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ORIGINAL ARTICLE

Tungsten (III) oxide (WO_3) – Silver/transformer oil hybrid nanofluid: Preparation, stability, thermal conductivity and dielectric strength

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Abstract This investigation has been carried out to study on preparation, thermal conductivity and dielectric strength of Ag- WO_3 hybrid nanofluid while the base fluid was transformer oil. The reasons of selecting silver and WO_3 as nanoparticles have been completely discussed. Applied nanofluids have been prepared by a one-step method known as Electrical Explosion of Wire (E.E.W). Measuring zeta potential of utilized hybrid nanofluids in three different weight fractions of 1%, 2% and 4% has been experimentally carried out. Thermal conductivity of applied nanofluids in temperature range of 40–100 °C has been measured by a KD2 pro thermal properties analyzer. The results showed that thermal conductivity of applied hybrid nanofluids increased by 41% in higher weight fraction and 100 °C. Finally, it has been observed that electrical conductivity of hybrid nanofluids decreased to 35 kV in 4% wt.

1. Introduction

Suspending nano sized particles to conventional base fluids such as water, ethylene glycol and oil which is known as nanofluid, has been studied over to the two past decades. Since the inventing nanofluid by Choi [1] in Argonne National Laboratory (ANL) and its development by the other pioneers [2–6], so many studies have been carried out to evaluate the thermo-physical properties and thermal characteristics of arious nanofluids. For example, Syam Sundar et al. [7] studied the mixture of ethylene glycol and water based Al_2O_3 and CuO nanofluids. They reported that, the thermal conductivity of Al_2O_3 and CuO nanofluids increased by rising the working temperature and nanoparticle concentration. They also reported that CuO nanoparticles have a better performance in enhancing thermal conductivity rather than Al_2O_3 in the same volume fraction and temperature. Aberoumand et al. [8] studied Ag/oil nanofluids experimentally. They observed enhancements up to 35% for thermal conductivity. They also released the results of their experiments on viscosity and reported that increasing in the nanoparticles concentration can enhance the viscosity of nanofluid. Fakoor Pakdaman et al. [9] carried out an experimental work on thermo-physical characteristics of MWCNT based heat transfer oil nanofluids in weight fractions of 0.1%, 0.2% and 0.4% and they reported that the higher

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enhancement of thermal conductivity is 15% at 70 °C. The maximum viscosity enhancement of their utilized nanofluids has been reported to be around 27%.

Besides, studying on heat transfer characteristics of nanofluids has been attracting the researchers of this field. The nanofluid capability of enhancing the convective heat transfer coefficient and Nusselt number has made the nanofluids as an interesting and potential fluid to work on. Some of the published papers have been reviewed here:

Abbasian et al. [10] conducted an experiment on Ag/ oil nanofluid. They applied their nanofluid in an annular tube with a constant heat flux condition of 204 W to study the performance of the nanofluid in convective heat transfer improvement. The impact of Ag/oil nanofluid on the forced and free convective heat transfer in curved tubes is investigated in [11]. They reported an average of enhancement in the convective heat transfer coefficient and Nusselt number in the condition of mixed convection heat transfer. In addition, Cu/ oil nanofluid has been studied in annular tubes in order to study the forced convective heat transfer in a constant thermal flux rate boundary condition by Jafarimoghaddam et al. [12]. Based on their study, Cu/ oil nanofluid does not have a substantial advantage than Ag/ oil nanofluid in convective heat transfer and even the Nusselt number.

In the very recent decade, researchers have been attracted to the hybrid nanofluids because of the impact of each material type of nanoparticles on the thermal properties of nanofluids individually. H. Hemmat Esfe et al. [13] studied rheological properties of Ag- MgO water hybrid nanofluids to achieve a better thermal conductivity, chemical stability and physical strength than individual nanofluids. They also proposed two correlations to predict thermal conductivity and viscosity of their applied nanofluids. Esfe et al. [14] reported the results of their investigation on thermal conductivity of Cu/TiO_2–water/EG hybrid nanofluids and a model that has been generated from neural network. They reported an enhancement of about 40% in thermal conductivity of their hybrid nanofluid in the higher weight fraction. Botha et al.[15] studied physicochemical properties of Ag- Silica/ transformer oil nanofluids. An enhancement in thermal conductivity of 15% was observed in their study when 0.60 wt.% silver was supported on 0.07 wt.% silica. They also reported that the viscosity of hybrid nanofluid was lower than individual nanofluids. Afrand [16] carried out an experiment study on the thermal conductivity of MgO-MWCNT hybrid nanofluid based Ethylene Glycol and reported a maximum enhancement of 21.3%. Afrand et al. [17–23] recently published several empirical studies on the properties of hybrid nanofluids. They almost released their results with an enhancement in thermo-physical properties of their utilized nanofluids.

The main aims of this study were to measure thermal conductivity and dielectric strength of WO_3- Ag/transformer oil hybrid nanofluids. In synthesis of the applied hybrid nanofluids, Electrical Explosion of Wire (E.E.W) as a novel one-step method has been implemented and the stability of hybrid nanofluids was measured due to measuring zeta potential. E.E.W has been used for preparing Ag/ oil and Cu/ Ethylene Glycol by Aberoumand et al. [8], Jafarimoghaddam et al. [24] and Abbasian Arani et al. [10] as a potential one-step method for preparing nanofluids. Transformer oil because of its high applications in industries which need high heat transfer rate, and the lack of investigation of it in the literature, was used as base fluid of this study. WO_3, because of its capacity in dielectric strength and silver, due to the high capability in thermal conductivity have been selected to be suspended in the base fluid.

2. Nanofluid preparation

For preparing utilized hybrid nanofluid, first of all, WO_3 nanoparticles with purity of 99.9% and maximum particle diameter of 60 nm were bought from PNF nano technology Co. These nanoparticles were dispersed in transformer oil via a novel one-step method known as Electrical Explosion of Wire (E.E.W) which has been described in detail below. Then, produced WO_3/transformer oil nanofluid was used as the base fluid for suspending Ag nanoparticles with E.E.W again, to produce Ag- WO_3/ - transformer oil hybrid nanofluids.

2.1. W method

The Electrical Explosion Wire (E.E.W) that has been known as a one-step method was applied to prepare utilized nanofluids. As a simple explanation on the method, considering Fig. 1, the nanofluid will be produced via an explosion in container of base fluid and thin metal wire. High current and electric voltage are the main operators of the explosion. The operating device is known as PNC1K which is shown in Fig. 1. In fact, nanoparticles and nanofluid production are made simultaneously in the PNC1K [25–27]. The main operating conditions and input and output characteristics are summarized in Table 1.

One of the best advantages of EEW is its capability of producing nanoparticle and of course nanofluid from any material that can make a thin wire from it.

2.2. Stability

Zeta potential measurement as one of the ways of evaluating the stability of nanofluids has been applied in this work. Assessing the stability by the zeta potential index is related to the electrostatic repulsion forces between the nanoparticles. When the repulsion is high, it can be concluded that the collisions between nanoparticles will be low. So, the nanofluid can be classified as a stable one. Nanofluid with a measured zeta potential greater than 30 mV is generally known as stable type [28,29]. Moreover, zeta potential lower than 20 mV indicates the poor stability of nanofluids [30]. Zeta potential of utilized nanofluids in three weight concentrations of 1%, 2% and 4% at two different temperatures of 313 K and 373 K was measured by a Zetasizer Nano ZS made by Malvern, Britain. The results show a very good stability for all of the test samples and Fig. 2 indicates the excellent stability of applied hybrid nanofluids.

3. Thermal conductivity measurement

A KD2 Pro made by Decagon Devices Inc. with the maximum deviation of 5.0% was utilized to measure thermal conductivity of applied hybrid nanofluids. Thermal conductivity in the range of 0.02–2.00 with the accuracy of ±0.001 could be measured by this device. Fig. 3 shows the used KD2 Pro in this

Figure 1 PNC1K device (left) and a schematic of EEW method (right).

Table 1 Operational characteristics of the PNC1K in this study.

MODEL	PNC1k
Output voltage	0.5–1 KV
Input power	1P 220 VAC 500 W
Max. diameter of wire	0.25 mm
Exploding wire length	1–5 mm
Input wire	Silver and tungsten oxide
Particle size	35–55 nm

Figure 3 Used KD2 Pro in this study.

experimental work. As it can be seen from Fig. 3, there is a probe with inside sensors to measure thermal conductivity and the working temperature. It is noted that KD2 can measure the thermal conductivity of oil based nanofluids accurately up to around 110 °C, while this temperature is 70 for water based nanofluids. This is because of the low thermal diffusivity of oil. Oils can hold thermal much longer than water and it can help us to measure the thermal conductivity of oil based nanofluids at 100 °C much accurate than water based nanofluids. The measurements were done four times

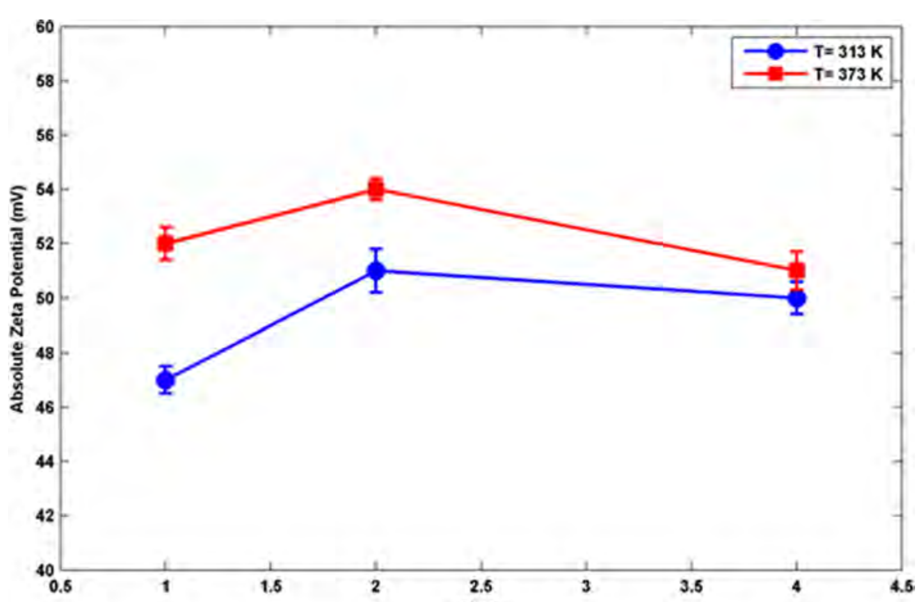


Figure 2 Absolute zeta potential of Ag- WO_3/Transformer oil nanofluids as a function of Weight concentration.

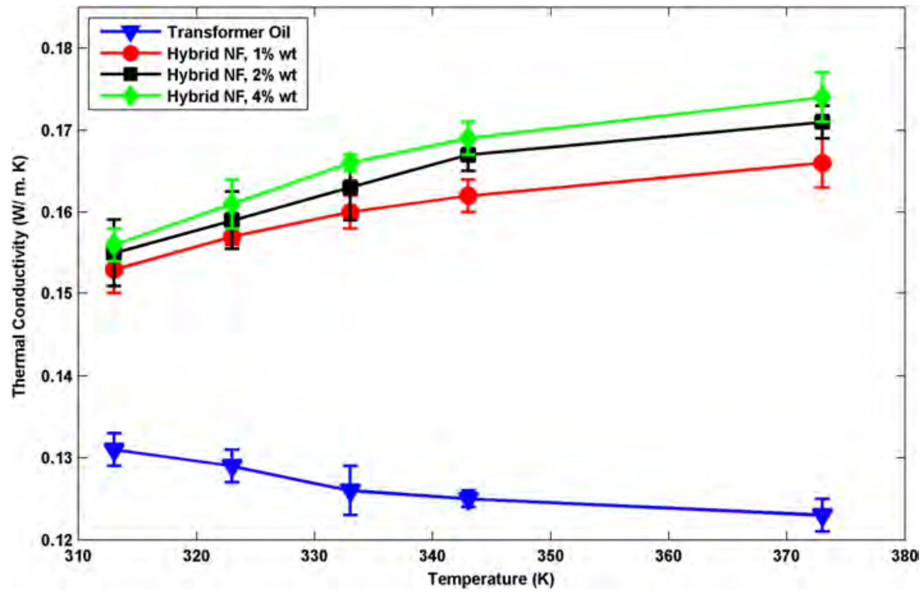
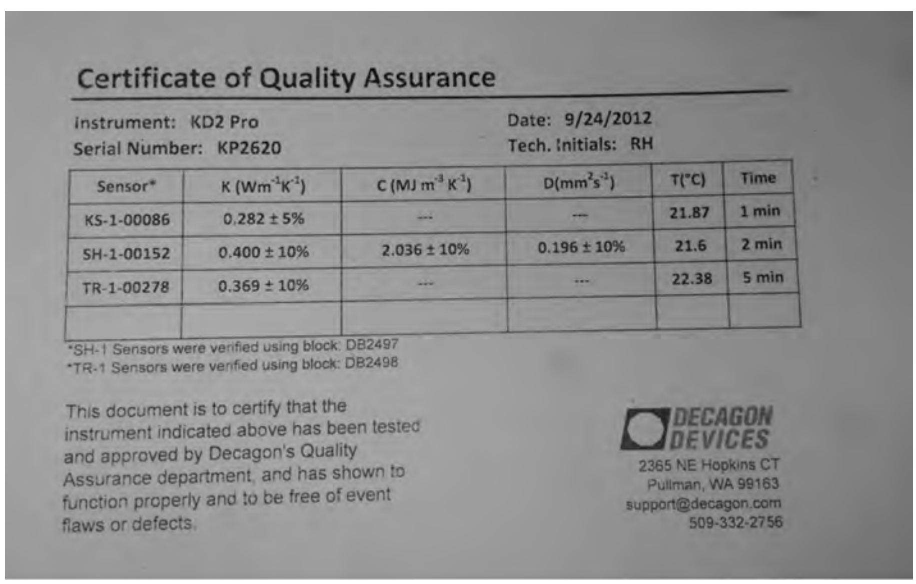


Figure 4 Thermal conductivity of hybrid nanofluids versus temperature (including error bars).



Certificate of Quality Assurance

Instrument: KD2 Pro
Serial Number: KP2620

Date: 9/24/2012
Tech. Initials: RH

Sensor*	K (Wm^{-1}K^{-1})	C (MJ m^{-3} K^{-1})	D(mm^{2}s^{-1})	T(°C)	Time
KS-1-00086	0.282 ± 5%	---	---	21.87	1 min
SH-1-00152	0.400 ± 10%	2.036 ± 10%	0.196 ± 10%	21.6	2 min
TR-1-00278	0.369 ± 10%	---	---	22.38	5 min

*SH-1 Sensors were verified using block: DB2497
*TR-1 Sensors were verified using block: DB2498

This document is to certify that the instrument indicated above has been tested and approved by Decagon's Quality Assurance department, and has shown to function properly and to be free of event flaws or defects.

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Figure 5 Certificate quality assurance of the utilized KD2 Pro.

for each temperature and weight fraction for more reliability, and the averages are presented in Fig. 4. As observed from Fig. 4, the increasing trend of thermal conductivity of the nanofluids is because of the increasing in bulk temperature which affects the growing of Brownian motion of nanoparticles. On the other hand, as it can be seen, temperature rising does not affect the thermal conductivity of pure transformer oil increasingly. In addition, the certificate of quality assurance of the used KD2 Pro in this study is shown in Fig. 5 for further considerations of the readers.

Predicting thermal conductivity of nanofluids depends on several parameters which are mainly nanoparticle concentration, bulk temperature of nanofluids and type of nanoparticles. These parameters affect Brownian movement of nanoparticles and thermal conductivity is affected by that. Due to the fact that Brownian movement is so difficult to be measured accurately, a reliable way to derive a general correlation for thermal conductivity is based on the published experimental results till now. A reliable correlation that is based on experimental results of any type of oil based nanofluids, has published recently in [8] and is introduced as Eq. (1). Although this equation does not include the published results of hybrid oil based nanofluids, the predicted values are considerable.

$$k_{nf}(T,\varphi,k_{np}) = (3.9\times10^{-5}T-0.0305)\varphi^2 + (0.086-1.6\times10^{-4}T)\times\varphi + 3.1\times10^{-4}T + 0.129 - 5.77\times10^{-6}k_{np} - 40\times10^{-4} \quad (1)$$

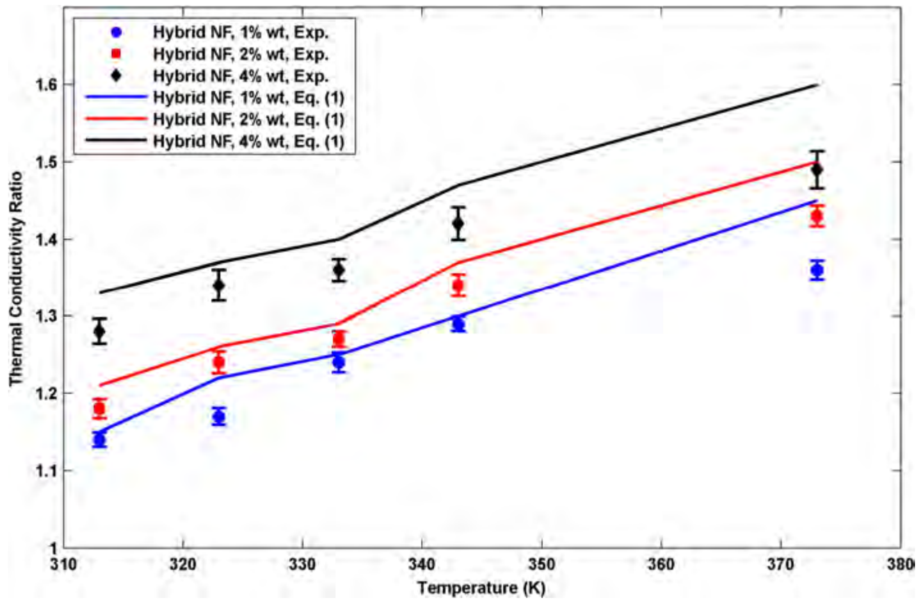

Figure 6 Thermal conductivity ratio of utilized nanofluids (measured and predicted by Eq. (1)).

Table 2 Dielectric strength of transformer oil-based nanofluid containing WO_3 and silver.

Sample	Dielectric strength (kV)
Pure transformer oil	53
Hybrid nanofluid, 1% wt	49
Hybrid nanofluid, 2% wt	43
Hybrid nanofluid, 4% wt	35

On the other hand, T is the bulk nanofluid temperature in Celsius degrees and φ is the volume fraction which ranged from 0% to 2%. Moreover, k_{np} is referred to as the thermal conductivity of the nanoparticle material.

Fig. 6 indicates a comparison between measured results of thermal conductivity ratio of applied hybrid nanofluids and predicted values by Eq. (1).

4. Dielectric strength

The dielectric strength of transformer oil based nanofluids should be studied because of the fact that transformer oil is designed to be an electrical insulator in transformer devices work under high electrical fields. Transformer oils will be failed, if the dielectric strength of oil is not able to prevent reaching the maximum electric field strength.

So, having a high dielectric strength is a main factor of good quality transformer oil. The dielectric strength of the transformer oil-based nanofluids containing WO_3 and Ag, was investigated. The results are mentioned in Table 2.

As it can be seen in Table 2, due to introducing WO_3 to the oil known as low electrical conductivity, the dielectric strength is reduced a little in comparison with the pure transformer oil. Another reason for this reduction is the electrical conductivity of silver nanoparticles. But, due to our first demand that was observing an enhancement in thermal conductivity, silver as a conductive metal cannot be ignored.

5. Conclusion

Tungsten (III) oxide (WO3)- Silver/Transformer Oil Hybrid Nanofluid in three weight fractions of 1%, 2% and 4% has been prepared via Electrical Explosion of Wire and its stability was evaluated by measuring zeta potential. In addition, thermal conductivity of hybrid nanofluids has been experimentally studied. An enhancement of 41% was observed in 4% wt and the thermal conductivity increased in an increasing way in contrast to pure transformer oil which behaves in a decreasing way. Finally, dielectric strength of hybrid nanofluids has been measured and in comparison with pure oil, a reduction has been observed which was probably due to the electrical conductivity of silver nanoparticles, because, WO_3 nanoparticles have a low electrical conductivity in all known nanoparticles till now.

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