement temperature were considered with tolerance values and units. Considering the relative errors in the individual factors denoted by, the error estimation was made using the equation [62]:

$$W = \sqrt{\left(x_1\right)^2 + \left(x_2\right)^2 + \ldots + \left(x_n\right)^2} \tag{10}$$

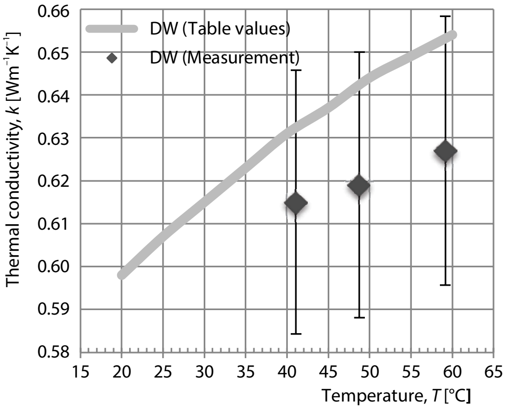

Figure 1. Comparison between DW data from measurement and from table

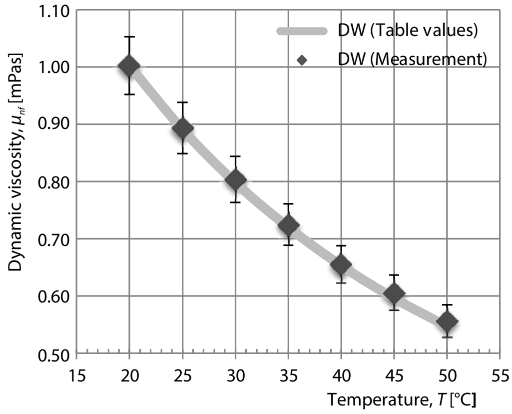

Figure 2. Comparison of measurement and table values of pure water (with error bars)

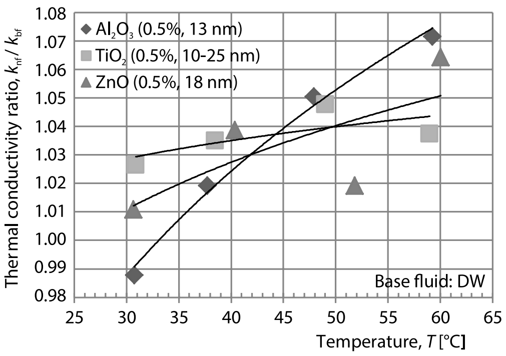

Figure 3. Comparison of ratio of thermal conductivity of nanofluids to base fluid with each other

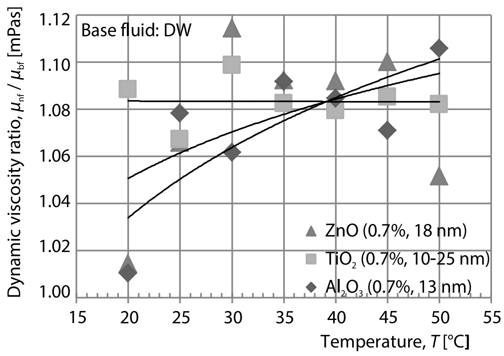

Figure 4. Comparison of ratio of dynamic viscosity of nanofluids to base fluid with each other

Also, some experiments were repeated to present reproducibility of the experiments.

Table 7. Uncertainties of the parameters

Parameters	Range	Unit	Comment
Thermal conductivity measurement	0.02-2	[Wm^{-1}K^{-1}]	±0.01
Temperature measurement*	–50 ~ +150	[°C]	±1
Viscosity measurement	0.3-10^4	[mPa·s]	±3%
Temperature measurement**	0 ~ +160	[°C]	±1

*During measurement of thermal conductivity, ** During measurement of viscosity

Results and discussion

Thermal conductivity of nanofluids

The obtained thermal conductivity ratios of nanofluids are given in tab. 8. Here, the base fluid is DW. Besides, comparisons of the thermal conductivity ratio of nanofluids with the equations, with the studies in literature and with each other are given in tab. 9, tab. 10, and fig.

3, respectively. The points in three different colors in fig. 3 represent the experimental results of the thermal conductivity ratio of nanofluids. Moreover, full lines were derived from the average of the points. Equation (4) were obtained from these full lines in fig. 3, and eqs. (5) and (6) were also obtained from experimental data as eq. (4). Equations' values depending on temperature were shown in tab. 9. All graphics are given as the ratio of thermal conductivity of nanofluid to base fluid since the ratio both shows increase according to base fluid and enables to compare with other researchers' results as dimensionless easily. Moreover, to be able to see the thermal conductivity trend and to make comparisons easy, the data points were added trend lines or were combined. Therefore, intermediate values may not always show the correct ones.

As seen in tab. 8, while temperature or volumetric concentration increases, the thermal conductivity ratio also generally increases. However, their increment trends or slopes change according to nanofluid type, volumetric concentration, and temperature. The highest thermal conductivity increase of Al_2O_3, TiO_2, and ZnO nanofluids according to base fluid (DW) are shown in tab. 8. Each experimental measurement was repeated three times to get an accurate result. Then, the mean of these measurements was considered, so some discrepancies for ZnO occurred because of measurement precision.

In tab. 9, to avoid complex graphics, they are given for only one volumetric concentration of nanofluids. Since the equations except Sharma *et al*. [22] do not have any parameter including temperature, they remain constant with temperature. Sharma *et al*. [22] equation is determined by curve fitting for 252 data points. As a result, the results of this study are found compatible with Sharma *et al*. [22] as a trend. From here, it can be said, if it is not possible to measure the thermal conductivity of nanofluid and however it is necessary to use a value for thermal conductivity to obtain a parameter like Nusselt number, equations that don't include temperature parameter must not be used. Because the equations that do not include temperature parameter give more correct results for different volumetric concentrations at the only same temperature.

Table 8. Comparison of thermal conductivity ratio of nanofluids to base fluid with the equations in literature

Thermal conductivity ratio k_{nf}/k_{bf}										
Nanofluid	Concentration	k_{nf}, [25]/k_{bf}	k_{nf}, [27]/k_{bf}	k_{nf}, [26]/k_{bf}	k_{nf}, [28]/k_{bf}	k_{nf}, [31]/k_{bf}	k_{nf}, [22]/k_{bf}			
		T [°C]	T [°C]	T [°C]	T [°C]	T [°C]	T [°C]			
	ϕ [%]	Independent of temperature	Independent of temperature	Independent of temperature	Independent of temperature	Independent of temperature	30	40	50	60
Al_2O_3	0.5%	1.014	1.026	1.015	1.022	1.019	1.074	1.102	1.129	1.154
TiO_2	0.5%	1.013	1.020	1.013	1.018	1.016	1.046	1.074	1.100	1.124
ZnO	0.5%	1.015	1.026	1.015	1.022	1.019	1.077	1.106	1.132	1.157

Nanofluid	This study (ϕ = 0.5%) (experimental)				This study (ϕ = 0.5%) (with equations)				This study (ϕ = 0.7%) (with equations)				This study (ϕ = 1.0%) (with equations)			
	T [°C]				T [°C]				T [°C]				T [°C]			
	30	40	50	60	30	40	50	60	30	40	50	60	30	40	50	60
Al_2O_3	0.988	1.019	1.050	1.071	0.989	1.017	1.050	1.088	1.029	1.048	1.072	1.100	1.087	1.091	1.101	1.116
TiO_2	1.026	1.035	1.048	1.037	1.022	1.036	1.044	1.045	1.043	1.054	1.057	1.054	1.068	1.072	1.070	1.060
ZnO	1.011	1.039	1.019	1.064	1.016	1.021	1.035	1.057	1.039	1.040	1.049	1.066	1.079	1.072	1.074	1.085

Table 9. Comparison of thermal conductivity ratio of nanofluids to base fluid with the studies in literature

Thermal conductivity ratio k_{nf}/k_{bf}																
Nano particle	Author	Concen-tation	T [°C]													Diameter
		ϕ [%]	15	20	25	30	35	40	45	50	55	60	70	80	90	d_{np}
Al_2O_3	[66]	0.50%	–	1.035	–	1.040	–	1.032	–	1.034	–	1.040	1.040	1.044	1.057	35 nm
	[63]	0.60%	–	–	–	1.009	–	1.071	–	1.089	–	1.109	1.146	1.267	–	75 nm
	[4]	0.50%	–	1.05	–	–	–	1.065	–	–	1.065	–	–	–	–	40 nm
	[55]	0.60%	–	1.035	–	–	–	1.051	–	–	–	1.063	–	1.099	–	<100 nm
	[67]	0.40%	–	1.005	1.014	1.024	–	–	–	–	–	–	–	–	–	44 nm
	[68]	0.50%	–	1.008	–	–	1.010	–	–	1.020	–	–	–	–	–	25 nm
	This study	0.50%	–	–	–	0.988	–	1.019	–	1.050	–	1.071	–	–	–	13 nm
TiO_2	[69]	0.24%	–	1.012	–	1.039	–	1.023	–	1.071	–	1.086	1.103	1.177	–	74 nm
	[64]	1.00%	–	1.010	–	1.025	–	1.045	–	–	–	–	–	–	–	40 nm
	[12]	0.60%	1.029	–	1.016	–	1.003	–	–	–	–	–	–	–	–	21 nm
	[10]	0.20%	–	–	1.003	–	–	1.005	–	1.003	–	–	–	–	–	21 nm
	[57]	0.50%	–	–	0.988	–	0.979	–	0.990	–	–	–	–	–	–	10 nm
	This study	0.50%	–	–	–	1.026	–	1.035	–	1.048	–	1.037	–	–	–	10-25 nm
ZnO	[65]	0.50%	–	1.105	–	1.105	–	1.130	–	1.200	–	–	–	–	–	125 nm
	[48]	0.82%	–	1.002	–	1.016	–	1.000	–	1.003	–	1.002	1.003	–	–	25 nm
	This Study	0.50%	–	–	–	1.011	–	1.039	–	1.019	–	1.064	–	–	–	18 nm

In tab. 10, as previous graphics, only one volumetric concentration of nanofluids is used to avoid complex graphics. Since there are many parameters that affect the absolute values of the thermal conductivity of nanofluids, it is more suitable to compare the trend of their ratio. As seen, both similar ref. [16, 63, 64] and dissimilar [4, 12, 65] trends are available.

Consequently, it is estimated that the differences that appeared at the thermal conductivity values result from lots of parameters. Some of them can be particle producer, particle purity (99%), particle size (13 nm), particle shape (spherical), nanofluid pH value, surfactant availability, surfactant type (SDS, oleic acid), preparation type of nanofluid (Step 1 or Step 2), nanofluid preparation parameters (30 min ultrasonicating), the device be done measurement.

Viscosity of nanofluids

The obtained dynamic viscosity values of nanofluids and their ratios are given in tab. 11. Here, the base fluid is DW. Besides, comparisons of the dynamic viscosity ratio of nanofluids with each other are shown in fig. 4.

As seen in tab. 11, while temperature or volumetric concentration increases, the dynamic viscosity ratio also generally increases. It can be confounding viscosity to increase with temperature.

This is due to ratios. Yet, if absolute values are examined in *e.g.* tab. 11, it must be paid attention that viscosity decreases with increasing temperature.

Table 10. Dynamic viscosity results of nanofluids

Nanofluid	Vol. concenttration	Dynamic viscosity ratio of nanofluid, μ_{nf}/μ_{bf} Temperature, T [°C]						
	ϕ	20	25	30	35	40	45	50
Al_2O_3 (13 nm)	0.5%	1.012	1.077	1.056	1.084	1.034	1.069	1.107
	0.7%	1.010	1.078	1.062	1.092	1.085	1.071	1.106
	1.0%	1.005	1.098	1.069	1.109	1.100	1.081	1.115
TiO_2 (10-25 nm)	0.5%	1.078	1.021	1.063	1.038	1.055	1.041	1.04
	0.7%	1.088	1.067	1.098	1.082	1.079	1.085	1.082
	1.0%	1.089	1.062	1.150	1.146	1.195	1.246	1.205
ZnO (18 nm)	0.5%	1.014	1.064	1.100	1.079	1.087	1.093	1.055
	0.7%	1.014	1.066	1.114	1.092	1.092	1.100	1.051
	1.0%	1.030	1.091	1.135	1.122	1.136	1.139	1.096

Table 11. Comparison of dynamic viscosity ratio of nanofluids to base fluid with the equations in the literature

Dynamic viscosity ratio, μ_{the}/μ_{bf}									
Nano-fluid	Concen-tration	[32] ($\mu_{[32]}/\mu_{bf}$)	[34] ($\mu_{[34]}/\mu_{bf}$)	[35] ($\mu_{[35]}/\mu_{bf}$)	[17] ($\mu[17]/\mu_{bf}$)	[22] ($\mu_{[22]}/\mu_{bf}$)			
		T [°C]	T [°C]	T [°C]	T [°C]	T [°C]			
	ϕ [%]	Independent of temperature	Independent of temperature	Independent of temperature	Independent of temperature	20	30	40	50
Al_2O_3	0.5%	1.013	1.013	1.013	1.040	1.043	1.039	1.035	1.032
TiO_2	0.5%	1.013	1.013	1.013	1.040	1.042	1.037	1.034	1.030
ZnO	0.5%	1.013	1.013	1.013	1.040	1.042	1.037	1.034	1.030

Nano-fluid	This study (ϕ = 0.5%) (experimantal), μ/μ_{bf}				This study (ϕ = 0.5%) (with equations), μ/μ_{bf}				This study (ϕ = 0.7%) (with equations), μ/μ_{bf}				This study (ϕ = 1.0%) (with equations), μ/μ_{bf}			
	T [°C]				T [°C]				T [°C]				T [°C]			
	20	30	40	50	20	30	40	50	20	30	40	50	20	30	40	50
Al2O3	1.012	1.056	1.034	1.107	1.024	1.061	1.079	1.078	1.030	1.069	1.089	1.091	1.035	1.078	1.101	1.107
TiO2	1.078	1.063	1.055	1.040	1.066	1.056	1.042	1.027	1.064	1.078	1.090	1.099	1.080	1.132	1.182	1.229
ZnO	1.014	1.100	1.087	1.055	1.018	1.088	1.098	1.050	1.017	1.091	1.106	1.061	1.040	1.120	1.140	1.101

In tab.12, a comparison of dynamic viscosity ratios in this study and with equations in the literature have been given in detail. The values of eqs. (7)-(9) have been shown in tab. 12. The results of this study are found compatible with Nguyen *et al*. [17] for only TiO_2 nanofluid as a trend. However, there are some discrepancies compared to other equations' results. As seen in tab. 13, the comparison of experimental results of dynamic viscosity ratios in this study and in the literature have been given in detail. The results of three different nanofluids used in this study agree with Akyürek's study [67] for Al_2O_3 nanofluid, Turgut's study [10] for TiO_2 nanofluid and Rajan's study [70] for ZnO nanofluid.

The difference explanations given for therm al conductivity graphics are valid viscosity ones, too.

Table 12. Comparison of dynamic viscosity ratio of nanofluids to base fluid with the studies in the literature

Dynamic viscosity ratio, μ_{the}/μ_{bf}																	
Nano particle	Author	Concen-tation	T [°C]														Diameter
		ϕ [%]	15	20	25	30	35	40	45	50	55	60	65	70	75	80	90	d_{np}
Al_2O_3	[66]	0.50%	–	1.186	–	1.214	–	1.195	–	1.192	–	1.208	–	1.223	–	1.225	1.206	35 nm
	[63]	0.60%	–	–	–	1.110	–	1.118	–	1.156	–	1.132	–	1.198	–	1.197	–	75 nm
	[4]	0.50%	–	1.090	–	1.100	–	1.110	–	1.120	–	1.130	–	–	–	–	–	40 nm
	[71]	0.55%	–	1.156	1.177	1.189	1.153	1.149	–	1.119	–	1.121	–	–	–	–	–	20 nm
	[67]	0.40%	–	1.116	1.143	1.101	1.111	1.149	1.210	1.284	1.196	1.186	1.162	1.223	1.202	–	–	44 nm
	[68]	0.50%	–	1.136	1.143	1.164	1.194	1.195	1.210	1.211	–	–	–	–	–	–	–	25 nm
	This study	0.50%	–	1.012	1.077	1.056	1.064	1.034	1.069	1.107	–	–	–	–	–	–	–	13 nm
TiO_2	[69]	0.24%	–	1.021	–	0.995	–	0.988	–	0.976	–	1.052	–	1.020	–	–	–	74 nm
	[64]	1.00%	–	1.200	–	1.200	–	1.200	–	–	–	–	–	–	–	–	–	40 nm
	[12]	0.60%	1.002	–	1.053	–	1.139	–	–	–	–	–	–	–	–	–	–	21 nm
	[10]	0.20%	–	1.041	1.050	–	1.055	1.051	1.063	1.085	1.076	–	–	–	–	–	–	21 nm
	[72]	0.99%	–	1.096	1.121	1.110	1.098	–	1.132	–	1.132	–	1.100	–	–	–	–	27 nm
	This study	0.50%	–	1.078	1.021	1.063	1.038	1.055	1.041	1.040	–	–	–	–	–	–	–	10-25 nm
ZnO	[70]	0.50%	–	–	1.070	–	1.035	1.050	–	–	1.037	–	–	–	–	–	–	37 nm
	[16]	0.82%	–	1.146	–	1.126	–	1.141	–	1.110	–	1.100	–	1.123	–	–	–	25 nm
	This Study	0.50%	–	1.014	1.064	1.100	1.079	1.087	1.093	1.055	–	–	–	–	–	–	–	18 nm

Conclusions

Thermodynamic properties of nanofluids change in time due to agglomeration and sedimentation. Therefore, it must be denoted how many times measurements are made after nanofluids are prepared.

The dynamic viscosity of fluid decreases during thermal conductivity measurements, when the device applies higher heat pulse to fluid or when the temperature of fluid increase. Since convection effects (natural-convection) appear, and bigger measurement mistakes may occur.

The thermal conductivity ratios of Al_2O_3 nanofluid in different volumetric concentrations are higher than TiO_2 and ZnO nanofluids at 50 °C and 60 °C. Also, k_{nf}/k_{bf} values of Al_2O_3 nanofluid increase depending on volumetric concentration. Dynamic viscosity of TiO_2 nanofluid for 1% volumetric concentration has the highest values with 24% compared with Al_2O_3 and ZnO nanofluids.

Using the classical nanofluids allows heat transfer enhancement and the increase in dynamic viscosity. As a result of these situations, the effects of the augmentation in dynamic viscosity on pumping power was considered as well as the increase in thermal conductivity. 0.5% volumetric concentration of Al_2O_3-water nanofluid provided 18.8% heat transfer enhancement, but it caused 21% increasing in pumping power. Thus, no abnormal heat transfer enhancement was observed. All these descriptions can considerably affect thermal conductivity and viscosity results, and their control is not easy, they can be showed as some of the controversial results in the literature.

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Nomenclature

d – nanoparticle diameter, [nm]
c_p – specific heat, [Jkg^{-1}K^{-1}]
k – thermal conductivity, [Wm^{-1}K^{-1}]
m – mass, [kg]
n – shape factor, particle number per unit volume, [m^{-3}]
T – temperature, [K, °C]
$\forall$ – volume, [m^3]

Greek symbols

α – thermal diffusivity, [m^{2}s^{-1}]
β – ratio of the nanolayer thickness original particle radius
γ – thickness ratio
μ – dynamic viscosity, [Pa·s]
ρ – density, [kgm^{-3}]
ϕ – volume concentration ratio, [–]
ϕ_{eq} – equivalent volumetric concentration
ϕ_{w} – weight concentration ratio, [–]

Acronyms

TEM – transmission electron microscopy

Subscripts

bf – base fluid
eq – equivalent
f – fluid
l – nanolayer
p – nanoparticle
nf – nanofluid
nl – nanolayer
np – nanoparticle

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