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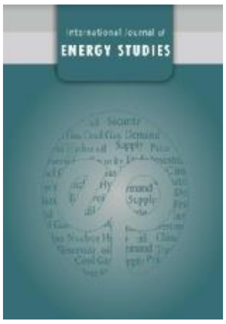

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Investigation of the thermophysical properties of AlN+ZnO/deionized water hybrid nanofluid

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Highlights

- Thermophysical properties of a hybrid nanofluid were specified theoretically.
- Calculations were performed both for unitary and hybrid nanofluid suspensions.
- Obtained results illustrated that hybrid nanofluids can be used as working fluid in thermal engineering applications.

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ABSTRACT

Nanofluids are the novel type heat transfer fluids since they provide undeniable increments in heat transfer characteristics. Thermophysical properties of nanofluids have a great importance on determination of heat transfer capabilities of them. Even though these suspensions initially have been prepared by using one type nanoparticle, a new nanofluid preparation process has arisen nowadays in which at least two different nanoparticles are used. By this study, such thermophysical properties of AlN+ZnO/deionized water hybrid nanofluid as density, heat capacity, thermal conductivity, and viscosity have been determined by using the theoretical correlations available and validated in literature. Besides, another important property, wetting capability has also been studied. The calculations have been performed not merely for hybrid nanofluid, both also for its one-component (AlN/deionized water and ZnO/deionized water) containing types. The mixing rate of the nanoparticles is (50:50) and final volume fraction of the hybrid nanofluid is 2.0%. The findings show that hybrid nanofluids are more stable than their unitary ones and can be enhanced the performance when they are used as working fluid in thermal systems.

Keywords: *Hybrid nanofluid, Thermophysical properties, AlN, ZnO.*

1. INTRODUCTION

Utilization of energy resources in an efficient way and energy efficiency studies have become popular these days since energy is one of the crucial parameters in terms of governments' future. As far as energy conversion systems are considered, the amount of recovery rate of the utilized energy is much higher in thermal systems, which has made many researchers study towards that field. One of the methods applied in thermal systems is to enhance the thermophysical properties of the working fluid. If a thermophysical property can be improved, it provides better heat transfer characteristics. For this aim, nanofluid suspensions have been started to use as working fluid in thermal systems where the heat transfer process realizes via a fluid. Many investigators in that field have illustrated that nanofluids can be used to obtain improved heat transfer performance. Some examples are as follows: Gürü et al. experimentally investigated the thermal performance of a heat pipe charged with bauxite nanofluid under various operating conditions and reported some increments in both efficiency and the thermal resistance of the heat pipe as 37% and 39%, respectively [1]. In a concentric tube heat exchanger, Khanlari et al. studied the effects of kaolin nanoparticles containing nanofluid utilization on thermal performance. They reported a maximum increment of 37% in the overall heat transfer coefficient [2]. A similar study was performed by Sözen et al. They prepared a fly ash nanofluid and tested it in a concentric tube heat exchanger under two different flow regime conditions. They reported some increments in both parallel and counter flow regimes [3]. Kumar et al. investigated the ZnO nanofluid usage in a plate heat exchanger and found out that nanofluid utilization improved the heat transfer characteristics substantially [4]. Similarly, the performance of the many thermal systems including solar collectors [5, 6], heat recovery units [7, 8], and combi boilers [9, 10] were enhanced via nanofluid usage as heat-carrying fluid.

A unitary nanofluid suspension includes a solid material in nanoparticle form, a base fluid (water, ethylene glycol, etc.), and a surfactant (if desired). If nanofluid will be prepared is dilute, no surfactant is used. However, high nanoparticle concentration requires to be used a surfactant because of the fact that the surfactant provides stability and homogeneity to the mixture by extending the suspension time of the nanoparticles doped into the base fluid. On the other hand, a hybrid nanofluid contains at least two different types of nanoparticles. The main goal of the hybrid utilization of the nanoparticles during the nanofluid preparation process is to benefit from each material's unique properties. To put it bluntly, in nanofluid preparation, metal nanoparticles upgrade the thermal conductivity of the base fluid thanks to their high thermal conductivity properties; yet, it deteriorates the stability of the mixture. Similarly, metal oxides like MgO, ZnO, etc. provide more stability than other kinds of materials; but, they are bad at improving the many thermophysical properties of the base fluid, specifically thermal conductivity. In this case, the hybrid utilization of metal and metal oxide compounds provides the desired characteristics to prepared nanofluid suspension [11].

In this study, thermophysical properties of the AlN+ZnO/deionized water hybrid nanofluid including density, heat capacity, thermal conductivity, viscosity, and wetting capability were investigated. The nanofluid suspension at the nanoparticle mixing rate of (50:50) and final volumetric concentration of 2% was considered during the calculations. Besides, Triton X-100 at the rate of %0.3 was added into the mixture as the surfactant. To measure the wetting capability, contact angle measurements on a flat copper plate were performed both for unitary (AlN/deionized water and ZnO/deionized water) nanofluids and hybrid nanofluid. It is expected that the outcomes of this study present an idea of whether such a hybrid couple in the nanofluid preparation process can be used in a thermal system for performance enhancement or not.

2. MATERIAL & METHOD

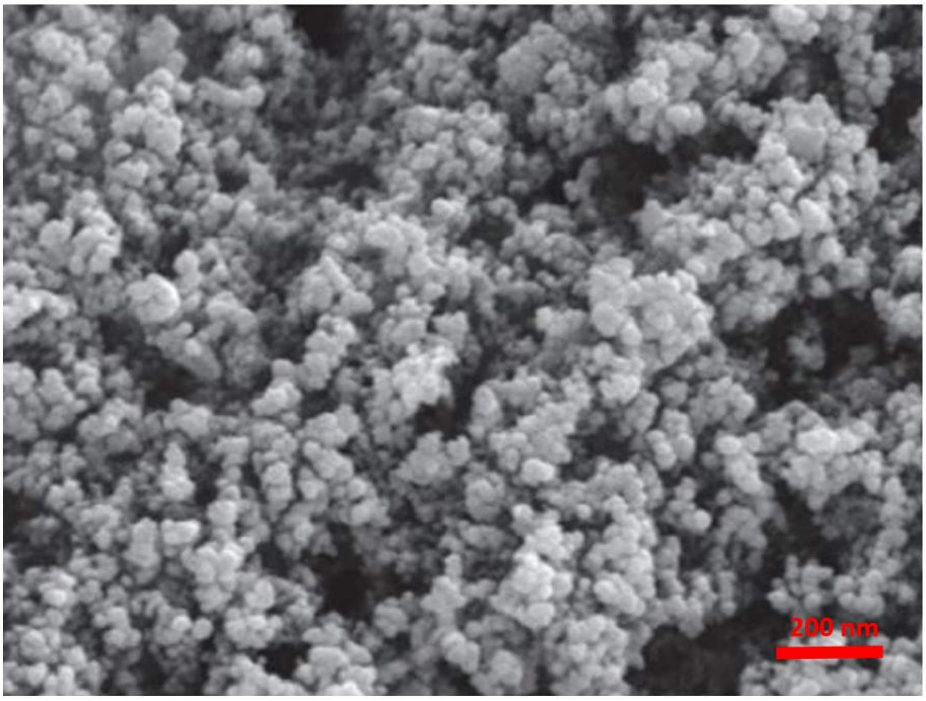
2.1. Preparation Process of Unitary and Hybrid Nanofluids

The utilized AlN and ZnO nanoparticles were purchased from the *Nanografi Nanotechnology Company*. Some properties of these nanoparticles were provided in Table 1. The average particle size is reported by the firm as 50-70 nm for AlN and 18 nm for ZnO nanoparticles, which is also clear in SEM images provided in Figure 1.

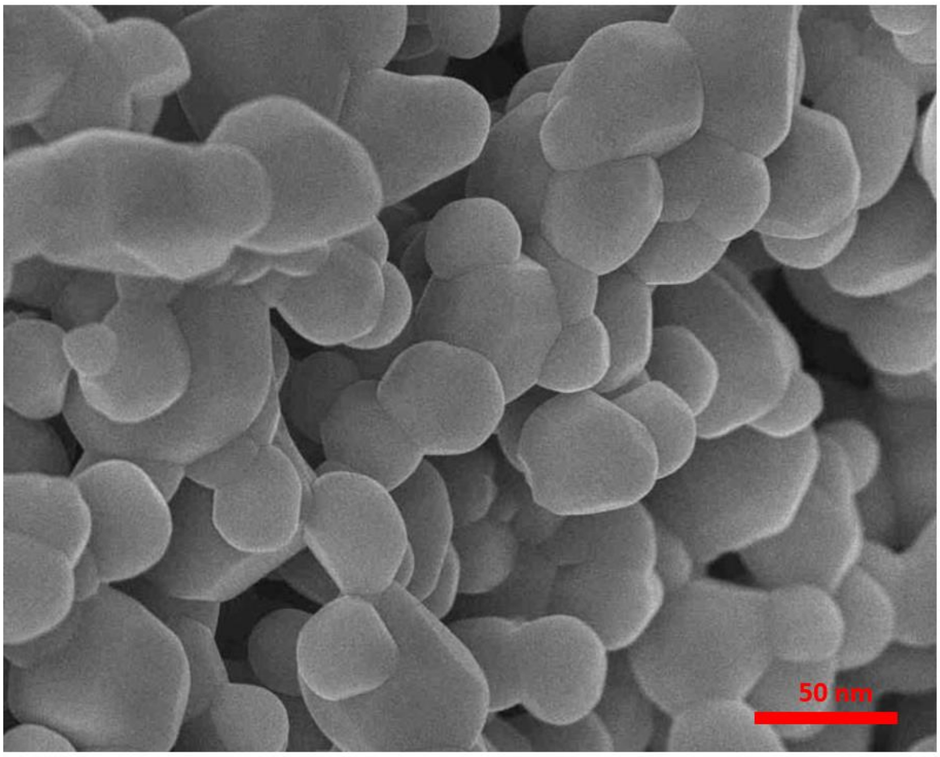
Table 1. Some specifications of AlN and ZnO nanoparticles

Specifications	AlN nanoparticles	ZnO nanoparticles
Average particle size (nm)	50-70	18
Density (g/cm^3)	3.25	5.61
Thermal conductivity (W/mK)	320	50
Heat capacity (J/kgK)	800	495.21
Specific surface area (m^2/g)	17.4	70

AlN is a non-oxidized ceramic-based material with high thermal conductivity and low electrical conductivity, and hence widely used in the microelectronic industry. On the other hand, even though its low thermal conductivity, ZnO provides stability when it utilizes in nanofluid preparation. Therefore, hybrid utilization of AlN and ZnO nanoparticles is likely to provide both high thermal conductivity and good stability properties to the base fluid.



(a)



(b)

Figure 1. SEM images of (a) AlN and (b) ZnO nanoparticles

The nanofluid preparation process included the preparation of each unitary suspension, namely AlN/deionized water and ZnO/deionized water, and hybrid suspension which is AlN+ZnO/deionized water. Each suspension was prepared at the volumetric concentration of 2% using deionized water as the base fluid. The nanoparticle mixing rate of hybrid suspension is (50:50). Triton X-100 was doped into each suspension to overcome the agglomeration problem. The prepared suspensions were also objected to the ultrasonication process in an ultrasonic bath (*ISOLAB Laborgeräte GmbH*) under constant bath fluid temperature in order to obtain more stable and homogenous suspensions (Figure 2). The used surfactant, Triton X-100, in preparation of nanofluid is a kind of nonionic surfactant. The ions within a nonionic surfactant are not dispersed inside the liquid. The dissolvability of the surface-active agent increases with parallel to any increment in temperature for anionic, cationic, and amphoteric type surfactants; but, dissolvability of surfactant keeps constant for a nonionic surfactant even if temperature changes. Therefore, as surfactant, Triton X-100 was chosen.

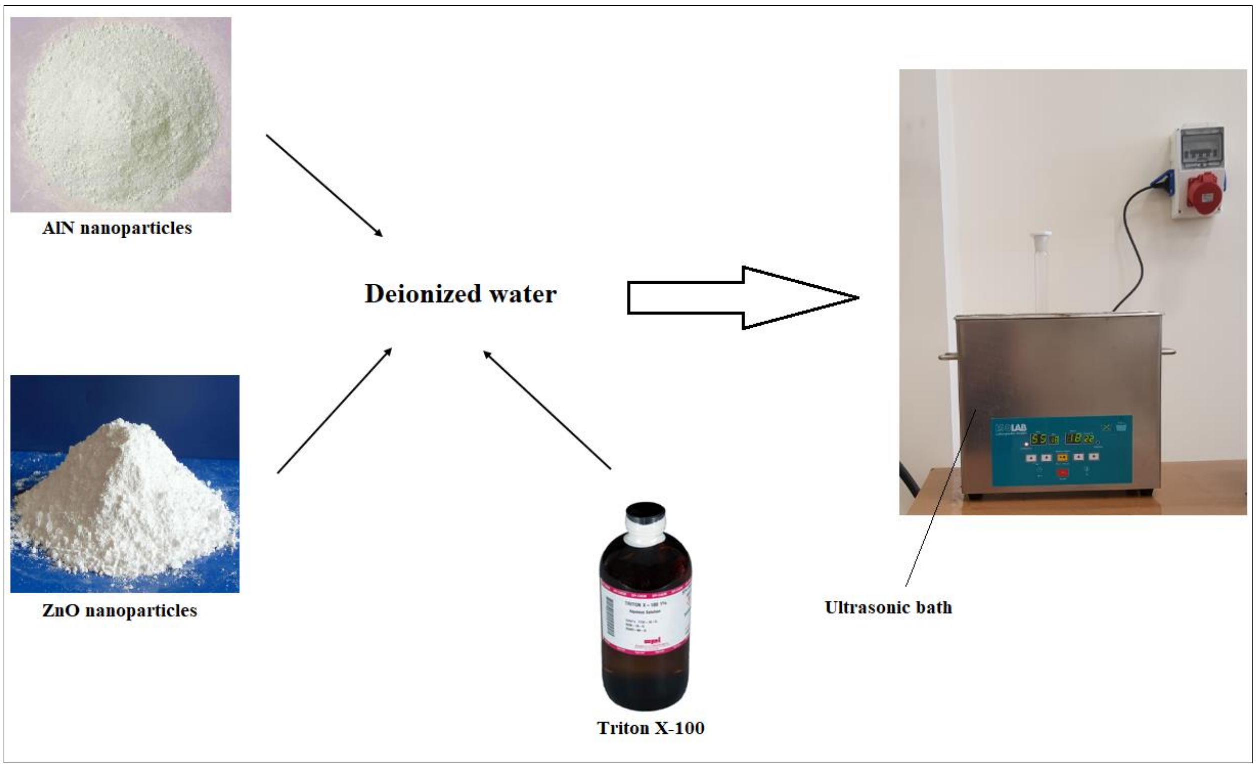


Figure 2. The hybrid nanofluid preparation & ultrasonication processes

3. THEORETICAL BACKGROUND

The fundamental thermophysical properties of density, heat capacity, thermal conductivity, viscosity, and wetting capability are crucial parameters in terms of heat transfer capability of prepared nanofluid suspensions. The density of the prepared nanofluid suspensions was calculated by using the following equation [12]:

$$\rho_{nf} = (1-\emptyset)\rho_{bf} + \emptyset\rho_{np} \tag{1}$$

where nf, bf, and np subscripts denote the nanofluid, base fluid, and nanoparticle, respectively. $\rho$is the density, and $\emptyset$ is the volumetric concentration of the nanofluid. For AlN/deionized water and ZnO/deionized water nanofluid suspensions, Eq. (1) can be written as follows:

$$\rho_{AlN\ nf} = (1-\emptyset)\rho_{dw} + \emptyset\rho_{AlN} \tag{2}$$

$$\rho_{ZnO\ nf} = (1-\emptyset)\rho_{dw} + \emptyset\rho_{ZnO} \tag{3}$$

where dw represents the deionized water.

For hybrid nanofluid suspension, the following modified formula was utilized [13]:

$$\rho_{hnf} = \left(1-\emptyset_{np1}-\emptyset_{np2}\right)\rho_{bf} + \emptyset_1\rho_{np1} + \emptyset_2\rho_{np2} \tag{4}$$

where subscript hnf displays hybrid nanofluid. If the formula is rewritten for the hybrid nanofluid used:

$$\rho_{AlN+ZnO\ nf} = (1-\emptyset_{AlN}-\emptyset_{ZnO})\rho_{dw} + \emptyset_{AlN}\rho_{AlN} + \emptyset_{ZnO}\rho_{ZnO} \tag{5}$$

Heat capacity (c_p) of the unitary nanofluid suspension was calculated through the following formula [14]:

$$c_{p,nf} = (1-\emptyset)c_{p,bf} + \emptyset c_{p,np} \tag{6}$$

Should the Eq. (6) is rewritten for the utilized nanofluid suspensions

$$c_{p,AlN\ nf} = (1-\emptyset)c_{p,dw} + \emptyset c_{p,AlN} \tag{7}$$

$$c_{p,ZnO\ nf} = (1-\emptyset)c_{p,dw} + \emptyset c_{p,ZnO} \tag{8}$$

The heat capacity of the hybrid nanofluid is calculated by the formula given below [13]:

$$\rho_{hnf}c_{p,hnf} = \left(\emptyset_{np1}\rho_{np1}c_{p,np1}\right) + \left(\emptyset_{np2}\rho_{np2}c_{p,np2}\right) + \left[(1-\emptyset_{np1}-\emptyset_{np2})\rho_{bf}c_{p,bf}\right] \tag{9}$$

Reformulating the Eq. (9)

$$\rho_{AlN+ZnO\ nf}c_{p,AlN+ZnO\ nf} = \left(\emptyset_{AlN}\rho_{AlN}c_{p,AlN}\right) + \left(\emptyset_{ZnO}\rho_{ZnO}c_{p,ZnO}\right) + \left[(1-\emptyset_{AlN}-\emptyset_{ZnO})\rho_{dw}c_{p,dw}\right] \tag{10}$$

The Maxwell model was preferred in the calculation of thermal conductivity of the nanofluid suspensions since it is frequently-used and validated by many investigators [15]:

$$\frac{k_{nf}}{k_{bf}} = \frac{k_{np} + 2k_{bf} + 2\emptyset(k_{np}-k_{bf})}{k_{np} + 2k_{bf} - \emptyset(k_{np}-k_{bf})} \tag{11}$$

where k denotes the thermal conductivity. Reformulating the Eq. (11) for each unitary nanofluids,

$$\frac{k_{AlN\ nf}}{k_{dw}} = \frac{k_{AlN} + 2k_{dw} + 2\emptyset(k_{AlN}-k_{dw})}{k_{AlN} + 2k_{dw} - \emptyset(k_{AlN}-k_{dw})} \tag{12}$$

$$\frac{k_{ZnO\ nf}}{k_{dw}} = \frac{k_{ZnO} + 2k_{dw} + 2\emptyset(k_{ZnO}-k_{dw})}{k_{ZnO} + 2k_{dw} - \emptyset(k_{ZnO}-k_{dw})} \tag{13}$$

The Maxwell model was modified for the determination of thermal conductivity of hybrid nanofluid suspensions as follows [13]:

$$k_{hnf}=k_{bf}\left[\frac{\frac{\emptyset_{np1}k_{np1}+\emptyset_{np2}k_{np2}}{\emptyset}+2k_{bf}+2\left(\emptyset_{np1}k_{np1}+\emptyset_{np2}k_{np2}\right)-2\emptyset k_{bf}}{\frac{\emptyset_{np1}k_{np1}+\emptyset_{np2}k_{np2}}{\emptyset}+2k_{bf}-\left(\emptyset_{np1}k_{np1}+\emptyset_{np2}k_{np2}\right)+\emptyset k_{bf}}\right] \quad (14)$$

Rewriting this formula for the Aln+ZnO/deionized water hybrid nanofluid:

$$k_{AlN+ZnO\ hnf}=k_{dw}\left[\frac{\frac{\emptyset_{AlN}k_{AlN}+\emptyset_{ZnO}k_{ZnO}}{\emptyset}+2k_{dw}+2(\emptyset_{AlN}k_{AlN}+\emptyset_{ZnO}k_{ZnO})-2\emptyset k_{dw}}{\frac{\emptyset_{AlN}k_{AlN}+\emptyset_{ZnO}k_{ZnO}}{\emptyset}+2k_{dw}-(\emptyset_{AlN}k_{AlN}+\emptyset_{ZnO}k_{ZnO})+\emptyset k_{dw}}\right] \quad (15)$$

For the theoretical calculation of the viscosity, Eq. (16) was utilized [13]:

$$\mu_{nf}=\mu_{bf}(1+2.5\emptyset) \quad (16)$$

Considering the Eq. (16), it is understood that the viscosity of the prepared nanofluid is independent of nanoparticle shape, type, and other properties. Actually, the addition of nanoparticles inside the base fluid affects the viscosity of nanofluid suspension; however, this effect is rather low, and thereby, it can be neglected as in this formula. In addition, a derived model is available for hybrid nanofluids' viscosity calculations, which is provided in Eq. (17) [13].

$$\frac{\mu_{hnf}}{\mu_{bf}}=1+13.5\emptyset+904.4\emptyset^2 \quad (17)$$

Reformulating the Eq. (17) for the hybrid nanofluid used

$$\frac{\mu_{AlN+ZnO\ hnf}}{\mu_{dw}}=1+13.5\emptyset+904.4\emptyset^2 \quad (18)$$

Wetting capability is an indicator of the degree of surface tension of the fluid. The capillary rise method, drop weight method, Du Nouy ring method and Wilhelmy plate method are some examples of surface tension measurement methods. Because of both simplicity and accuracy, capillary rise and drop weight methods are frequently preferred. Contact angle measurements also give an idea regarding the alteration of surface tension. It is anticipated that nanofluids have lower surface tension compared to their base fluids to be able to perform improved characteristics in use. A set of measurements was conducted to illustrate the changes in contact angles, and obtained results were discussed in the following section.

4. RESULTS & DISCUSSION

Taking into consideration the formulas presented in the preceding section, density, heat capacity, thermal conductivity, and viscosity of the AlN/deionized water, ZnO/deionized water, and AlN+ZnO/deionized water hybrid nanofluid were specified. Calculated density values of

AlN/deionized water, ZnO/deionized water, and AlN+ZnO/deionized water hybrid nanofluid suspensions were found as follows:

$$\rho_{AlN\ nf} = (1-0.02)\times 997 + 0.02\times 3260 = 1042.26\ kg/m^3 \quad (19)$$

$$\rho_{ZnO\ nf} = (1-0.02)\times 997 + 0.02\times 5610 = 1089.26\ kg/m^3 \quad (20)$$

$$\rho_{AlN+ZnO\ hnf} = (1-0.01-0.01)\times 997 + 0.01\times 3260 + 0.01\times 5610 = 1065.76\ kg/m^3 \quad (21)$$

The calculated values showed that there was a slight change, which can be neglected, in the density of the nanofluid suspension irrespective of unitary or hybrid utilization of nanoparticles.

Based on Eqs. (7) - (10), heat capacity values of AlN/deionized water, ZnO/deionized water, and AlN+ZnO/deionized water hybrid nanofluid suspensions are calculated as follows:

$$c_{p,AlN\ nf} = (1-0.02)\times 4180 + 0.02\times 800 = 4.112\ \frac{kJ}{kgK} \quad (22)$$

$$c_{p,ZnO\ nf} = (1-0.02)\times 4180 + 0.02\times 495.207 = 4.106\ \frac{kJ}{kgK} \quad (23)$$

$$1065.76\times c_{p,AlN+ZnO\ nf} = (0.01\times 3260\times 0.8) + (0.01\times 5610\times 0.495) + [(1-0.01-0.01)\times 997\times 4.18] \quad (24)$$

$$c_{p,AlN+ZnO\ hnf} = 3.883\ \frac{kJ}{kgK} \quad (25)$$

The obtained results displayed that nanoparticle addition into the base fluid declined the heat capacity of the fluid, which was improved the heat transfer rate remarkably. Should the nanoparticles were used as a hybrid, the decrement rate in heat capacity was observed as about 7%.

As presented below, the thermal conductivity values of the unitary nanofluids were calculated based on the Eqs. (12) and (13).

$$\frac{k_{AlN\ nf}}{0.613} = \frac{320 + 2\times 0.613 + 2\times 0.02\times(320-0.613)}{320 + 2\times 0.613 - 0.02\times(320-0.613)} \quad (26)$$

$$k_{AlN\ nf} = 0.6503\ \frac{W}{mK} \quad (27)$$

$$\frac{k_{ZnO\ nf}}{0.613} = \frac{60 + 2\times 0.613 + 2\times 0.02\times(60-0.613)}{60 + 2\times 0.613 - 0.02\times(60-0.613)} \quad (28)$$

$$k_{ZnO\ nf} = 0.6494\ \frac{W}{mK} \quad (29)$$

Similarly, for hybrid nanofluid suspension

$$= 0.613\left[\frac{\frac{0.01\times 320 + 0.01\times 60}{0.02} + 2\times 0.613 + 2(0.01\times 320 + 0.01\times 60) - 2\times 0.02\times 0.613}{\frac{0.01\times 320 + 0.01\times 60}{0.02} + 2\times 0.613 - (0.01\times 320 + 0.01\times 60) + 0.02\times 0.613}\right] \quad (30)$$

$$k_{AlN+ZnO\ hnf} = 285.773\ \frac{W}{mK} \tag{31}$$

The thermal conductivity values of the nanofluid suspensions were slightly changed when unitary nanofluids were considered. Nevertheless, changes in thermal conductivity were so much in hybrid nanofluid solution, compared to unitary counterparts. It is thought that this huge increment in thermal conductivity of the hybrid nanofluid results from the high stability and high thermal conductivity of ZnO and AlN nanoparticles, respectively. This result also illustrates that AlN+ZnO/deionized water hybrid nanofluid can be used as a working fluid in a thermal system for achieving high efficiency.

Based on the theoretical calculations, there is no change in the viscosity of the unitary nanofluids because there is no term regarding the nanoparticle's properties except volumetric concentration. Therefore, it is assumed that AlN/deionized water and ZnO/deionized water nanofluids have the same viscosity.

$$\mu_{AlN\ nf} = \mu_{ZnO\ nf} = 8.90 \times 10^{-4} \times (1 + 2.5 \times 0.02) = 0.9345\ mPa.s \tag{32}$$

For hybrid nanofluid suspension prepared, the viscosity value was calculated as below.

$$\frac{\mu_{AlN+ZnO\ hnf}}{8.90 \times 10^{-4}} = 1 + 13.5 \times 0.02 + 904.4 \times 0.02^2$$

$$\mu_{AlN+ZnO\ hnf} = 1.4523 \times 10^{-3} Pa.s = 1.4523\ mPa.s$$

As can be seen, the viscosity of the hybrid nanofluid was higher than that of unitary nanofluids. The increase in viscosity is generally undesired since it facilitates the accumulation of nanoparticles, but this problem can be eliminated somehow using an appropriate surfactant.

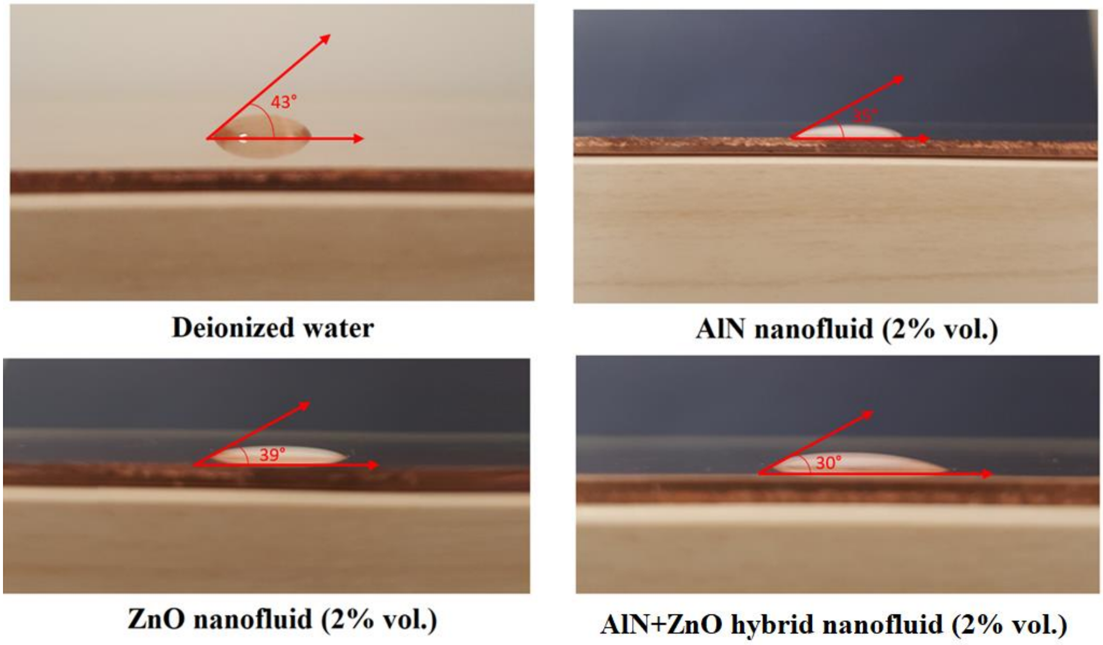


Figure 3. Contact angle measurement results

The contact angle measurement results were presented in Figure 3. The surface-active agent addition into the nanofluid suspensions was decreased the contact angle, which also means a decline in surface tension values. The contact angle of the base fluid, deionized water, can be declined from 43° up to 30° by Triton X-100 surfactant utilization. To sum up, surfactant addition inside the nanofluid suspension increased the wetting capability of the mixture. In an experimental study conducted by Martin et al. the similar findings were reported. They reported that Fe+CuO hybrid nanofluid utilization in a plain heat pipe improved the efficiency of the plain heat pipe because of the enhanced thermophysical properties of the nanofluid suspension [11]. In a different study, Gürbüz et al. experimentally and numerically illustrated that hybrid nanofluid of $CuO+Al_2O_3$ nanoparticles upgraded more the thermal performance of the U-type heat exchanger than single type (CuO-water) nanofluid suspension, which also validated the obtained outcomes of this study [16].

5. CONCLUSION

In this paper, the density, heat capacity, thermal conductivity, viscosity as well as the wetting capability of the AlN/deionized water, ZnO/deionized water, and AlN+ZnO/deionized water hybrid nanofluid suspensions were investigated. The theoretical, validated formulas and modified models were employed in calculations. A series of measurements were carried out to show off how a surfactant influences the wetting capability. The obtained results revealed that hybrid utilization of nanoparticles could enhance the thermophysical properties of the utilized working fluid more than the unitary nanofluid suspensions, specifically the thermal conductivity. The contact angle of the deionized water could be decreased with the usage of Triton X-100 surfactant. It is anticipated that the findings of this study present an idea for hybrid nanofluid preparation and its usage in a thermal system for performance upgrading.

Declaration of Ethical Standards

The author of the paper submitted declares that nothing which is necessary for achieving the paper requires ethical committee and/or legal-special permissions.

NOMENCLATURE

c_p	*Specific heat capacity* (kJ/kgK)
hnf	*hybrid nanofluid*
k	*Thermal conductivity* (W/mK)
nf	*nanofluid*
np	*nanoparticle*
μ	*Viscosity (Pa.s)*
ρ	*Density* (kg/m^3)
$\emptyset$	*Volumetric concentration (-)*
SEM	*Scanning Electron Microscopy*

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