archives
of thermodynamics
Vol. **36**(2015), No. 4, 35–47
DOI: 10.1515/aoter-2015-0031

Measurement of temperature-dependent viscosity and thermal conductivity of alumina and titania thermal oil nanofluids

JANUSZ T. CIEŚLIŃSKI[a 1]
KATARZYNA RONEWICZ[a]
SŁAWOMIR SMOLEŃ[b]

[a] Gdansk University of Technology, Narutowicza 11/12, 80-233 Gdańsk, Poland

[b] Hochschule Bremen, Neustadswall 30, 28-199 Bremen, Germany

Abstract In this study the results of simultaneous measurements of dynamic viscosity, thermal conductivity, electrical conductivity and pH of two nanofluids, i.e., thermal oil/Al_2O_3 and thermal oil/TiO_2 are presented. Thermal oil is selected as a base liquid because of possible application in ORC systems as an intermediate heating agent. Nanoparticles were tested at the concentration of 0.1%, 1%, and 5% by weight within temperature range from 20 °C to 60 °C. Measurement devices were carefully calibrated by comparison obtained results for pure base liquid (thermal oil) with manufacturer's data. The results obtained for tested nanofluids were compared with predictions made by use of existing models for liquid/solid particles mixtures.

Keywords: Nanofluids; Dynamic viscosity; Thermal conductivity; Electrical conductivity

Nomenclature

T – temperature, °C

[1]Corresponding Author. E-mail: jcieslin@pg.gda.pl

Greek symbols

β – electrical conductivity, μS/cm
λ – thermal conductivity, W/(mK)
ρ – density, kg/m^3
η – dynamic viscosity, mPa s
Φ – volume nanoparticle concentration

Subscripts

m – weight
nf – nanofluid
p – nanoparticle
TO – base fluid (thermal oil)
v – volume

1 Introduction

Nanofluids [1] represent a new class of working fluids, that – due to enhanced thermophysical properties, can find application in many cooling/heating systems [2–4]. Therefore, it is of great importance to precisely establish such properties of nanofluids like thermal conductivity, viscosity, surface tension or contact angle.

Viscosity is one of the decisive factors in convective heat transfer, therefore knowledge about exact values of dynamic/kinematic viscosities is of primary importance in generalization of the experimental data in the form of Nusselt-type correlations [5] or in numerical modeling of heat transfer processes. Published data show substantial increase of nanofluid's viscosity in comparison with the base liquid. The concentration and size of the nanoparticles in nanofluids have been shown to affect the viscosity. It was emphasized that agglomeration of nanoparticles would affect the rheological properties of nanofluids [6].

The fact that thermal conductivity of the suspensions is higher than that of the base liquids results from the higher – even orders-of-magnitude, thermal conductivities of solids than that of liquids. It is a well known fact that thermal conductivities of nanofluids showed linear variation with nanoparticle loading. The majority of studies confirmed that at lower particle size, there is a significant increase in the effective conductivity of nanofluids. Moreover, the published data show that there exists an extremely strong temperature effect on the thermal conductivity enhancement of nanofluids. Unfortunately, the theoretical predictions from present models [7–10] – established for mixtures (slurries) with mili- and microparticles display dramatic discrepancy compared to experimental data.

The pH value is important because it affects thermal conductivity and first of all the isoelectric point. At the pH value of the isoelectric point, the repulsive forces between the particles are reduced to zero, which increases the possibility of agglomeration. On the other hand, hydration forces among the particles increase with increasing difference in pH from the value at the isoelectric point. This gives greater mobility to the nanoparticles and increases the thermal transport capability [9].

Despite the vast scientific and technological importance of electrical conductivity characteristics of nanoparticle suspensions, studies concerning the issue of the effective electrical conductivities of nanofluids have largely been ignored. Also, there is very few data published when it comes to the electrical properties of nanofluids. On the other hand, among the transport properties, electrical conductivity might bring information on the state of dispersion and stability of the particulate suspension [11].

In present study simultaneous measurements of dynamic viscosity, thermal conductivity, electrical conductivity and pH of two nanofluids, i.e., thermal oil/Al_2O_3 (TO-Al_2O_3) and thermal oil/TiO_2 (TO-TiO_2), were conducted. Thermal oil (TO) was selected as a base liquid, because of possible application in organic Rankine cycle (ORC) systems as an intermediate heating agent [12]. Measurement devices were carefully calibrated by comparison of obtained results for pure base liquid (thermal oil) with manufacturer's data. The results obtained for tested nanofluids were compared with predictions made by application of existing models for liquid/solid particles mixtures (slurries).

2 Experimental apparatus and procedure

2.1 Experimental setup

Figure 1 shows a view of the experimental equipment. The viscosity was measured using a low viscosity capillary type viscometer Rheotest® LK 2.2 (Medingen GmbH, Ottendorf-Okrillan). This viscometer measures the dynamic viscosity predominant of Newtonian fluids within the viscosity range of 1 to 10 000 mPa s (for different capillaries) within the temperature range from 10 °C to 80 °C and accuracy of $\leq 2\%$. Measurement time equals 35 s. The thermal conductivity was measured using a KD 2 Pro thermal properties analyzer (Decagon Devices Inc.). The instrument has a specified accuracy of 5%. Electrical conductivity was measured using a CPC-401 meter (Elmetron Ltd., Zabrze). The conductivity meter has a measuring range between 0 and 2000 μS/cm and a resolution of 0.1%. pH was measured using a CPC-401 meter (Elmetron, Ltd., Zabrze, Poland) with a sensor pH E-2627.

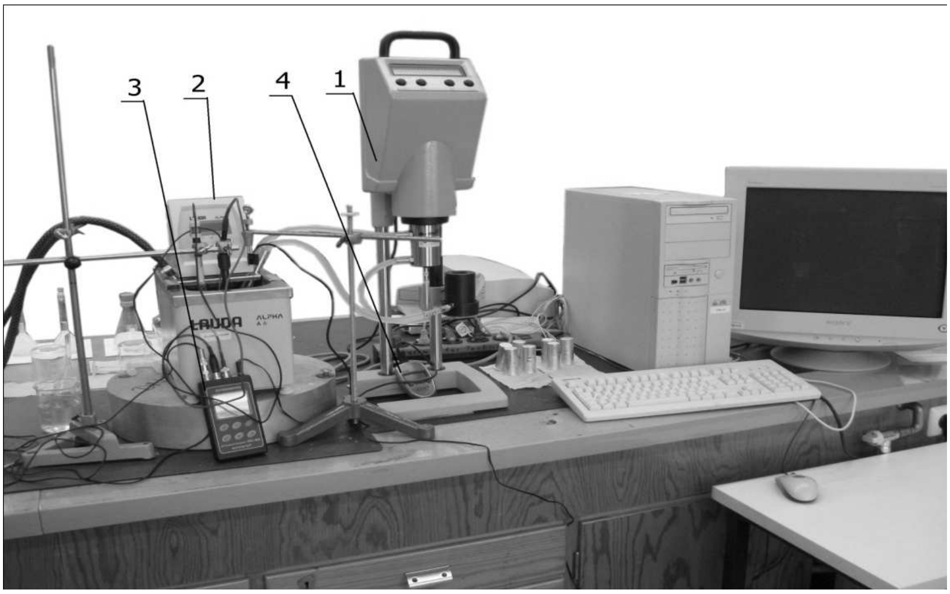


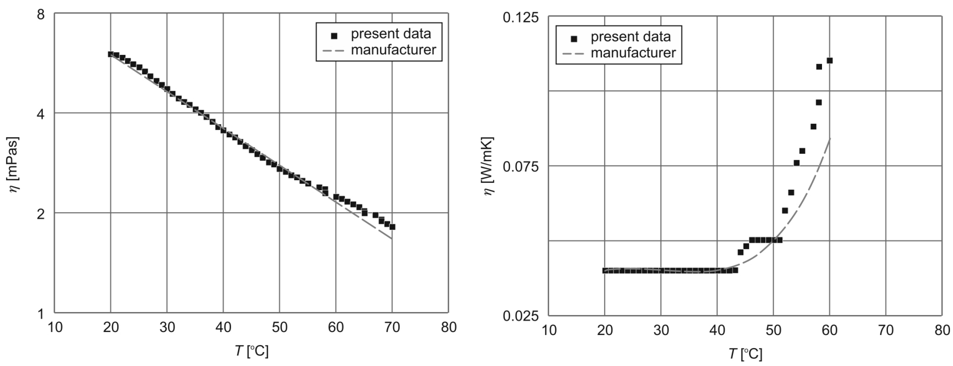
Figure 1: View of the experimental apparatus: 1 – viscometer, 2 – thermostat, 3 – pH and electrical conductivity meter, 4 – thermal conductivity meter.

2.2 Preparation and characterization of nanofluids

In the present study Al_2O_3 and TiO_2 were used as nanoparticles while thermal oil was applied as a base fluid. Nanoparticles of the required amount and base fluid were mixed together. Alumina (Al_2O_3) nanoparticles, of spherical form had a diameter ranging from 5 nm to 250 nm; their mean diameter was estimated to be 47 nm according to the manufacturer (Sigma-Aldrich Co.). Titania (TiO_2) nanoparticles, of spherical form had diameter ranging from 5 nm to 250 nm; their mean diameter was estimated to be 47 nm according to the manufacturer (Sigma-Aldrich Co.). Dispersants were not used to stabilise the suspension. Ultrasonic vibration was used for 30–60 minutes in order to stabilise the dispersion of the nanoparticles. Nanoparticles were tested at the concentration of 0.1%, 1%, and 5% by weight.

3 Results and discussion

Before the viscosity and thermal conductivity of tested nanofluids were measured, the viscosity and thermal conductivity of pure thermal oil were measured at temperatures of 20 °C to 70 °C to validate the used viscometer and the transient hot-wire system. Then, the measured data were compared with the reference data provided by the vendor. As shown in Fig. 2, the results show relatively good concurrence between measured values and the reference values and the uncertainty of the viscosity and the thermal conductivity measurement are maximally around 4% and 31%, respectively.



a) b)

Figure 2: Comparison of the measured properties of the tested pure thermal oil with reference data: a) viscosity, b) thermal conductivity.

As an example Fig. 3 shows the viscosity of TO-Al_2O_3 nanofluid as a function of temperature and nanoparticle weight concentration. The results show that for both tested nanofluids viscosity decreases with temperature increase and the slope is almost the same as for pure thermal oil. Moreover, viscosity increases with nanoparticle concentration increase, particularly for TO-Al_2O_3 nanofluids. Figure 4, in turn, shows the relative viscosity of the TO-TiO_2 nanofluid as a function of temperature and nanoparticle weight concentration. The results show that the increase of the viscosity of both tested nanofluids is almost independent of temperature for lower tested nanoparticle concentrations, i.e., 0.1% and 1%. For the highest nanoparticle concentration, i.e., 5%, relative viscosity of the TO-Al_2O_3 nanofluid substantially increases with temperature increase, while for TO-TiO_2 nanofluid is still independent of temperature – Fig. 4.

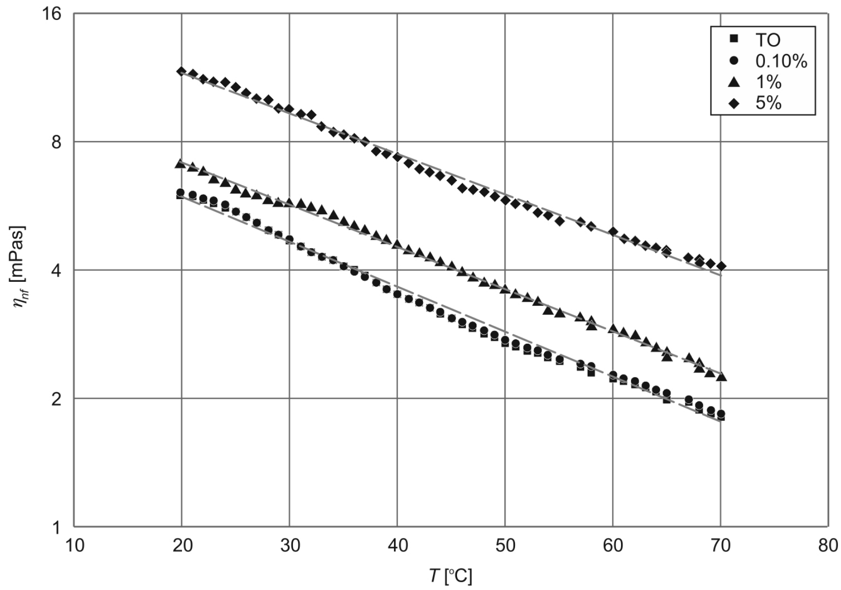


Figure 3: Viscosity of the TO-Al_2O_3 nanofluid versus temperature and nanoparticle concentration.

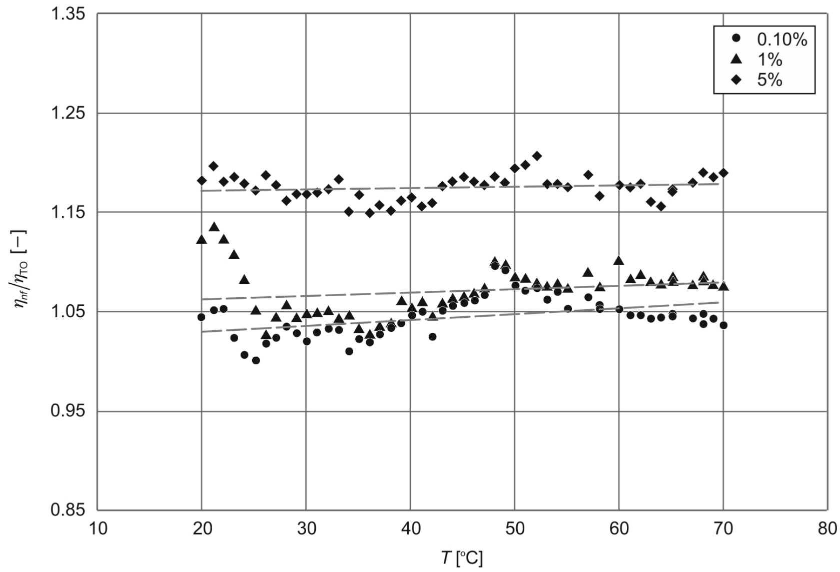


Figure 4: Relative viscosity of the TO-TiO_2 nanofluid versus temperature and nanoparticle concentration.

Figure 5 shows a comparison of the measured viscosity of TO-Al_2O_3 and TO-TiO_2 nanofluids with the values predicted from the Brinkman correlation [13]

$$\mu_{nf} = \mu_{TO} / \left(1 - \Phi_v\right)^{2.5} \tag{1}$$

and Einstein correlation [14]

$$\mu_{nf} = \left(1 + 2.5\Phi_v\right)\mu_{TO} \,. \tag{2}$$

The nanoparticle concentration by volume was recalculated by use of the formula proposed by Bang and Chang [15]

$$\Phi_v = \frac{1}{\left(\frac{1-\Phi_m}{\Phi_m}\right)\frac{\rho_p}{\rho_{TO}} + 1} \,. \tag{3}$$

Measured values of viscosities of both tested nanofluids are rather close with the predictions made by the use of Brinkman and Einstein correlations for the lowest tested nanoparticle concentration, i.e. 0.1%. The maximum discrepancy between measured and predicted values did not exceed 8%. However, for the highest nanoparticle concentration, i.e. of 5%, both correlations estimate the viscosity of TO-TiO_2 nanofluid with reasonable agreement, although underpredict the experimental data by about 15% and completely fail in the case of TO-Al_2O_3 nanofluid – predicted values are underestimated by about 100% independent of nanofluid temperature – Fig. 5.

Exemplarily, Fig. 6 shows the thermal conductivity of TO-TiO_2 nanofluid as a function of temperature and nanoparticle concentration. The results obtained for both tested nanofluids reveal that thermal conductivity increases with temperature and nanoparticle concentration increase. However, the higher was the nanoparticle concentration the lower was the relative thermal conductivity. As an example Fig. 7 illustrates relative thermal conductivity of TO-Al_2O_3 nanofluid against temperature and nanoparticle concentration.

Figure 8 shows a comparison of the measured thermal conductivity of TO-Al_2O_3 and TO-TiO_2 nanofluids with the values predicted from Hamilton-Crosser correlation [16]

$$\lambda_{nf} = \lambda_{TO}\frac{\lambda_p + 2\lambda_{TO} - 2\Phi_v\left(\lambda_{TO} - \lambda_p\right)}{\lambda_p + 2\lambda_{TO} + \Phi_v\left(\lambda_{TO} - \lambda_p\right)} \,. \tag{4}$$

Independent of the nanoparticle concentration and temperature Hamilton-Crosser correlation underpredicts the thermal conductivity of both tested

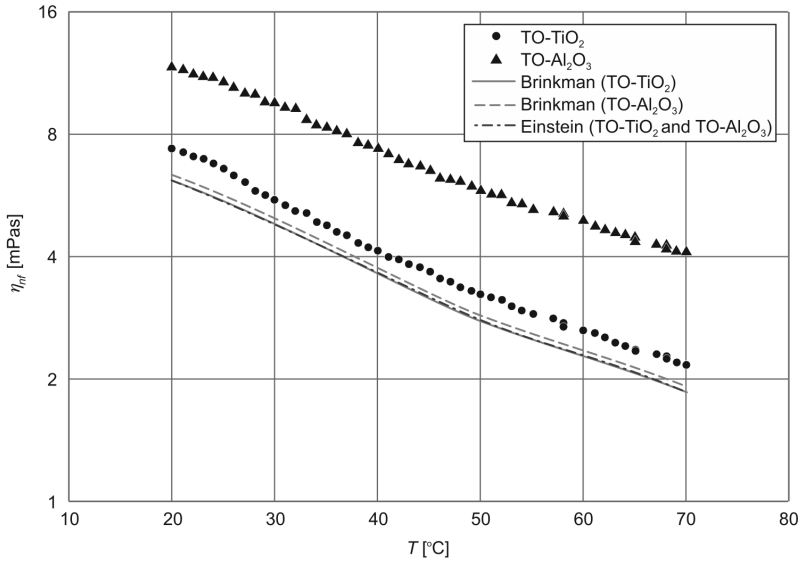


Figure 5: Comparison of measured viscosities with predictions made by the use of Brinkman's correlation, Eq. (1), and Einstein's correlation, Eq. (2), for nanoparticle mass concentration of 5%.

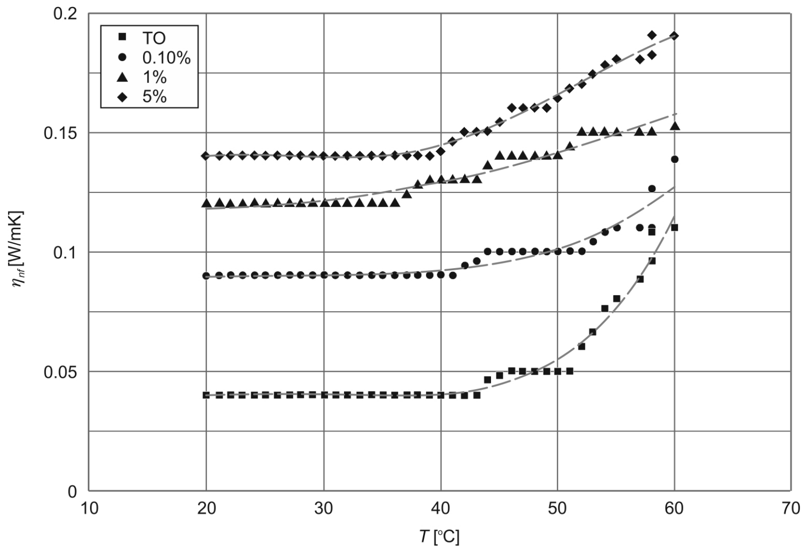


Figure 6: Thermal conductivity of TO-TiO_2 nanofluid versus temperature and nanoparticle concentration.

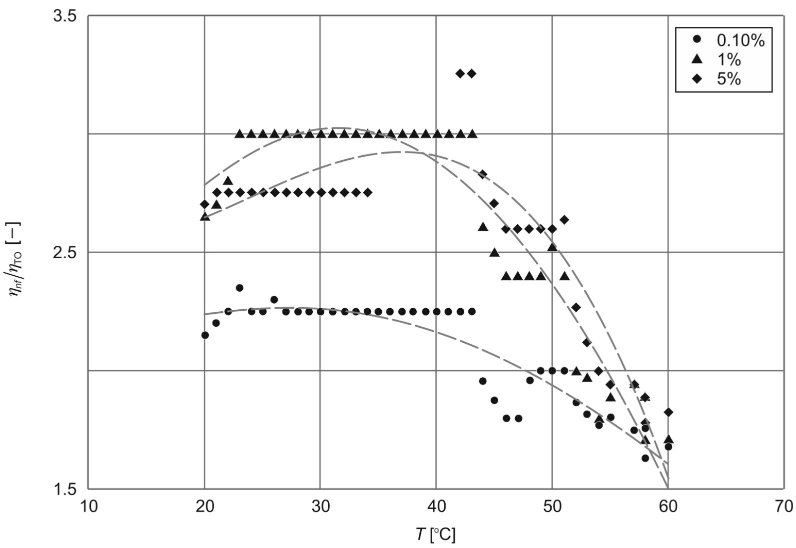


Figure 7: Relative thermal conductivity of TO-Al_2O_3 nanofluid versus temperature and nanoparticle concentration.

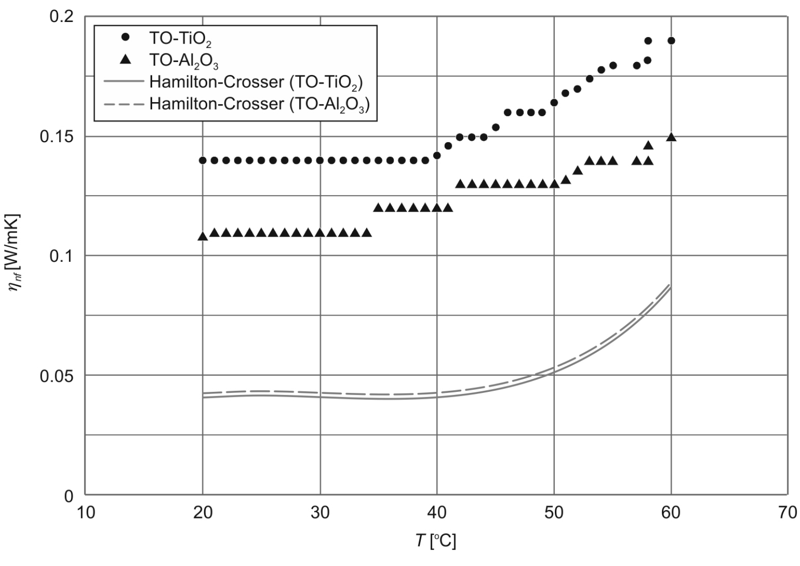


Figure 8: Comparison of the measured thermal conductivity with predictions made by use of Hamilton-Crosser's correlation, Eq. (3), for nanoparticle concentration of 5%.

nanofluids by about 100%. As an example Fig. 8 illustrates the comparison of predicted against experimental data for TO-Al_2O_3 and TO-TiO_2 nanofluids with nanoparticle concentration of 5%.

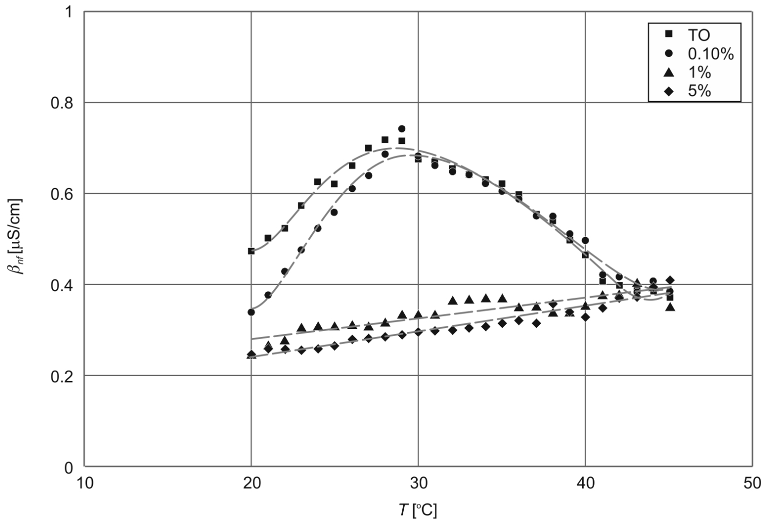


Figure 9: Electrical conductivity of TO-Al_2O_3 nanofluids against nanoparticle concentration.

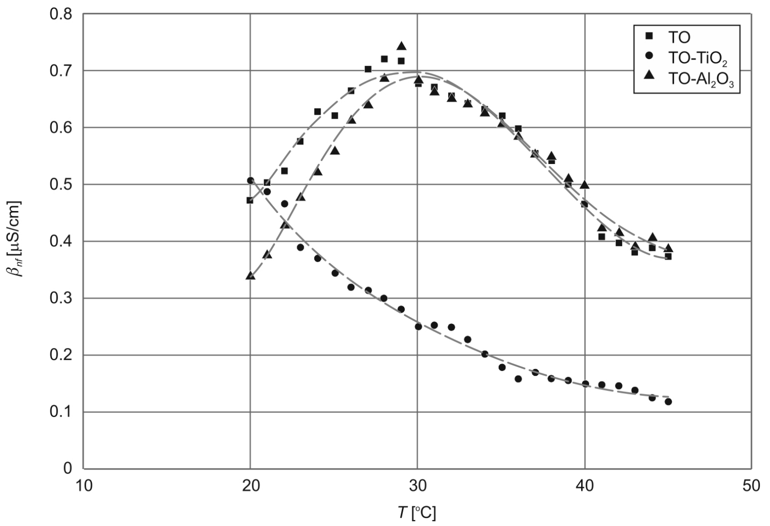


Figure 10: Electrical conductivity of TO-Al_2O_3 and TO-TiO_2 nanofluids for nanoparticle concentration of 0.1%.

Figure 9 shows electrical conductivity of TO-Al_2O_3 nanofluid as a function of temperature and nanoparticle concentration. Contrary to the results for pure thermal oil and TO-Al_2O_3 nanofluid with nanoparticle concentration of 0.1%, the electrical conductivity of TO-TiO_2 nanofluid decreases monotonically with temperature increase – Fig. 10.

Independent of nanoparticle material and concentration, pH of the tested nanofluids increased with temperature increase. As an example Fig. 11 illustrates the pH of the tested nanofluids with nanoparticle concentration of 0.1%.

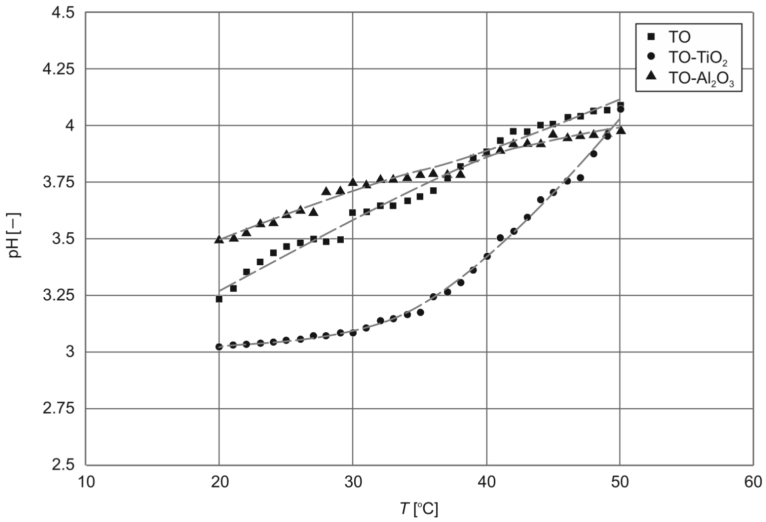


Figure 11: PH of TO-Al_2O_3 and TO-TiO_2 nanofluids with nanoparticle concentration of 0.1%.

4 Conclusions

The study revealed that:

- for both tested nanofluids viscosity decreases with temperature increase and increases with nanoparticle concentration increase, particularly for TO-Al_2O_3 nanofluid;
- increase of viscosity of both tested nanofluids is almost independent of temperature for lower tested nanoparticle concentrations, i.e., 0.1% and 1%;

- Brinkman's correlation predicts the viscosity of TO-TiO_2 nanofluid with reasonable agreement and completely fails in the case of TO-Al_2O_3 nanofluid;
- for both tested nanofluids thermal conductivity increases with temperature and nanoparticle concentration increase,
- Hamilton-Crosser correlation underpredicts the thermal conductivity of both tested nanofluids by about 100%.

Received 23 June 2015

References

[1] Choi S.: *Enhancing thermal conductivity of fluids with nanoparticles, Developments and Applications of Non-Newtonian Flows.* ASME, FED-Vol. 231/MD-Vol. 66, 1995, 99–105.

[2] Wong K.V., De Leon O.: *Applications of Nanofluids: Current and Future.* Advances Mech. Eng. 2010, ID 519659, DOI:10.1155/2010/519659.

[3] Saidur R., Leong K.Y., H.A. Mohammad H.A.: *A review on applications and challenges of nanofluids.* Renew. Sust. Energ. Rev. **15**(2011), 1646–1668.

[4] Cieśliński J.T.: *Application of nanofluids in selected thermal technologies.* In: Proc. 22nd Int. Symp. Research-Education-Technology, Bremen, Sept. 24, 2015.

[5] Cieśliński J.T., Kaczmarczyk T.: *Pool boiling of nanofluids on rough and porous coated tubes: experiment and correlation.* Arch. Thermodyn. **35**(2014), 2, 3–20.

[6] Mahbubul I.M., R. Saidur R., M.A. Amalina M.A.: *Latest developments on the viscosity of nanofluids.* Int. J. Heat Mass Trans. **55**(2012), 874–885.

[7] Eastman J.A., Choi S.US. *et al.*: *Anomalously increased effective thermal conductivities of ethylene glycol-based nanofluids containing copper nanoparticles.* Appl. Phys. Lett. **78**(2001), 718–720.

[8] Kleinstreuer C., Feng Yu.: *Experimental and theoretical studies of nanofluid thermal conductivity enhancement: a review.* Nanoscale Res. Lett. **6**(2011), 229.

[9] Chandrasekar M., Suresh S.: *A Review on the Mechanisms of Heat Transport in Nanofluids.* Heat Transfer Eng. http://dx.doi.org/10.1080/01457630902972744.

[10] Buongiorno J. *et al.*: *A benchmark study on the thermal conductivity of nanofluids.* J. Appl. Phys. **106**(2009), 094312-1-094312-14.

[11] Ganguly S., Sikdar S., Basu S.: *Experimental investigation of the effective electrical conductivity of aluminium oxide nanofluids.* Powder Technol. **196**(2009), 326–330.

[12] Bandean D.C., Smoleń S., Cieśliński J.T.: *Working fluid selection for organic Rankine cycle applied to heat recovery systems.* World Renewable Energy Cong. 2011, Linköping, May 8-11, 2011, Linköping University, 2011.

[13] Brinkman H.C.: *The viscosity of concentrated suspensions and solution*. J. Chem. Phys. **20**(1952), 571–581.

[14] Einstein A.: *Eine neue Bestimmung der Moleküldimensionen*. Annalen der Physik **19**(1906), 289–306.

[15] Bang I.C., Chang S.H.: *Boiling heat transfer performance and phenomena of Al_2O_3– water nano-fluids from a plain surface in a pool*. Int. J. Heat Mass Trans. **48**(2005), 2407–2419.

[16] Hamilton R.L., Crosser O.K.: *Thermal conductivity of heterogeneous two-component systems*. Ind. Eng. Chem. Fund. **1** (1962), 187–191.