Experimental investigation of base oil properties containing modified TiO₂/CuO nanoparticles additives

Mustafa Raad Fahad, *¹), Prof Dr. Basma Abbas Abdulmajeed, ²)
¹Chemical Engineering Department, University of Baghdad, Baghdad, Iraq
²Chemical Engineering Department, University of Baghdad, Baghdad, Iraq

¹m.fahad1207@coeng.uobaghdad.edu.iq
²basma-abdulmajeed@coeng.uobaghdad.edu.iq

Abstract. The majority of lubricating oil properties are the product of a material being used to enhance or produce the desired properties. Different materials with various nanostructures are now being used as new additives to improve lubricants' properties due to their peculiar characteristics. In this study, oleic acid was used to surface-modified TiO₂ and CuO nanoparticles to enhance the dispersion and stability of Nanofluid. The X-ray diffraction and Fourier transform Infrared spectroscopy FT-IR used to characterize the nanoparticles. The main objective of this paper was to investigate the influence of adding TiO₂-CuO nanoparticles on the thermal-physical properties such as kinematic viscosity, viscosity index, pour point and flash point of base oil and nano-lubricating oil, which is prepared by different concentration (0, 0.2, 0.5, 0.8, and 1 %) by weight, and also the contact pressure (load–carrying capacity) was examined by using commercial portable Timken tester. The results showed increases in viscosity index and flash point of nano-lubricant oil by 7.69% and 7.07%, respectively.

Keywords: base oil, TiO₂-CuO NPs, viscosity, surface modification, FTIR

1. Introduction

The frictional resistance produced between the sliding surfaces during moving causes engine wear and corrosion. As a result, engine parts are often damaged. Lubricity is associated with the formation of a tribofilm on contact surfaces. Lubricating oil's high lubricity reduces the contact surfaces and lowers wear, friction, and energy losses. Moreover, lubricants are commonly used in engines to minimize friction because lubricants perform essential functions such as lubricating, cooling, and protecting metal surfaces from corrosion damage. Lubricant oils are made up of up to 80% of oil base stocks, which give the lubricant its viscosity, stability, and pour point and additives to increase these properties. The majority of lubricant oils used worldwide contains mineral base stocks made up of hydrocarbons derived from heavy fractions of crude oil refining. The base oil's primary purpose is to lubricate and act as a carrier of additives [1]–[4]. Additives are synthetic microchemical compounds used to enhance various lubricating oil parameters and are typically mixed with engine oils to decrease friction. These have commonly contained highly toxic sulfur and phosphorus and are specifically designed for processes requiring the use of high temperatures [5], [6]. Recently, the macro-sized additives have been replaced by nano-sized additives, which have been reported in the literature. These are nano-sized Cu, CuO, TiO₂, ZnO, SiO₂ Al₂O₃, nano-diamond, graphite, tungsten disulfide, etc. [7]–[13]. Because of their ability to reduce emissions and improve fuel economy, nanoparticles
(NPs) have begun to play more important roles as lubricant additives. Their small size, typically less than 100 nm, allows them to reach the contact area in contrast to organic additives. Nanoparticles are thermally stable at high temperatures, making them suitable for use as lubricant additives. Fig 1 shows that nanoparticles used as lubricant additives can be categorized into seven kinds based on their chemical elements: carbon and its derivatives, metals, metal oxide, sulfides, rare earth compounds, nanocomposites, and others [14].

![Figure 1. Studies of the use of different kinds of nanoparticles as lubricant additives [14]](image)

Studies have extensively used various metal oxide nanoparticles as additives, which can be used to enhance the rheological and tribological properties of lubricants. Wu et al. investigated the effects of TiO$_2$, nanodiamond, and CuO nanoparticles on the tribological properties of API-SF engine oil and base oil, finding that CuO as an additive to oils reduce the friction coefficient, and the worn scar depth for engine oil and the base oil were reduced by 16.7% and 78.8%, respectively. [15]. Alves et al. examined the tribological properties by different additive concentrations (0.1 wt%, 0.25 wt%, and 0.5 wt %.) of CuO NPs dispersed in synthetic oil PAO. The results showed that the 0.1 Wt % CuO gave a better anti-wear performance. Concentrations of 0.25% and 0.5 % demonstrated the same friction-reduction activity. However, small CuO nanoparticles are more efficient in reducing wear than friction reduction [16]. Nik Roselina, Mohamad, and Kasolang investigated the impact of TiO$_2$ nanoparticles (0, 0.5, and 1.0 weight %) on palm oil and synthetic lubricant viscosity. The results show increasing in viscosity index of palm oil and synthetic lubricant by 4.1% and 7.3%, respectively, at 1wt%. And it can be observed with 0.5 wt% TiO$_2$ nanoparticles do not affect the VI for palm oil [17]. Kumar, Vasu, and Gopal studied the influence of Cu-Zn nanoparticles on the rheological properties of vegetable oil, paraffin oil, and SAE oil. It can be observed that the adding of nanoparticles can improve the thermal conductivity of vegetable oil at 30°C. And also, the flashpoint was increased with the addition of hybrid Cu-Zn nanoparticles for all oil. In this study, the best enhancement of thermal conductivity was for the vegetable oil compared with paraffin oil and SAE oil [18]. Ali et al. investigated the effect of Al$_2$O$_3$ and TiO$_2$ on rheology and tribology properties of engine oil (5W-30) and obtain that 0.25 wt. % of nanoparticles with oleic acid surfactant reduce the viscosity slightly at 40°C and 100°C, also the viscosity index of nano lubricants increased by 1.84 %. The higher the viscosity index, could contribute to better fuel efficiency in automobile engines. On the other hand, frictional power losses for Al$_2$O$_3$ and TiO$_2$ nano-lubricants were decreased by 45 % and 50 %, respectively. This decrease is attributed to the conversion of sliding into rolling friction and the forming of tribo-films on the worn surfaces [19]. Adding nano particulates to a lubricating oil...
significantly decreases the coefficient friction and increases the friction sections' load-carrying power in mechanical machinery. Several mechanisms are proposed to explain the lubrication increase in nanoparticle lubricating [20]–[22]. Lee et al. proposed four possible mechanisms of nanoparticles in lubricating oil, including (1) rolling of nanospheres, (2) protecting tribofilm formation (3) mending effect, and (4) polishing, as shown in fig 2 [23].

![Figure 2. Possible lubrication mechanisms NPs in a lubricant [23].](image)

These lubrication mechanisms are divided into two types: direct lubrication mechanisms and indirect lubrication mechanisms. Rolling ball bearing and protective film mechanisms are examples of direct lubrication mechanisms when ball bearings have a role between the frictional surfaces for nanoparticles suspended in the lubricating oil. Furthermore, they form a protective film to some extent on the rough friction surfaces. On the other hand, mending and polishing mechanisms are examples of indirect lubrication mechanisms. The nanoparticles accumulated on the friction surface and form on the rubbing surfaces to reduce the abrasion referred to as the mending effect. The polishing effect is also known as the smoothing of the surface by abrasion with nanoparticles-assist that may fill the gaps on the rough surfaces, thus reducing friction and wear [22], [24]. To enhance nanoparticles' stability in lubricating oil and avoid the growth of the particles' size and overcome the spontaneous aggregation. Many types of research used surfactants commonly in surface modification for preparing the nanoparticles as lubricating oil additives are sodium dodecyl sulfate (SDS), stearic acid, oleic acid, silane coupling agent KH560, etc.[25]–[24].

In the current study, a new technique for increasing CuO and TiO₂ NPS stability as hybrid additives in base oil was proposed, which included surface modification with oleic acid surfactant and FTIR analysis. Simultaneously, rheology and tribology properties such as load-bearing capacity will be investigated.

2. Materials and Experiment.

2.1. Material

In this study, copper oxide CuO and Titanium (IV) oxide TiO₂ were purchased from (Sky Spring Nanomaterials, Inc. Houston, USA) and (Hongwu International Group Ltd., Guangdong, China), respectively. Oleic acid is required for the surface modification of TiO₂ and CuO nanoparticles were purchased from (Alpha Chemika, India). The base oil (60-stock) is from (Al-Dura Refinery, Middle refineries Company, Baghdad, Iraq). The nanoparticles' characterizations are shown in Table 1, and the base oil (60-stock) properties are presented in Table 2.
Table 1. Specifications of nanoparticles

| Specification       | TiO₂  | CuO  |
|---------------------|-------|------|
| Average diameter(nm)| 71.14 | 73.09|
| Color               | White | black|
| Purity (%)          | >99.9 | 99   |
| Surface area (m²/g) | 119.9 | 50   |
| Pore volume (cm³/g) | 0.237 | 0.1606|

Table 2. Properties of base oil 60 stock

| Specification                      | Base oil(60stock) |
|------------------------------------|-------------------|
| Kinematic viscosity @ 40 °C (cSt)  | 61.163            |
| Kinematic viscosity @ 100 °C (cSt)| 8.2209            |
| Viscosity index                    | 102.6             |
| Density @ 15 °C (g/cm³)            | 0.8617            |
| Flash Point (°C)                   | 226               |
| Pour point (°C)                    | -6                |

2.2. Measuring and Analysing Apparatus.

Probe ultrasonic type VCX 750 (Sonics & Materials Inc., USA) used to dispersion NPs in base oil and making Nano-lubricating oil. X-ray Diffract meter (XRD-6000, Shimadzu, Japan) and Fourier Transform Infrared Spectroscopy (FTIR-8400S, Shimadzu, Japan) were used in the characterization of TiO₂ and CuO nanoparticles. The rheological properties of nano-lubricating oil were examined in kinematic viscosity, Viscosity Index (VI), flashpoint, and pour point. The VI was conducted from kinematic viscosity at 40 °C and 100 °C using a viscometer type CVM 3000 (Anton Paar, Austria) according to ASTM D-7042. Flashpoint and pour point of base and nano-oil were measured using COC device according to ASTM D-92 and CPP5Gs device according to ASTM D-97, respectively.

Contact pressure (load-carrying capacity) of nano-lubricating oil was measured using a portable Timken machine (Chongqing top oil Purifier Co., Ltd, China), as shown in fig 3. Based on the Timken method ASTM D-2782 to investigate the contact pressure of prepared nano-lubricating oil compared with the base oil. The calculations of the contact pressure according to the Timken Method equation (1) [30].

\[ C, \text{ PSI} = \frac{[L(X+G)]}{YZ} \]  

Where:
- \( C \) = contact pressure (load-carrying capacity) psi
- \( L \) = mechanical advantage of the load-lever arm, 10
- \( X \) = mass (weight) placed on the weight, lb
- \( G \) = load-lever constant, (weight of the long arm and short arm)
- \( Y \) = length of test scar, inch
- \( Z \) = average width of test scar, inch
The test runs with a stationary block bearing forced against a rotating roller in a bearing at 800 rpm. The cup is filled with 25 ml of lubricating oil at temperature 40°C, and the load is applied by weights to a lever with a mechanical advantage of 1:10. The test was carried out according to the ASTM D2782 procedure, and runs were 10-minutes long. They are then inspected for the scar. If there is none, the load is raised for another 10-minute run until a scar occurs.

2.3. Surface modification of CuO and TiO₂ nanoparticles

Surface modification of inorganic nanoparticles in oil-based suspensions using organic alteration agents organic compounds were used as modifying agents. They typically have polar groups and long alkyl chains that can chemically adsorb onto inorganic nanoparticles, allowing inorganic nanoparticles to become modified [31]. Oleic acid OA (1 g) was added to 100 ml of anhydrous ethanol and thoroughly mixed until the solution was homogenized. Some amount of TiO₂ and CuO NPs was added separately to the solution by mixing using a magnetic stirrer. The resulted solution was heated to 75°C for two hours. After the reaction was completed, the sample was put in the oven for four hours under 80°C to ensure all the ethanol was evaporated. Then, it was washed with methanol to remove unbonded OA. The sample was dried at 80°C for six hours to produce OA/TiO₂ and OA/CuO. Fig.4 illustrates the mechanism of surface modification for capping oleic acid on the nanoparticles that explain the reaction of carboxyl in oleic acid with the hydroxyl of NPs. The oleic acid functionalized the surface of nanoparticles could be proved by FT-IR results.
2.4. Preparation of TiO₂-CuO Nano-lubricating oil.

Different methods used like a magnetic stirrer and probe ultrasonic and surface modification were mentioned and studied for making stable nano-lubricants. Nano-lubricating oil preparing by dispersing modified nanoparticles into the base oil with a weight concentration range (0.2 wt. % - 1 wt. %) as shown in fig 5. TiO₂ and CuO as hybrid NPS with a weight ratio of 50:50 were weighed using an accurate electronic balance. A magnetic stirrer was used to mix the NPs with base oil for two hours, and then an ultrasonic probe-type VCX 750 (Sonics & Materials Inc., USA) was used for one hour to obtain high dispersion and prevent agglomeration of NPs. Sonication was carried out of each pulsed irradiation, alternating 5 s of t/ON and 5 s of t/off at 60% power.

3. Result and discussion.

3.1. X-ray Diffraction Patterns

The X-ray diffraction pattern of TiO₂ nanoparticles is shown in fig.6a. The eight characteristic anglesviz 20 equal to 25.3°, 38.03°, 47.9°, 54.9°, 62.62°, 69.3°, 70.04° and 75.21°. These peaks agree with JCPDS card No. 21-1272. Also, it can be seen that TiO₂ nanoparticles are high-purity with a single anatase phase. Fig.6b shows the X-ray diffraction pattern of the CuO NPs and confirms the monoclinic phase formation. The observed sharp diffraction peaks at 20 are 32.6°, 35.6°, 38.8°, 48.9°, 53.59°, 58.39°, 61.6°, 66.4°, 68.12°, 72.5°, and 75.06°. This corresponds to JCPDS card No. 05-0661.
3.2. FT-IR Characterization of OA/TiO₂ and OA/Al₂O₃ nanoparticle.

The FT-IR spectrum of TiO₂ in fig. 7a indicates a major band around 500 and 750 cm⁻¹, related to TiO₂ [32]. The observed band at 3415 and 1633 cm⁻¹ refer to hydroxyl group –OH and water Ti-OH [33]. In fig. 7b and fig. 8a, the absorption bands around 1710.8 and 2852.7 cm⁻¹ are attributed to C=O stretch vibration and –CH₂ stretch vibration from oleic acid [34], In Fig. 8a, the absorption band around 542 cm⁻¹ refers to the Cu–O functional group's vibrations, and the peak at 3448.7 and 3452 cm⁻¹ relate to the –OH group [35], [36]. The –OH groups on the surface of CuO and TiO₂ NPs decreased in modified TiO₂ and CuO nanoparticles. Meanwhile, OA groups of carboxyl (COOH) reacted with hydroxyl (OH) groups to produce carboxylate in modified NPs.

![Figure 7 FT-IR spectrum of TiO₂ (a) and OA/TiO₂ (b)](image1)

![Figure 8 FT-IR spectrum of CuO (a) and OA/CuO (b)](image2)
3.3. Effect of TiO₂-CuO NPs on the kinematic viscosity and viscosity index of base oil.

Viscosity is one of the essential properties of any lubricant. The samples' kinematic viscosity and viscosity index of nano-lubricants was measured based on ASTM D-7042. Fig. 9 and fig. 10 describe the kinematic viscosity and viscosity index of TiO₂-CuO hybrid nano-lubricants compared with base oil. The results showed that there is a slight decrease in the viscosity of both lubricating oil. The decreases may be attributed to a loss of inter-particle and intermolecular adhesion forces [3]. The kinematic viscosity decreased slightly at a low concentration of TiO₂-CuO NPs in the base oil. The reduction in viscosity is attributable to NPs between oil layers, leading to ease of movement between nano-lubricating oil layers[19]. Then, at high concentrations, the kinematic viscosity increased due to the agglomerate or large particle size, which hinders the movement of oil layers[37]. In fig. 8, the results showed that the viscosity index increased by 7.21% with increasing the concentration of NPs at 0.8 wt. % compared with parent oil, and it indicates more stable kinematic viscosity with changes in temperatures.

**Figure 9** Effect of TiO₂-CuO NPs on the kinematic viscosity on the base oil at 40°C and at 100°C

**Figure 10** Effect of TiO₂-CuO NPs on the viscosity index of base oil.
3.4. Effect of TiO$_2$-CuO NPs on the pour and flash point of base oil

The flash point is the lowest temperature that can create an inflammable mixture in the air. Fig. 11 illustrates the trend of flash point changes as a result of TiO$_2$-CuO nanoparticle concentration added to the base oil. It can be observed that with the increasing concentration addition of NPs to base oil at 1 wt. %, the flashpoint of base oil increased by 7.07%. Pour point is one of the specifications that determines the lowest temperature of lubricating oil. Pour point is described as the minimum temperature at which the oil can be poured under the standardized test conditions. Fig. 12 demonstrates the changes in the pour point of base oil after adding TiO$_2$-CuO NPs concentration. The pour point of base oil at 0.8 wt. % concentration of NPs is noticeably reduced to -12 °C and increased slightly to -9 °C at 1% concentration of NP.
3.5. Effect of TiO₂-CuO NPs on the contact pressure (load carrying capacity) of base oil.

The results of load-carrying capacity as shown in the figure 13 demonstrates the slight increase in contact pressure at low concentration of NPs, and the highest increase of obtained at 1% of TiO₂-CuO NPs concentration by 11290 psi at 7-pound load. As a result, the load-carrying capacity of TiO₂-CuO nano-lubricants was considerably higher than that of base oil. The scar damage was reduced clearly with adding NPs concentrations. This indicates that NPs enhance the lubricity of base oil and decrease the friction due to nanoparticle lubricating oil and tribo-film formation on the sliding surface. Fig.14 shows the scarring effect of base oil and nano-lubricating oil.

![Figure 13](image13.png)

**Figure. 13** Effect of nano additive TiO₂-CuO wt. % on the load-carrying capacity of base oil

![Figure 14](image14.png)

**Figure.14** Wear scar effect of base oil (a).nano-lubricating oil (b)

4. Conclusions

- To improve the stability of NPs and prevent agglomeration, ultrasonic probe and surface modification of TiO₂ and CuO with oleic acid surfactant were used in which change the surface of the nanoparticles from hydrophilic to hydrophobic.
• The existence of organic groups on the surface of NPs was demonstrated by FT-IR spectra, which revealed that oleic acid is bound to the carboxylate form.
• The modified TiO₂-CuO NPs as a base oil additive can improve the viscosity index by 7.6 %.
• Nanoparticles at different concentrations increased the flash point of the nano-lubricant oil compared to the base oil. At 1 % wt. concentration, the flashpoint of nano-lubricating oil increased by 7.07 %.
• The best concentration of NPs added to base oil is 0.8 %, considering the slight change in kinematic viscosity. Moreover, the contact pressure test of TiO₂-CuO 50:50 nano-lubricants indicated an improvement of load-carrying capacity compared with a base oil, and the higher increase of load-carrying capacity was at 1 wt. % concentration of NPs.

References

[1] Shahnazar S, Bagheri S and Abd Hamid S B 2016 Enhancing lubricant properties by nanoparticle additives Int. J. Hydrogen Energy 41 3153–70
[2] Jason Y J J, How H G, Teoh Y H and Chua H G 2020 A study on the tribological performance of nanolubricants Processes 8 1–33
[3] Subedi B R, Trital H M and Rajbhandari A 2017 Characterization of CuO-nanoadditives blended engine oil J. Inst. Sci. Technol. 22 152–8
[4] Ravindra M K and Ramkrishna G E 2014 An Investigation of Tribological Behaviour of Lubricating Oil With the Addition of Nanoparticle Additives 5
[5] Delgado-Tobón A E, Aperador-Chaparro W A and Miszana-Rodriguez Y G 2018 Evaluation of the lubricating power of chemical modified Sesame oil additized with Cu and Al2O3 nanoparticles DYN A 85 93–100
[6] Ahmed N S, Nassar A M, Kamal R S and Hafez S 2017 Prepararion, characterization and evaluation of some metallic lube oil additives Nehal Pet. Coal 59 866–76
[7] Sukkar K A, Karamalluh A A and Jaber T N 2019 Rheological and Thermal Properties of Lubricating Oil Enhanced by the Effect of CuO and TiO2 Nano-Additives Al-Khwarizmi Eng. J. 15 24–33
[8] Kumar M, Afzal A and Ramis M K 2017 Investigation of physicochemical and tribological properties of ti02 nano-lubricant oil of different concentrations Tribologia 35 6–15
[9] Gopinatha S and Nagarajanb N 2015 Nano particles of zn and zno as extreme pressure (EP) additives for lubricants J. Appl. Res. Technol. 13 374–81
[10] Peng D X, Chen C H, Kang Y, Chang Y P and Chang S Y 2010 Size effects of SiO2 nanoparticles as oil additives on tribology of lubricant Ind. Lubr. Tribol. 62 111–20
[11] Verma S, Kumar V and Gupta K D 2015 Tribological effects of Cu, Fe and Zn nano-particles, suspended in mineral and bio-based oils Lubr. Sci. 28 157–76
[12] Lee G J, Park J J, Lee M K and Rhee C K 2017 Stable dispersion of nanodiamonds in oil and their tribological properties as lubricant additives Appl. Surf. Sci. 415 24–7
[13] Aberoumand S and Jafarimoghaddam A 2018 Tungsten (III) oxide (WO3) – Silver/transformer oil hybrid nanofluid: Preparation, stability, thermal conductivity and dielectric strength Alexandria Eng. J. 57 169–74
[14] Dai W, Kheireddin B, Gao H and Liang H 2016 Roles of nanoparticles in oil lubrication Tribol. Int. 102 88–98
[15] Wu Y Y, Tsui W C and Liu T C 2007 Experimental analysis of tribological properties of lubricating oils with nanoparticle additives Wear 262 819–25
[16] Alves S M, Mello V S, Faria E A and Camargo A P P 2016 Nanolubricants developed from tiny CuO nanoparticles Tribol. Int. 100 263–71
[17] Nik Roselina N R, Mohamad N S and Kasolang S 2020 Evaluation of TiO2 nanoparticles as viscosity modifier in palm oil bio-lubricant IOP Conf. Ser. Mater. Sci. Eng. 834
[18] Kumar M S, Vasu V and Gopal A V 2016 Thermal conductivity and rheological studies for Cu–Zn hybrid nanofluids with various basefluids J. Taiwan Inst. Chem. Eng. 66 321–7

[19] Ali M K A, Xianjun H, Mai L, Qingping C, Turkson R F and Bicheng C 2016 Improving the tribological characteristics of piston ring assembly in automotive engines using Al2O3 and TiO2 nanomaterials as nano-lubricant additives Tribol. Int. 103 540–54

[20] Rapoport L, Leshchinsky V, Lvovsky M, Nepomnyashchy O, Volovik Y and Tenne R 2002 Mechanism of friction of fullerences Ind. Lubr. Tribol. 54 171–6

[21] Chinas-Castillo F and Spikes H A 2003 Mechanism of action of colloidal solid dispersions J. Tribol. 125 552–7

[22] Sriveyas P D and Charoo M S 2018 A review on tribological characterization of lubricants with nano additives for automotive applications Tribol. Ind. 40 594–623

[23] Lee K, Hwang Y, Cheong S, Choi Y, Kwon L, Lee J and Kim S H 2009 Understanding the role of nanoparticles in nano-oil lubrication Tribol. Lett. 35 127–31

[24] Maharaja K, Vijayan S N and Karthik S 2016 Tribological Effect of Size, Shape and Structure of Nanoparticle in Lubricant Oil-A Review Sci. Control. Commun. Eng. Technol. 730–4

[25] Zhang L, Chen L, Wan H, Chen J and Zhou H 2011 Synthesis and tribological properties of stearic acid-modified anatase (TiO2) nanoparticles Tribol. Lett. 41 409–16

[26] Gu K, Chen B and Chen Y 2013 Preparation and tribological properties of lanthanum-doped TiO2 nanoparticles in rapeseed oil J. Rare Earths 31 589–94

[27] Chen T, Xia Y, Jia Z, Liu Z and Zhang H 2014 Synthesis, characterization, and tribological behavior of oleic acid capped graphene oxide J. Nanomater. 2014 8

[28] Ma S, Zheng S, Cao D and Guo H 2010 Anti-wear and friction performance of ZrO2 nanoparticles as lubricant additive Particuology 8 468–72

[29] Koshy C P, Rajendrakumar P K and Thottackkad M V 2015 Evaluation of the tribological and thermo-physical properties of coconut oil added with MoS2 nanoparticles at elevated temperatures vol 330–331 (Elsevier)

[30] ASTM D2782 1998 Standard Test Method for Measurement of Extreme-Pressure Properties of Lubricating 88 1–8

[31] Azman N F and Samion S 2019 Dispersion Stability and Lubrication Mechanism of Nanolubricants: A Review Int. J. Precis. Eng. Manuf. - Green Technol. 6 393–414

[32] Lv Y zhen, Li C, Sun Q, Huang M, Li C rong and Qi B 2016 Effect of Dispersion Method on Stability and Dielectric Strength of Transformer Oil-Based TiO2 Nanofluids Nanoscale Res. Lett. 11 4–9

[33] León A, Reuquen P, Garin C, Segura R, Vargas P, Zapata P and Orihuela P A 2017 FTIR and raman characterization of TiO2 nanoparticles coated with polyethylene glycol as carrier for 2-methoxyestradiol Appl. Sci. 7 1–9

[34] Song X, Zheng S, Zhang J, Li W, Chen Q and Cao B 2012 Synthesis of monodispersed ZnAl 204 nanoparticles and their tribology properties as lubricant additives Mater. Res. Bull. 47 4305–10

[35] El-Trass A, Elshamy H, El-Mehasseb I and El-Kemary M 2012 CuO nanoparticles: Synthesis, characterization, optical properties and interaction with amino acids Appl. Surf. Sci. 258 2997–3001

[36] Ashokan S, Ponnuswamy V, Jayamurugan P and Rao Y V S 2015 Fabrication and characterization of CuO nanoparticles : Its Humidity sensor application Int. J. Ind. Chem. 4 28