# Comparison between multi-walled carbon nanotubes and Titanium dioxide nanoparticles as additives on performance of Turbine meter oil nano lubricant

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**Research Article**

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# Comparison between multi-walled carbon nanotubes and Titanium dioxide nanoparticles as additives on performance of Turbine meter oil nano lubricant

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**Abstract:**

This research work purpose to compare the impact of the mass fraction of multi-walled carbon nanotubes (MWCNTs) and Titanium dioxide ($TiO_2$) nano additive on the tribological and thermophysical attributes of turbine meter oil. These attributes are including the average friction coefficient, pressure drop, wear, flash point, pour point, relative viscosity, kinematics viscosity, and viscosity index. Also, the pressure drops and the average friction coefficient inside the copper tube were simulated and compared with experimental results. In this study, for the synthesis of nano lubricants from turbine meter oil as a pure fluid and from MWCNTs and $TiO_2$ as nano additives in the mass fraction of 0.05, 0.1, 0.2, 0.3, and 0.4 wt.% and from oleic acid and Triton x100 as surfactants were utilized. The diameter of MWCNTs and $TiO_2$ nano additives were ranging from 5 nm to 16.1 nm and 7.9 nm to 13.9 nm, respectively. The average particle size of $TiO_2$ and MWCNTs nano additives in 0.4 wt.% in the pure lubricant were 221nm and 320 nm, respectively. The results illustrated that the wear depth of copper pins in the presence of nano lubricant with 0.4 wt.% of MWCNTs and 0.1 wt.% $TiO_2$ was improved by 88.26% and 71.43%, respectively. Nano lubricants with 0.3 wt.% of $TiO_2$ and 0.4 wt.% of MWCNTs nano additives illustrated the maximum improvement in the flash point temperature with enhancement 4 °C and 10 °C. By increasing of 0.3 wt.% of $TiO_2$ and MWCNTs into the pure oil caused to improve in viscosity index with enhancement 6.68% and 2.43% compared to the pure lubricant, respectively. The simulation data and experimental data for the pressure drop were closer together and indicated a minor error that the maximum error is less than 10%.

**Keywords:** Nano-$TiO_2$; MWCNT; Turbine meter oil; Nanofluid; Tribology, Thermophysical behavior

## 1. Introduction

The lubrication systems have essential duties in the moving mechanical equipment. Since much of the mechanical damage and loss of energy is due to wear and friction, improving the tribological properties of the lubricants used in this equipment is of particular importance, and it is necessary to conduct extensive research in this field. Because almost all traditional lubricants have reached the threshold point of enhancing base oils, a new type of lubricant needs to develop to meet the lubrication requirements of mechanical equipment [1-3]. Nano lubricants are a solution to this challenge and have received much attention in recent years; studies have indicated that adding small amounts of nano additives (about 0.2 to 2%) to the base fluid can improve its tribological properties [4-7]. Various types of nanoparticles, such as carbon-based materials [8,9], metal oxides [10-12], and metals [13,14], have been used as additives. The nanoparticles have unique features due to their high specific surface area and smaller size than other materials. Also, potential advantages of nanoparticles such as low reactivity with other additives, film formation on various surfaces, insolubility in non-polar oils, durability, and withstand high-temperature conditions has led nanoparticles to be interested as additives to improve tribological attributes of oil [15]. However, the principal challenge with the use of nanoparticles is their dispersion and long-term stability in the base fluids. Nanoparticles are highly prone to agglomeration because of the strong van der Waals force, which causes the nanoparticles to precipitate and become unstable. Hence, prepare a stable dispersion of nano additives in base fluids is of particular significance. So far, various types of physical and chemical techniques, such as the addition of stabilizing agents, ultrasonic agitation, surface modifications, and mechanical stirring have been used to prepare a stable nano lubricant, which is very beneficial for excellent lubrication performance [16-18]. $TiO_2$ nanoparticles are one of the additives that have been highly regarded for lubrication applications because of their unique attributes such as wear resistance, environmental compatibility, high specific surface area, superior load, and friction attributes. Examples of studies on examining the influence of $TiO_2$ nano additives on the tribological attributes of lubricants include the following studies. Kao and Lin [19] investigated the impact of $TiO_2$ nano additives on the tribological features of paraffinic lubricant. They used a reciprocating sliding tester to test the wear and friction of the base oil and the nano lubricant. Also, they reported that the friction coefficient achieved for the nano lubricant was less than the value obtained for the base oil and nanoparticles provides surface repair, rolling function as lubricants. Therefore, spherical $TiO_2$ nanoparticles are a good choice for tribological and lubrication applications in the mechanical industry. Sabareesh et al. [20] examined the impact of $TiO_2$ nano additives on the tribological behavior of mineral lubricant. Their results revealed that by increasing the mass fraction of nanoparticles, the viscosity of the nano lubricants rises, which decreases the friction coefficient. Ingole et al. [21] used $TiO_2$ nano additive to improve the tribological performance of the oil and found that by increasing of nano additives significantly reduced the friction coefficient. Also, they illustrated that by increasing of nano additives more than 2 wt.%, reduces the stability of the nanoparticles and increases the friction coefficient. Ali et al. [22] investigated the effect of $TiO_2$, $Al_2O_3$ nanoparticles on the tribological characteristics of engine oil. Their results showed that by adding nanoparticles as nano-lubricant additives in base fluid, the wear, power losses, and friction coefficient are decreasing. They also found that adding nanoparticles could improve fuel consumption and reduce energy consumption in automotive engines. Alghani et al. [23] examined the enhancement of the tribological performance of nano lubricant containing $TiO_2$ and graphene nanoparticles. They reported that the nano lubricant containing 0.2 wt.% of graphene and 0.4 wt.% of $TiO_2$ provided the best performance with a reduction in specific wear rate and friction coefficient, 15.78 and 38.83, respectively. Hong et al. [24] investigated the lubrication and dispersion performance of $TiO_2$ nanoparticles modified with polyphenol derivatives and unmodified nanoparticles in two base oils, commercial engine oil and polyalphaolefin. The results of their analysis showed that the surface modification of nanoparticles by producing thick tribofilms and strengthening the mechanical properties of the surface helps them to reduce more friction than unmodified nanoparticles. Sharma et al [25] reported that $TiO_2$ nano additive could provide promising lower friction coefficients and anti-wear attributes when used as nano additives in the pure lubricant. Carbon nanotubes (CNTs) are another nanomaterial that has always been of interest to researchers due to their anti-wear attributes and high thermal and electrical conductivity. Many researchers have been evaluated the influence of CNTs on the rheological and tribological features of base oils. Based on their results, CNTs are recognized as the best additive to improve the tribological performance of pure oils. Vakilinezhaad and Dorani [26] experimentally and theoretically studied the impact of CNTs on the viscosity index of the base fluid. They reported that increasing nano additives to the base oil improves the viscosity index by 14%. Bhaumik et al. [27] found that adding multi-walled carbon nanotubes (MWCNTs) to mineral oil improves the anti-wear attributes and load capacity of the pure oil. They reported that mineral oil containing 0.05 wt.% of nano-additives reduced wear by 70-75%. Cornelio et al. [28] reported that by increasing of CNTs to pure lubricants cause to improve the friction coefficient and wear rate. Khalil et al. [29] studied the impact of CNTs with the different mass fraction on the tribological property of two base oils (paraffinic mineral and Mobil gear 627 oils). They used a four-ball tribometer to perform wear and friction experiments. Their results showed that by increasing of CNTs to the pure lubricant reduced the wear by 39% and 68% in nano lubricant compared with base paraffinic mineral and Mobil gear 627 oils, respectively. Salah et al. [30] analyzed the tribological performance of various base oils containing CNTs as lubricating additives. They proved that the nano lubricants were containing 0.1 wt.% CNTs reduce the coefficient of friction compared to the pure fluid by 20%. Gao et al. [31] analyzed the dispersing properties, molecular structures, and physicochemical properties of six types of surfactants, also investigated the tribological properties of CNTs nanofluid with different surfactants. They found that among the six surfactants, nanofluids containing APE-10 showed the optimal dispersion and tribological properties. Li et al. [32] studied the impact of CNT, graphene, and fullerene on the friction coefficient of the linear alpha olefin. They reported with the addition of graphene and fullerene to the base oil improved the friction coefficient by 90% and 76%, respectively. While the negative effect of CNT on the friction coefficient an increase from 0.21 to 0.32 was observed. Naddaf et al. [33] studied the tribological performance of diesel oil containing graphene and MWCNT as lubricating additives. Their results indicated that heat transfer properties of nanofluids improved compared to the base oil. Esfe et al. [34] reported that by increasing of MWCNT and $TiO_2$ nanoparticles to engine oil cause to increase the dynamic viscosity. Pourpasha et al. [35, 36] studied the tribological and the thermophysical performance of turbine meter oil containing MWCNT and $TiO_2$ nanoparticles as additives. Their results indicated that tribological and thermophysical properties of nanofluids improved compared to the pure lubricant.

Based on the many investigations conducted on the basis of the lubricating oils, wide-ranging investigations have been led to lubricants, whereas no research has been done on turbine meter oil except for two articles published on it lately [35, 36]. Turbine meters are used at a gas pressure reducing and metering stations to measure gas volume. In this system, turbine meter oil is used to reduce wear and friction to the parts of the turbine meter. The main purpose of this study is the numerically and experimentally evaluate the impacts of MWCNTs and $TiO_2$ nano additives on the tribological and thermophysical properties of turbine meter oil. To achieve this goal, the first nano lubricants containing MWCNTs and $TiO_2$ nanoparticles in various mass fractions (0.05 wt.%, 0.1 wt.%, 0.2 wt.%, 0.3 wt.%, and 0.4 wt.%) were synthesized through a two-step method. Then, the effect of concentration of nanoparticle on thermophysical and tribological features, including pressure drop, average friction coefficient, pour point, flash point, kinematic viscosity, relative viscosity, viscosity index, and wear were studied. Some parts of the present study used the previously our published papers data's [35,36] in order to better compared the results of 2 different TiO2 nanoparticles and MWCNT nanotubes in turbine-meter oil rheological properties improving.

## 2. Material and method

### 2.1. Materials

MWCNTs and $TiO_2$ nanoparticles as additives to improve the base fluid attributes were purchased from the VCN Materials Company and Sigma-Aldrich, respectively. The specifications of MWCNTs and $TiO_2$ nanoparticles are shown in Table 1. Oleic acid and Triton x100 as the coating agents purchased from Merck. Table 2 shows the characteristics of Turbine meter oil as the base fluid that was purchased from Shell Oil Company.

### *2.2.* Synthesis of nano lubricants

In order to prepare the $TiO_2$/turbine meter oil, nano lubricants a two-step method was used. Considering our previously published papers [35,36] for this purpose, a certain amount of oleic acid (weight ratio of 1 to 2 with nanoparticles) as a surfactant and turbine meter oil were blended with the mixer at 1300 rpm for 30 min. Then, $TiO_2$ nanoparticles were added to the solution and mixed for 4 h. Finally, to increase the stability and better distribution of additives in the pure lubricant, the prepared nano lubricants were exposed to ultrasonic waves for 3 hours using an ultrasonic bath (Panasonic 2600 s). A similar method was used to synthesize nano lubricants containing MWCNTs, except that Triton x100 (weight ratio of 1 to 3 with nanoparticles) was used as a surfactant.

Table 1. Nano additives characteristics

| Nanoparticles | Morphology | Diameter (nm) | Regular length (µm) | Purity (%) | Density (kg/m$^3$) |
|---|---|---|---|---|---|
| MWCNTs | Tube shape | 5-16.1 | 5-10 | 99 | 2100 |
| $TiO_2$ | Spherical shape | 7.9 – 13.9 | - | 99 | 4230 |

Table 2. Oil characteristics

| Fluid | Density (kg/m$^3$) | Flash point (˚C) | Pour point (˚C) | Viscosity in 40 ˚C (cSt) | Viscosity in 100 ˚C (cSt) |
|---|---|---|---|---|---|
| Turbine meter oil | 775 | 220 | -40 | 21.88 | 4.6 |

Figure 1 shows a schematic of the experimental system used to measure the friction coefficient and pressure drop of pure turbine meter oil and nano lubricant. The experimental system includes a manometer, oil tank, valves, pump, and decanter. This experiment was performed in different flow rates and the following equation was used to calculate the flow rate (Q).

$$Q = \frac{V}{t} \quad (1)$$

Where v is a certain volume (ml) of circulating fluid in the system that comes out of the copper pipe at a constant time (t).

Equations 2 to 5 were used to calculate velocity (U), Reynolds for laminar flow (Re), friction coefficient (f), and the density of the nanofluid ($\rho_{nf}$), respectively.

$$U = \frac{Q}{A} \quad (2)$$

Where A is the cross-section of the copper tube.

$$Re = \frac{Ud}{\upsilon} \quad (3)$$

In this equation, d is copper pipe's diameter and $\upsilon$ is the viscosity of operating fluids.

$$f = \frac{64}{Re} \quad (4)$$

$$\rho = \rho_n \phi + (1 - \phi)\rho_{bf} \quad (5)$$

Where $\rho_n$ is the density of nanoparticle, $\phi$ is the particle volume fraction and $\rho_{bf}$ is the density of the base fluid.

The experimental pressure drop was measured through the manometer installed in the experimental system. For this purpose, water and $CCl_4$, which are immiscible solvents, were used in the manometer, and the following equation was used to calculate the experimental pressure drop:

$$\Delta P_{exp} = \rho_{CCl_4} g h_{CCl_4} - \rho_w g h_w \quad (6)$$

In this equation, $h_{CCl_4}$ and $\rho_{CCl_4}$ are the height and density of $CCl_4$ in the manometer, $h_w$ and $\rho_w$ are the height and density of water in the manometer, and g is the gravitational constant. Also, the theoretical pressure drop was calculated using equations 7 and 8, respectively.

$$\Delta P_{theo} = \frac{f L \rho U^2}{2d} \quad (7)$$

where L is the length of the copper tube

Figure 2 shows the schematic of the device designed to measure wear depth and coefficient of friction. This device includes a gearbox, electromotor, pin, oil shield, and ball bearing. All experiments were done under the same operating conditions, such as the load of 7 N, rotation at 200 rpm for 4 h, and the 60° angle between the pin and disc.

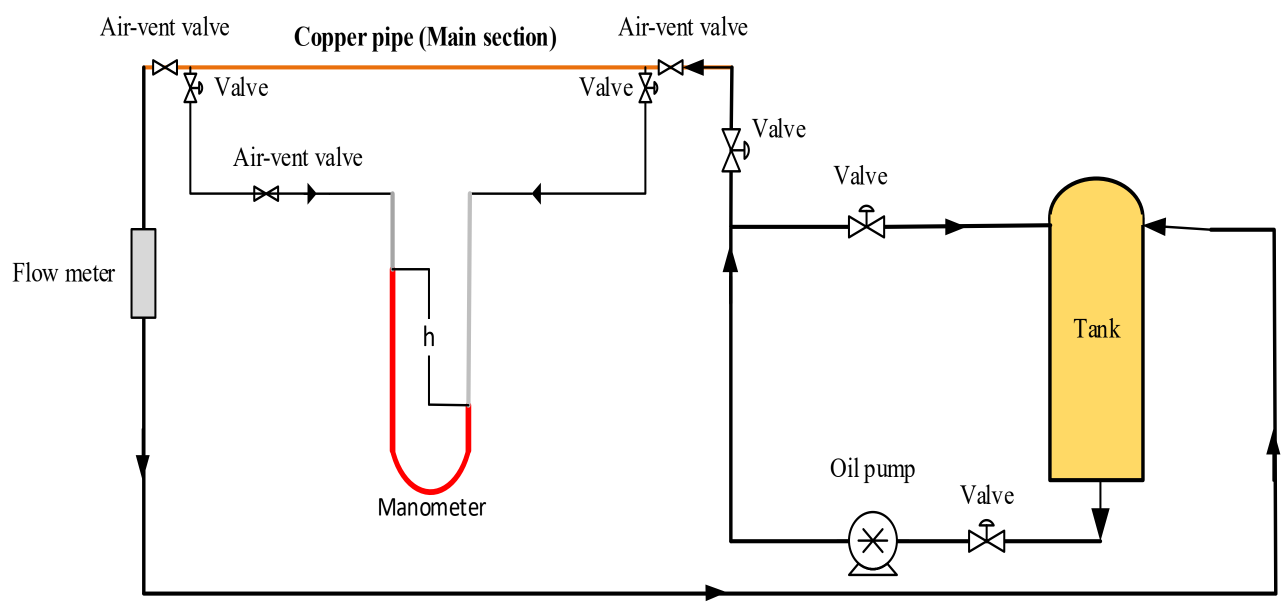



Figure 1. Schematic of the experimental system

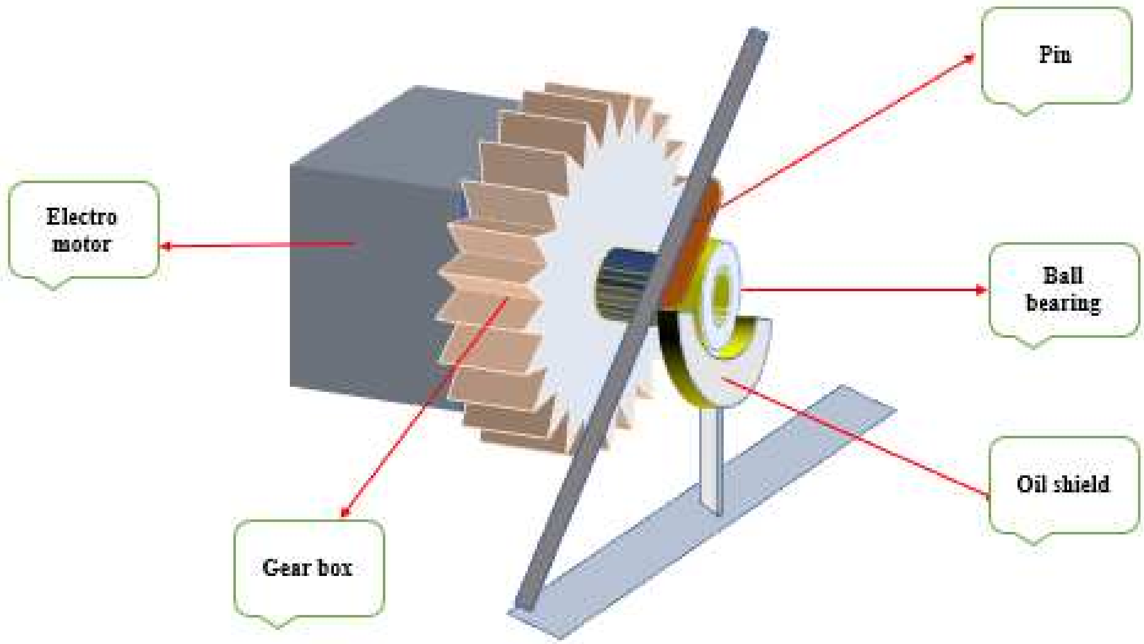



Figure 2. Schematic of the wear apparatus

## 3. Simulation description and Numerical analysis

The pressure drops and the average friction coefficient inside the copper tube were calculated by continuity, momentum balance, and friction coefficient equations, as follows [35, 37]:

$$\frac{\partial \rho}{\partial t} + \nabla.(\rho\vec{v}) = 0 \quad (8)$$

$$\frac{\partial}{\partial t}(\rho\vec{v}) + \nabla.(\rho\vec{v}\vec{v}) = -\nabla P + \nabla\tau + \rho\vec{g} + \vec{F} \quad (9)$$

$$f = \frac{2d\,\Delta p}{L\rho u^2} \quad (10)$$

Where P, $\rho\vec{g}$, and $\vec{F}$ are the static pressure, the gravitational body force, and external body force, respectively [35]. Utilizing boundary conditions and possible simplifications, the equations are solved, and the results are reported as a figure and table.

Boundary conditions play a necessary function in the computational fluid dynamics methods to enhance the convergence and validation of the resolution. The numeral figure of the computational domain of the pipe is indicated in Figure 3.

The velocity inlet measuring range is between 0.069 m/s and 0.698 m/s, the copper pipe containing an interior diameter of 0.009 m and a length of 1.1 m. The attributes of the lubricant are imported into the materials section. The lateral configuration of the copper pipe has been considered a solid wall, the wall of the pipe has been weighed as an immovable wall, and no-slip boundary condition has been supposed in the wall of this tube. All of the inlet fluid exits the pipe, and the pump repeats this cycle until it attains a steady state.

The diagram of the copper pipe of the experimental setup has been designed and meshed by Gambit software, and the momentum balance and the friction coefficient equations have been solved by ANSYS-Fluent software based on the finite volume method. The mesh size of 1 mm was selected to simulate in this research work according to Table 3 [35], which represents a mesh independence analysis in three mesh sizes for lubricant as the working fluid with a velocity inlet of 0.069. The value of the friction coefficient and pressure drop are converged by decreasing the mesh size. Case 3 was selected as the optimum. The problem under study is a three-dimensional (symmetrical), steady, laminar flow of nano lubricant inside a copper pipe, and the pressure-based solving algorithm is appropriate. In the solution methods section of ANSYS-Fluent, the scheme, gradient, pressure, and momentum have been considered simple, least-squares cell-based, second-order, and second-order upwind, respectively. Convergence absolute criteria of continuity equations and velocity equations have been assumed with residual lower than $10^{-13}$.

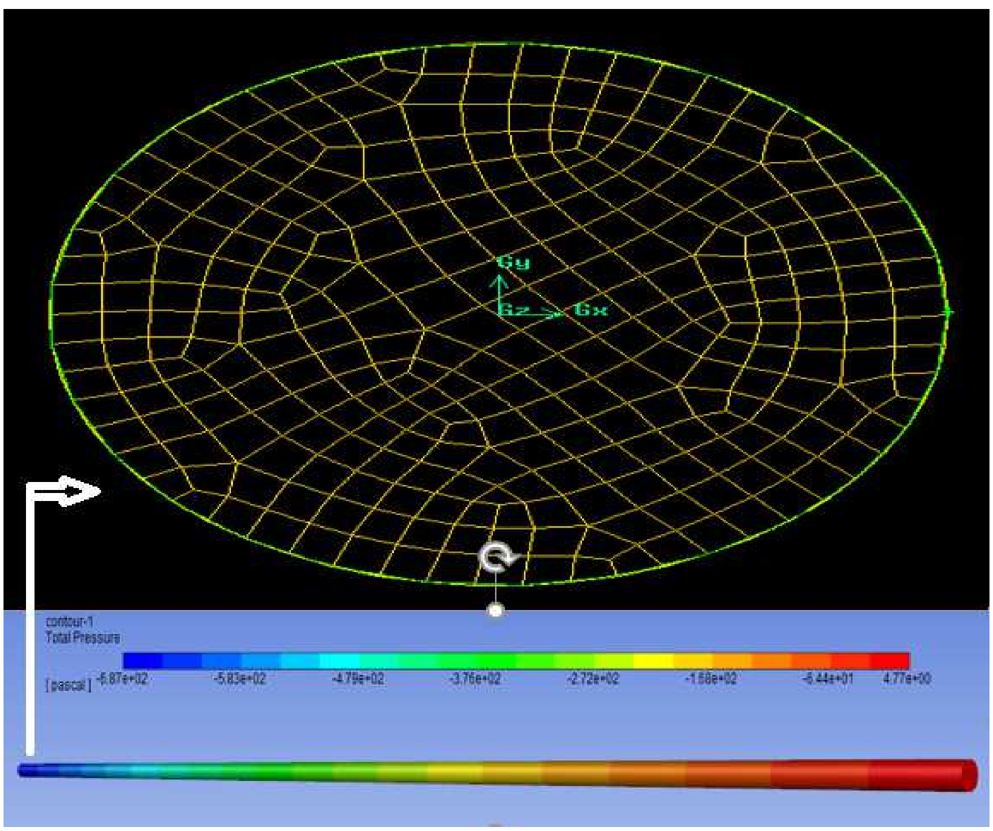



Figure 3. Schematic and mesh diagram of copper tube

Table 3: Mesh independence analysis mesh independence analysis in three different mesh size for turbine meter oil as the operating fluid with a velocity inlet of 0.069 [35]

| Case | Mesh size (mm) | Number of elements | Aspect ratio | F | $\Delta P_{sim}$ (pa) |
|---|---|---|---|---|---|
| 1 | 4 | 3509 | 2-4 | 3.0164 | 680.21 |
| 2 | 3 | 7110 | 1-4 | 3.0374 | 684.91 |
| 3 | 1 | 91728 | 1-3 | 3.0396 | 685.39 |

## 4. Result

In this part, the impact of adding $TiO_2$ and MWCNTs nanoparticles on lubricant properties, including viscosity, viscosity index, flash point, pour point, wear, friction coefficient, and pressure drop has been discussed in detail. Also, the impact of velocity inlet on the friction coefficient and pressure drop has been investigated.

### 4.1. Characteristics analysis

Figures 4 and 5 indicate the SEM images of $TiO_2$ and MWCNTs [36, 35]. These SEM images were taken from $TiO_2$ and MWCNTs at 200000 and 400000 magnifications, respectively. The diameter of $TiO_2$ nano additive is ranging from 7.9 nm to 13.9 nm, and the diameter of MWCNTs is ranging from 5nm to 16.1 nm. In addition, the $TiO_2$ and MWCNTs additives are spherical shaped and tube shaped, respectively [35, 36]. As can be seen the $TiO_2$ and MWCNTs have a uniform distribution range.

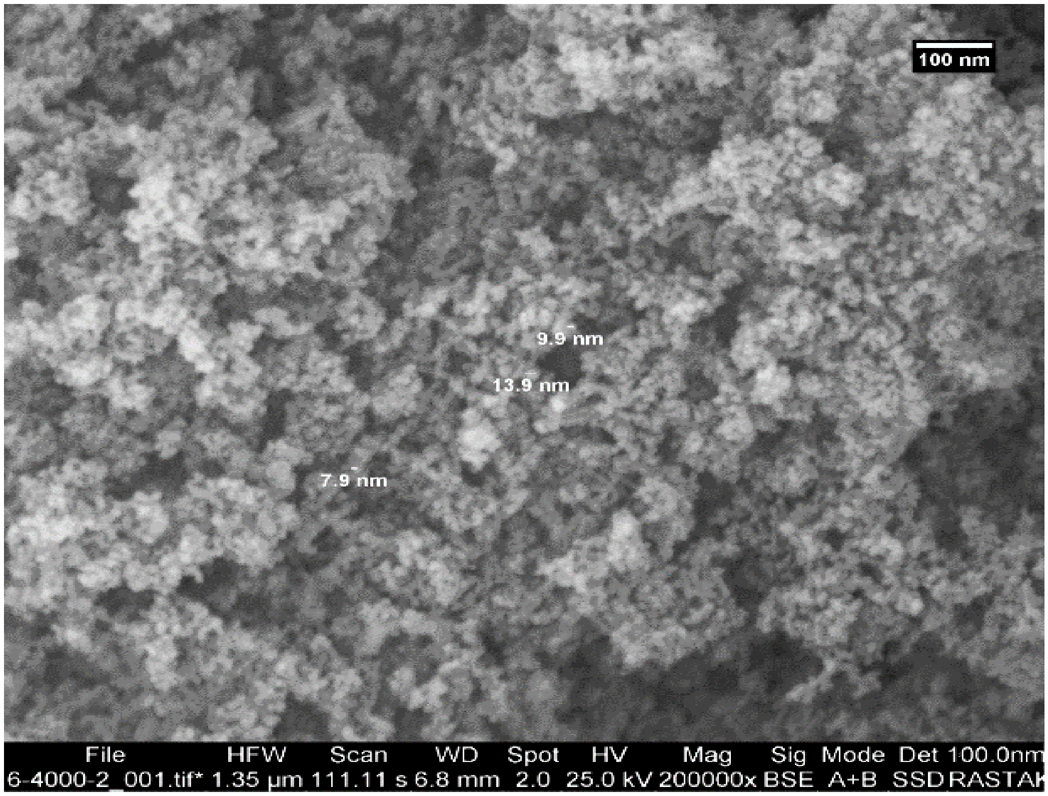



Figure 4. SEM images of the $TiO_2$ nanoparticles [36].

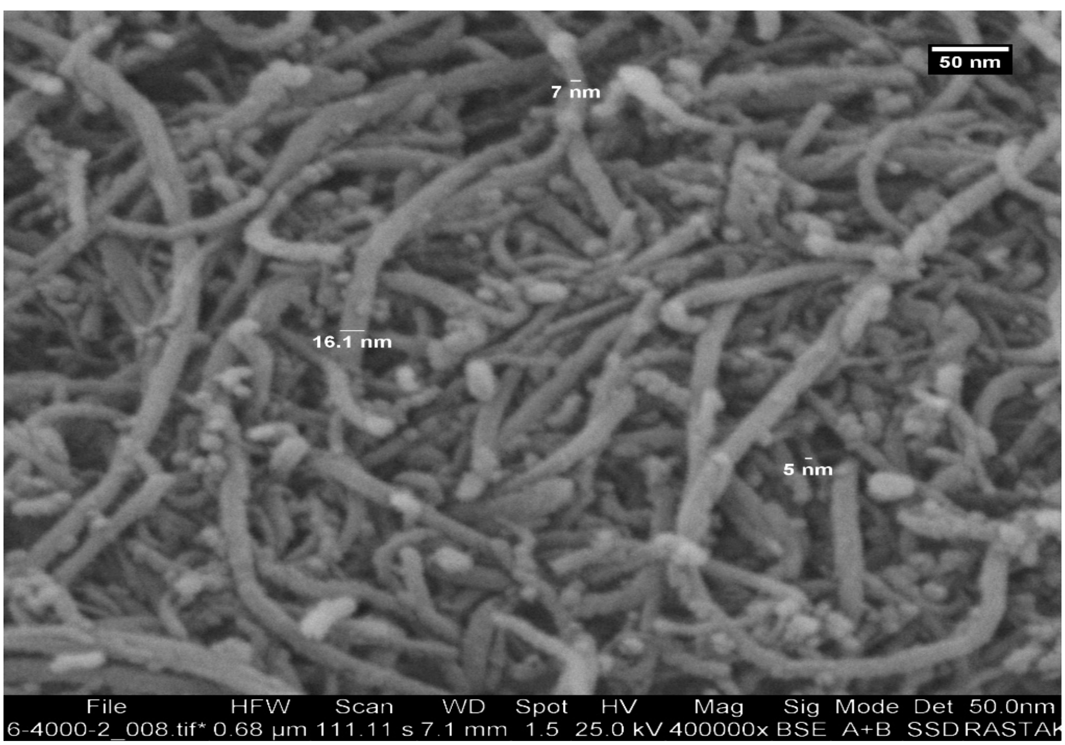



Figure 5. SEM images of the MWCNTs nanoparticles [35].

According to Figures 6 and 7, the size distribution of $TiO_2$ and MWCNTs nanoparticles in 0.4 wt.% in the paraffinic base lubricant indicate that the average particle size of $TiO_2$ and MWCNTs are 221nm and 320 nm [35], respectively. The mean diameter of the MWCNT in the pure lubricant was higher than $TiO_2$ nanoparticles. According to research articles [38- 40], the addition of nano additives in the pure lubricant reason for increases the size of the nano additives in the lubricant. Some critical parameters in the distribution of nano additive size in the pure fluid are the size, form of the nano additives, the type of pure fluid, and nano additives. If the proportion of the length to the diameter of nano additives is near to one, the form of the nano additives becomes near to spherical, and the average particle size is declined.

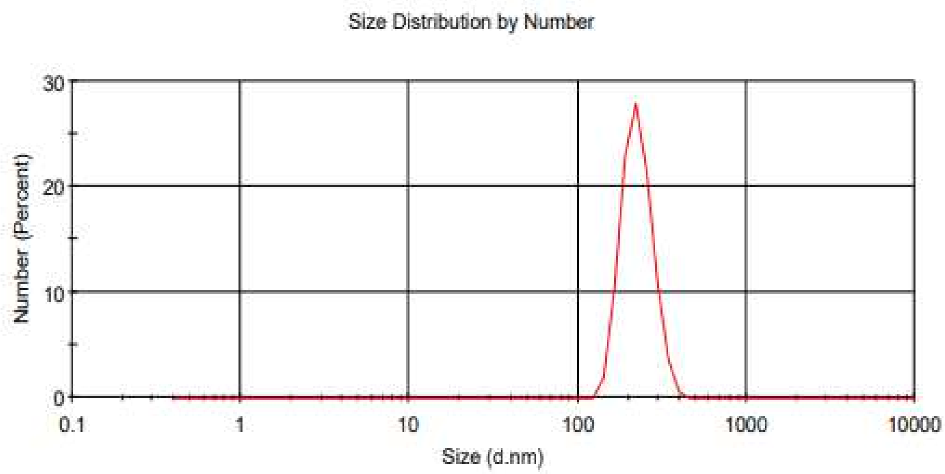



Figure 6. DLS images of the $TiO_2$ nanoparticles.

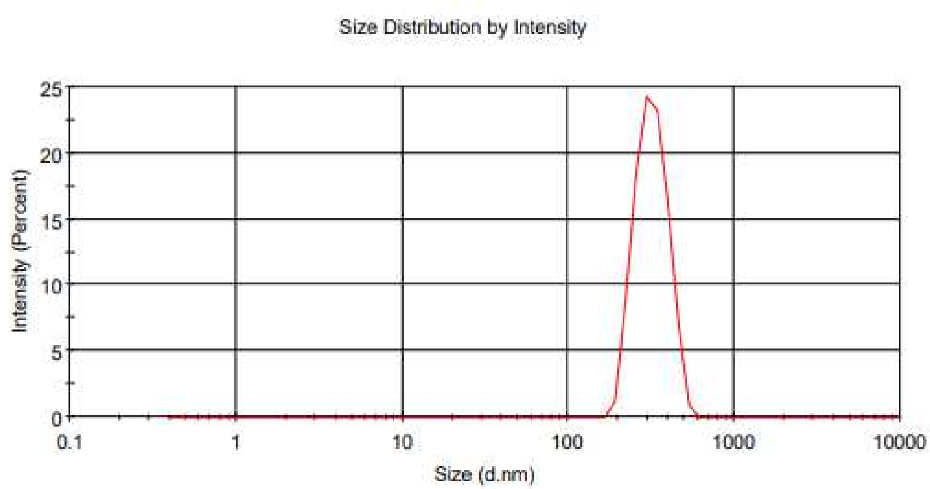



Figure 7. DLS images of the MWCNTs nanoparticles [35].

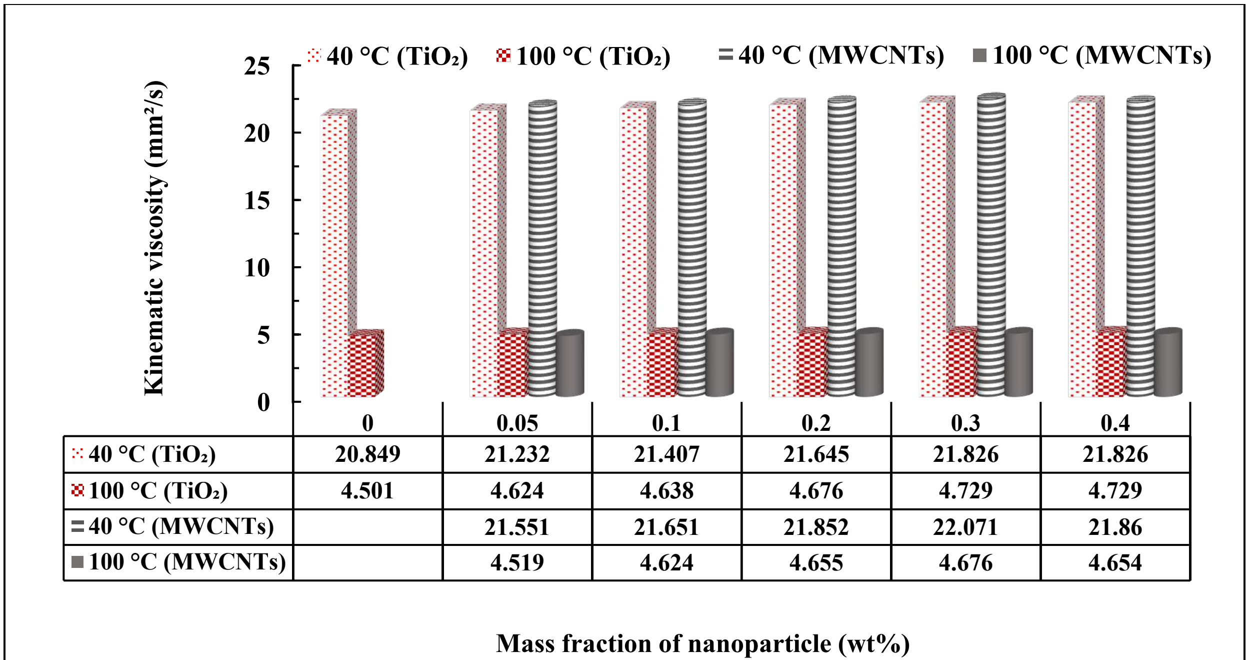
### 4.2. Thermophysical analyses

Table 4 illustrates the kinematic viscosity changes of nano lubricants with the different mass fraction of $TiO_2$ and MWCNTs nano additives at temperatures ranging from 30 °C to 100 °C. With increasing temperature from 30 °C to 100 °C, the kinematic viscosity of the nano lubricants and the base lubricant decreased. With increasing temperature, growth occurs in the Brownian motion of particles in the base lubricant. Hence, increasing the random rate of the particles declines the intermolecular forces among the pure fluid and the surface of the particles. The intermolecular forces of the lubricant are reduced with temperature rise and increasing molecular energy, which leads to an increment in the intermolecular distance. As a result, the kinematic viscosity of nano fluids was declined with temperature rise [35, 36]. With the addition of $TiO_2$ and MWCNTs nano additives to the pure lubricant, the kinematic viscosity of the nano lubricants in the different mass fraction of nano additives relative to the pure lubricant enhanced at all temperature ranges. Thus, the maximum enhancement and the minimum enhancement of the kinematic viscosity (i.e., 6.83% and 2.59%, respectively) were obtained by increasing of $TiO_2$ nanoparticles to 0.4 wt.% at 30°C and 60°C, respectively. The maximum enhancement and the minimum enhancement of kinematic viscosity (i.e., 8.82% and 3.35%, respectively) were obtained with the addition of MWCNTs to 0.4 wt.% at 30°C and 60°C, respectively [35].

Table 4: Comparison of the kinematic viscosity for $TiO_2$/turbine meter oil and MWCNTs/turbine meter oil lubricants at different temperatures.

| | Kinematic Viscosity at various temperatures | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Concentration | 30 °C | 40 °C | 50 °C | 60 °C | 70 °C | 80 °C | 90 °C | 100 °C |
| Pure oil | 29.95 | 20.849 | 15.158 | 11.243 | 8.599 | 6.762 | 5.472 | 4.501 |
| 0.05 wt.% MWCNTs | 31.96 | 21.551 | 15.271 | 11.282 | 8.628 | 6.794 | 5.483 | 4.519 |
| 0.1 wt.% MWCNTs | 31.942 | 21.651 | 15.408 | 11.418 | 8.754 | 6.907 | 5.583 | 4.624 |
| 0.2 wt.% MWCNTs | 32.22 | 21.852 | 15.557 | 11.532 | 8.832 | 6.954 | 5.64 | 4.655 |
| 0.3 wt.% MWCNTs | 32.593 | 22.071 | 15.693 | 11.62 | 8.903 | 7.019 | 5.67 | 4.677 |
| 0.4 wt.% MWCNTs | 32.228 | 21.86 | 15.651 | 11.533 | 8.843 | 6.977 | 5.639 | 4.658 |
| 0.05 wt.% $TiO_2$ | 30.982 | 21.232 | 15.192 | 11.342 | 8.736 | 6.818 | 5.599 | 4.624 |
| 0.1 wt.% $TiO_2$ | 31.684 | 21.407 | 15.372 | 11.418 | 8.767 | 6.931 | 5.61 | 4.638 |
| 0.2 wt.% $TiO_2$ | 31.768 | 21.645 | 15.313 | 11.418 | 8.797 | 6.969 | 5.659 | 4.676 |
| 0.3 wt.% $TiO_2$ | 31.996 | 21.826 | 15.64 | 11.535 | 8.887 | 7.044 | 5.721 | 4.729 |
| 0.4 wt.% $TiO_2$ | 31.996 | 21.826 | 15.64 | 11.535 | 8.887 | 7.044 | 5.721 | 4.729 |

The kinematic viscosity of $TiO_2$/turbine meter oil and MWCNTs/turbine meter oil, nano lubricants in different mass fraction at 40 °C and 100 °C, as shown in figure 8. The viscosity index was calculated using the kinematic viscosity values of base lubricant and nano lubricants at 40 °C and 100 °C, as shown in figure 9. The kinematic viscosity of the nanofluid with the addition of $TiO_2$ nanoparticle at the mass fraction of 0.05 wt.% to 0.4 wt.% at 100 °C is higher than the kinematic viscosity of the nanofluid by increasing of MWCNTs with the same mass fraction. Consequently, nano lubricants with 0.3 wt.% of $TiO_2$ and MWCNTs nano additives illustrated the maximum percentage of improvement in viscosity index with enhancement of 6.68% and 2.43% compared to the pure lubricant, respectively.




| | 0 | 0.05 | 0.1 | 0.2 | 0.3 | 0.4 |
|---|---|---|---|---|---|---|
| 40 °C ($TiO_2$) | 20.849 | 21.232 | 21.407 | 21.645 | 21.826 | 21.826 |
| 100 °C ($TiO_2$) | 4.501 | 4.624 | 4.638 | 4.676 | 4.729 | 4.729 |
| 40 °C (MWCNTs) | | 21.551 | 21.651 | 21.852 | 22.071 | 21.86 |
| 100 °C (MWCNTs) | | 4.519 | 4.624 | 4.655 | 4.676 | 4.654 |

Figure 8. Comparison of the kinematic viscosity of $TiO_2$/turbine meter oil and MWCNTs/turbine meter oil nanofluids in different mass fraction at 40°C and 100°C.

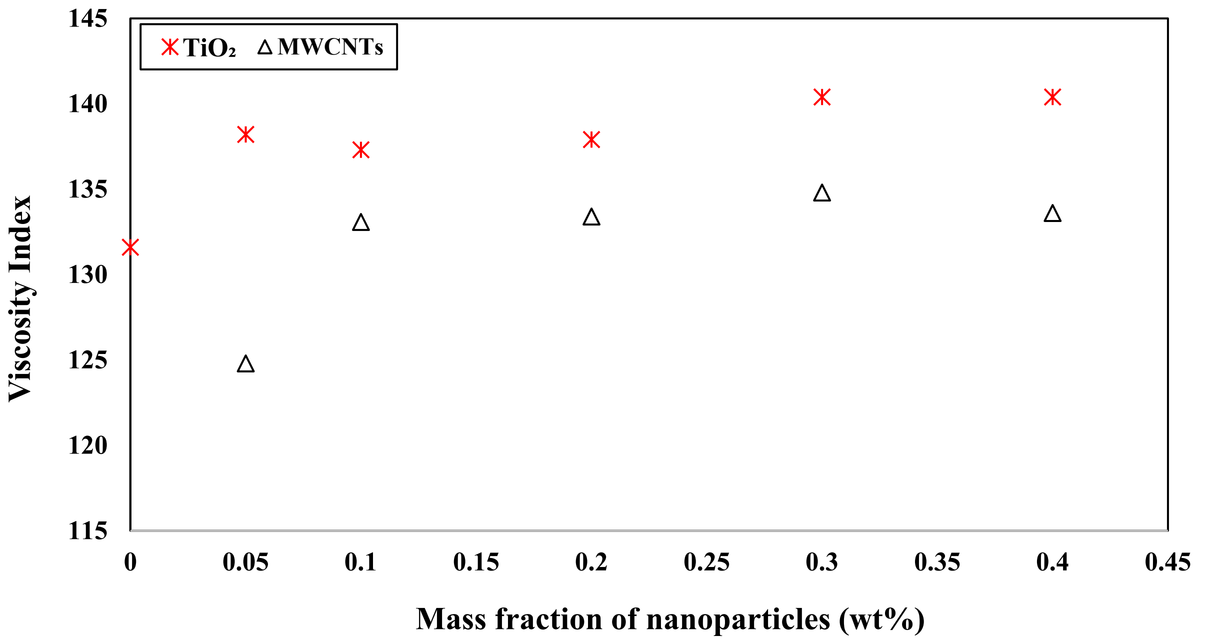



Figure 9. Comparison of viscosity index of $TiO_2$/turbine meter oil and MWCNTs/turbine meter oil nanofluids.

Figures 10 and 11 illustrate the relative viscosity changes of the nano lubricant with the addition of $TiO_2$ and MWCNTs nano additives in mass fraction of 0.05 wt.%, 0.1 wt.%, 0.2 wt.%, 0.3 wt.%, and 0.4 wt.% of the temperature measuring range from 30 °C to 100 °C. By increasing the concentration of MWCNTs nanoparticles to base oil, the relative viscosity at the temperature measuring range increased, and also the same trend has been presented for nanofluids with $TiO_2$ nanoparticles. The correlation for estimating the ratio of kinematic viscosity of MWCNTs/turbine meter oil nanofluid was obtained curve-fitting of experimental data of nano lubricant temperature (°C) and MWCNTs mass fractions (wt.%). The following correlations were obtained for the temperature measuring range from 30 °C to 60 °C with $R^2$ =0.9795 and sum of squares=$2.278\times10^{-4}$ (equation (11)) and the temperature measuring range from 70 °C to 100 °C with $R^2$=0.9401 and sum of squares=$3.4\times10^{-3}$ (equation (12)) for estimating the ratio of kinematic viscosity of nano lubricants. The correlation for estimating the ratio of kinematic viscosity of $TiO_2$/turbine meter oil nanofluid with 0.05, 0.1, 0.2, 0.3, and 0.4 wt.% of nanoparticles was obtained curve-fitting of experimental data of nano lubricant temperature (°C) and $TiO_2$ mass fractions (wt.%). The following correlations were obtained for the temperature measuring range from 30 °C to 60 °C with $R^2$ =0.9419 and sum of squares=$5.4\times10^{-3}$ (equation (13)) and the temperature measuring range from 70 °C to 100 °C with $R^2$=0.9323 and sum of squares=$3.4\times10^{-3}$ (equation (14)) for estimating the ratio of kinematic viscosity of nano lubricants.

$$\mu_r = \frac{\mu_{nf}}{\mu_{bf}} = 1.225 + 0.232w - 7.792\times10^{-3}T - 0.3672w^2 + 6.617\times10^{-5}T^2 \quad (11)$$

$$\mu_r = \frac{\mu_{nf}}{\mu_{bf}} = 1.0061 + 0.3066w - 5\times10^{-4}T - 0.5217w^2 + 3.8376\times10^{-6}T^2 \quad (12)$$

$$\mu_r = \frac{\mu_{nf}}{\mu_{bf}} = 1.18 + 0.1624w - 6.506\times10^{-3}T - 0.1973w^2 + 5.717\times10^{-5}T^2 \quad (13)$$

$$\mu_r = \frac{\mu_{nf}}{\mu_{bf}} = 0.9794 + 0.142w + 3\times10^{-4}T - 0.156w^2 + 1.265\times10^{-6}T^2 \quad (14)$$

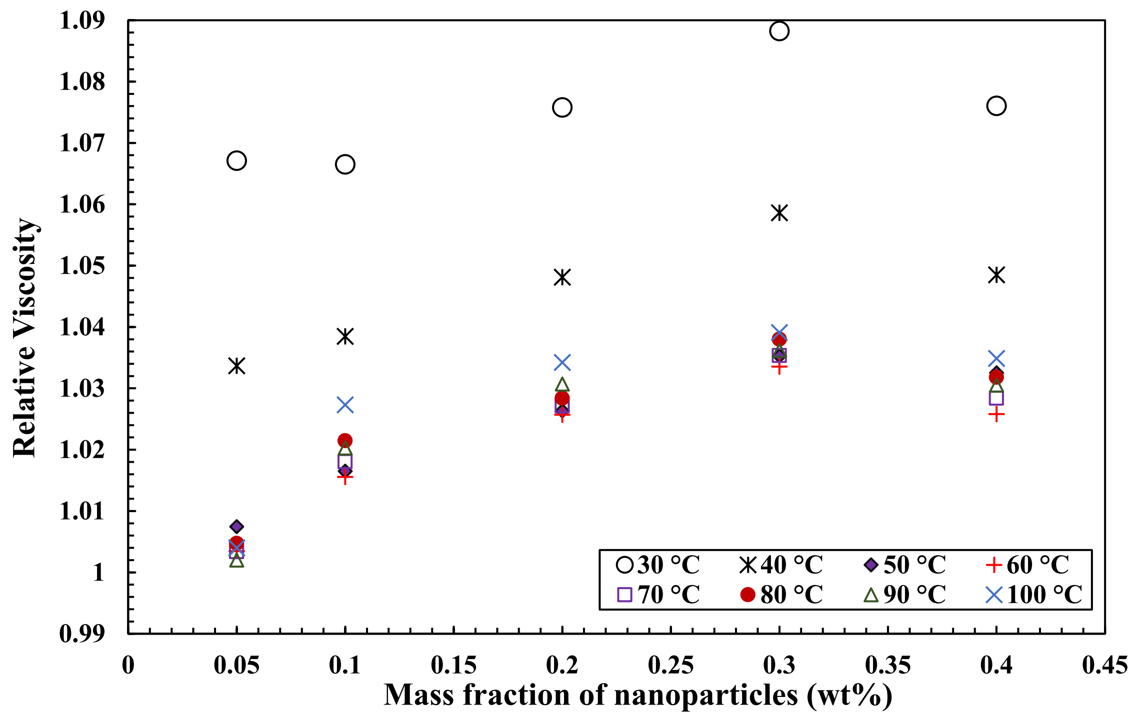



Figure 10. Variation of relative viscosity of MWCNTs/turbine meter nanofluids in different mass fraction

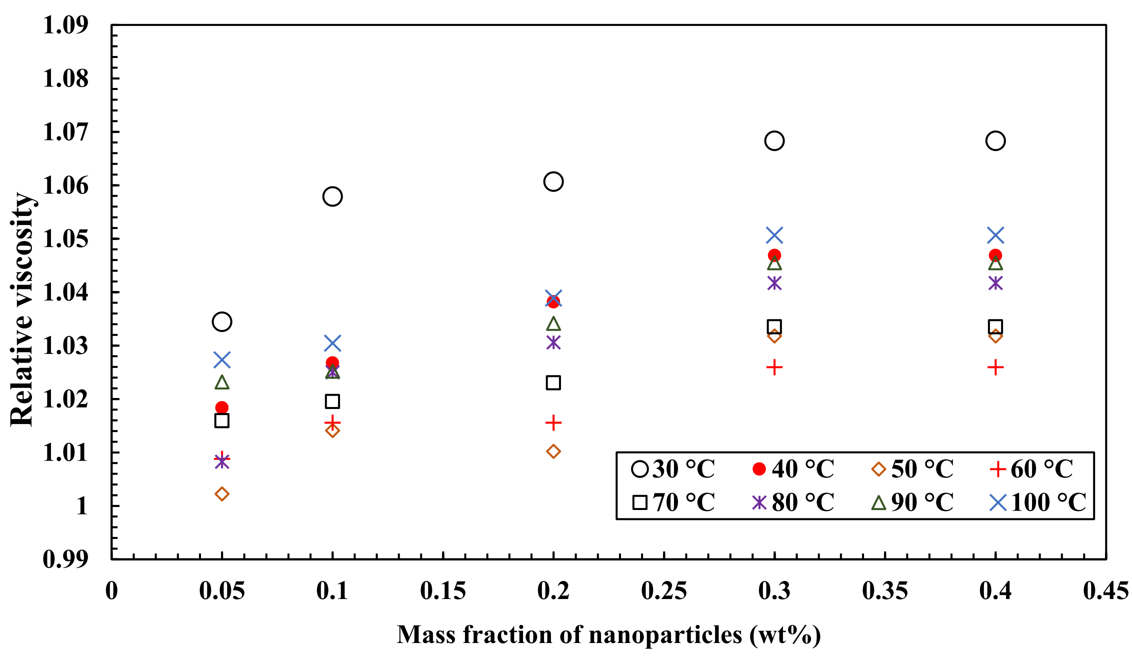



Figure 11. Variation of relative viscosity of $TiO_2$/turbine meter nanofluids in different mass fraction

Figure 12 indicates experimental data and the correlation outputs from equations (11), (12), (13), and (14) for the ratio of kinematic viscosity nanofluids with 0.05 wt.%, 0.1 wt.%, 0.2 wt.%, 0.3 wt.%, and 0.4 wt.% of $TiO_2$ and MWCNTs nano additives at 40 °C and 80 °C. The correlation outputs and experimental data are closer together or show a minor deviation that calculation of Margin of deviation (equation (15)) indicate the maximum deviation margin is 1%.

$$\text{Margin of deviation} = \frac{\mu_{r_{Exp}} - \mu_{r_{Correlation}}}{\mu_{r_{Exp}}} \quad (15)$$

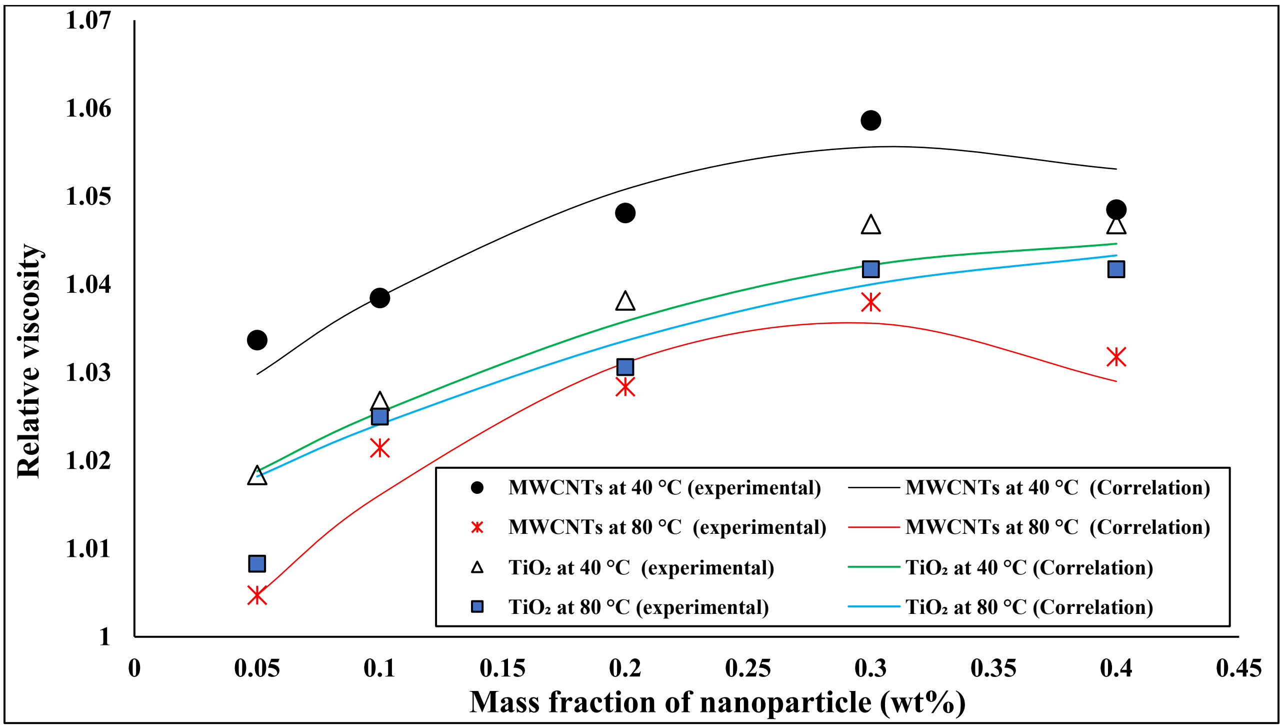



Figure 12. Variation of relative viscosity of $TiO_2$/turbine meter and MWCNTs/turbine meter oil nanofluids in different mass fraction

Figure 13 illustrates the impact of $TiO_2$ and MWCNTs nano additives on the pour point of turbine meter oil. By increasing $TiO_2$ and MWCNTs to the base fluid, the pour point temperature of nanofluids improved compared with base fluid. Consequently, nano lubricants with 0.1 wt.% of $TiO_2$ and 0.4 wt.% of MWCNTs nano additives illustrate the maximum improvement in the pour point temperature with the decrease of 1.2 °C and 2.6 °C compared to the pour point temperature of pure oil, respectively. Turbine meter oil has the lowest the pour point temperature among other lubricants. The addition of any additives including nanoparticles and polymers will have little effect on the pour point temperature of base oil, which is due to the type of refining lubricant and additives used in the production of this oil, which prevents the growth of wax crystals up to -40 °C. Figure 14 illustrates the impact of $TiO_2$ and MWCNTs nano additives on the flash point of turbine meter oil. By increasing $TiO_2$ and MWCNTs to the pure oil, the pour point temperature of nanofluids improved compared with base oil. Consequently, nano lubricants with 0.3 wt.% of $TiO_2$ and 0.4 wt.% of MWCNTs nano additives illustrate the maximum improvement in the flash point temperature with enhancement 4 °C and 10 °C compared to the flash point temperature of pure oil, respectively. The addition of $TiO_2$ and MWCNTs nano additives cause to improve in the thermal conductivity of the lubricant and cause to delay in the evaporation of ignitable vapor cause to enhance the resistance of the pure lubricant to ignition.

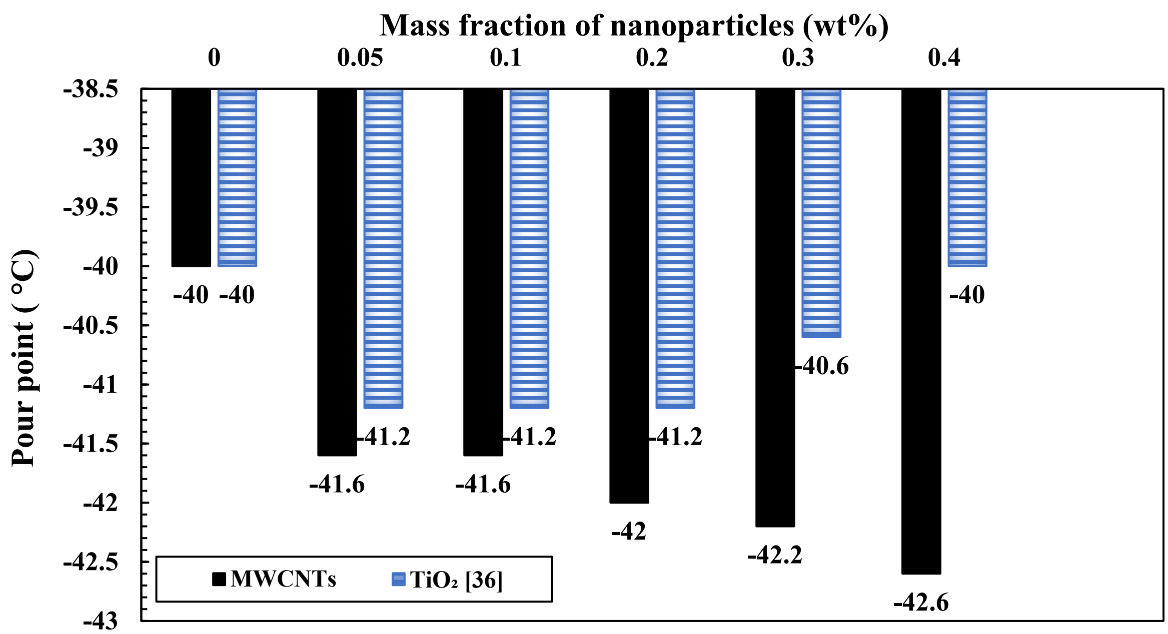



Figure 13. Comparison of pour point of $TiO_2$/turbine meter oil and MWCNTs/turbine meter oil nanofluids in different mass fraction

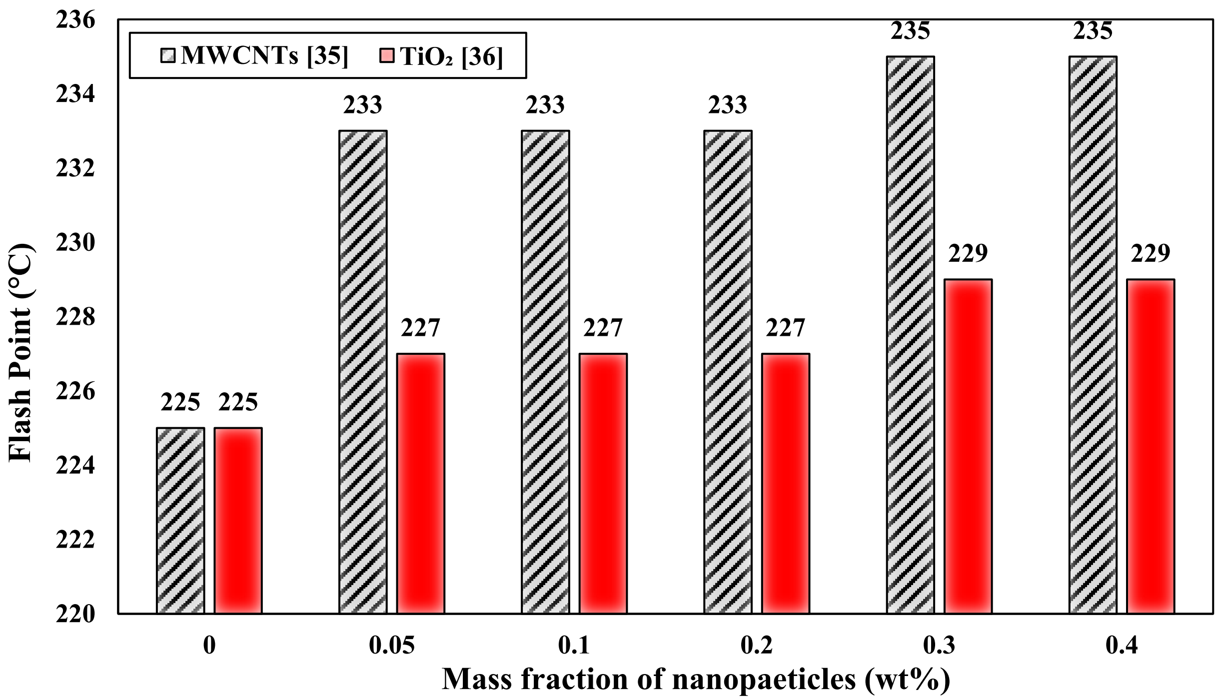



Figure 14. Comparison of flash point of $TiO_2$/turbine meter oil and MWCNTs/turbine meter oil nanofluids in different mass fraction.

### 4.3. Tribological analyses

The wear depth of copper pins was calculated by the SEM image, and results of abrasion are reported in figure 15. By increasing of MWCNTs nano additives to the base oil cause to decline in the wear depth of copper pins , the least abrasion or the most correction are related to 0.4 wt.% MWCNTs nano additives with a wear depth of 15.8 µm, compared to pure lubricant, it was bettered by 88.26%. SEM images of wear pins are shown in Figure 16. The wear depth of the pins are indicated by a white line and two white arrows. Generally, the addition of MWCNTs nano additives to pure oil decreased the abrasion of pins. Also, Pourpasha et al. [36] have presented the same trend for variations in the wear depth of copper pins by increasing of $TiO_2$ nano additives to the base oil. Their result, as shown in Figure 14 with Adding $TiO_2$ nano additives to the pure lubricant cause to reduce abrasion of pins that the least abrasion or the most correction are related to 0.1 wt.% $TiO_2$ nano additives with a wear depth of 38.45 µm, compared to pure lubricant, was bettered by 71.43% [36].The highest wear depth when using pure lubricant is 134.6 µm [36]. According to the results, the wear depth of copper pins with increasing of MWCNTs to pure lubricant has been more improved compared with increasing of $TiO_2$ nano additive to the base oil.

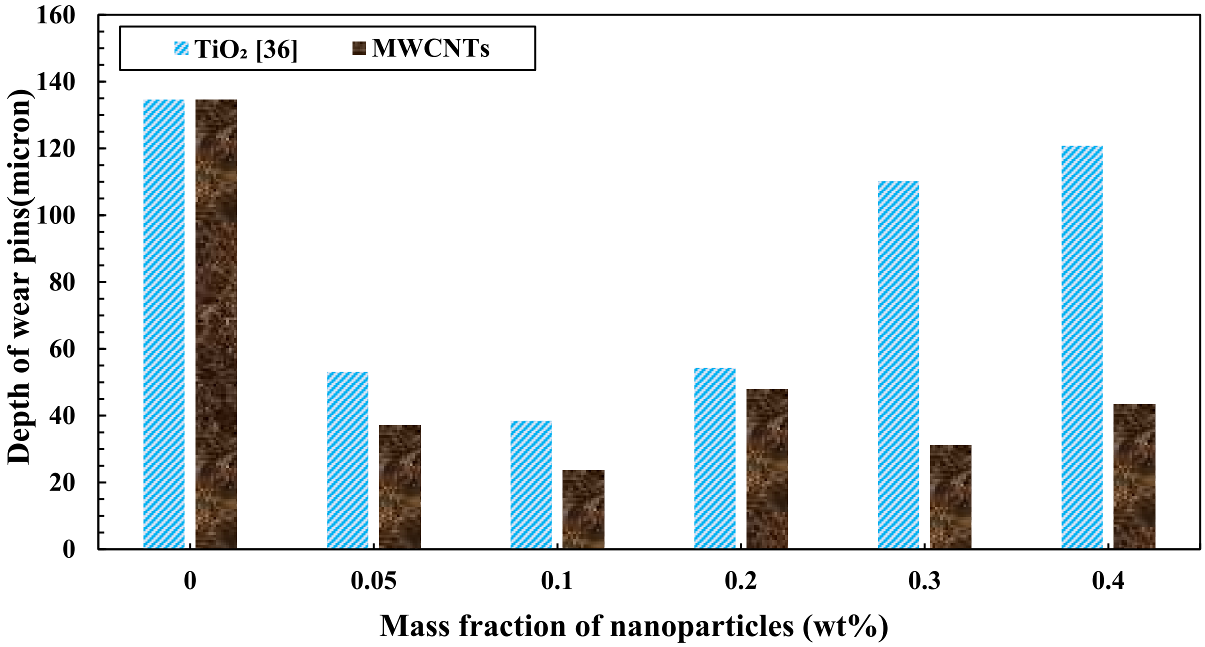
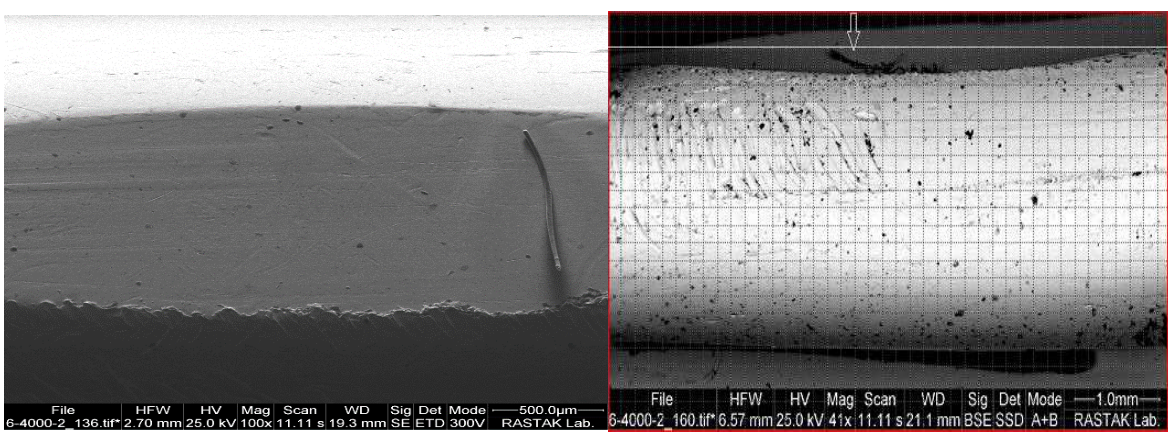
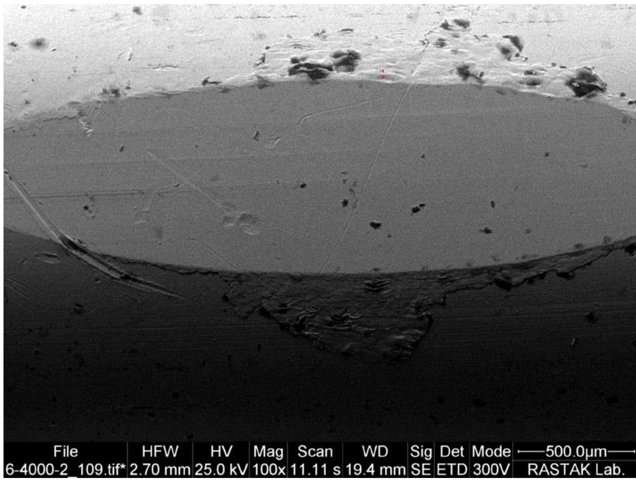
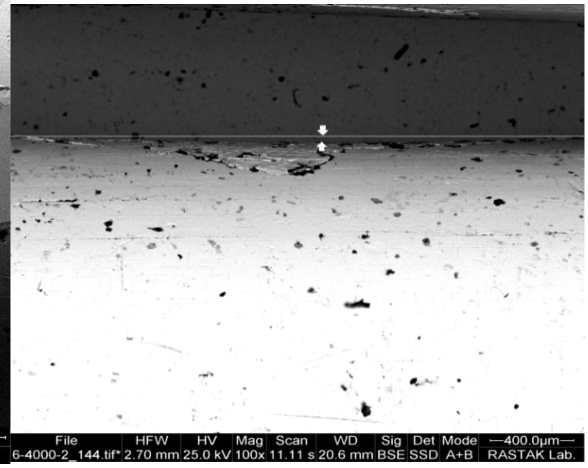



Figure 15. Comparison of the wear depth of copper pins with the addition of MWCNTs and$TiO_2$ to the pure oil

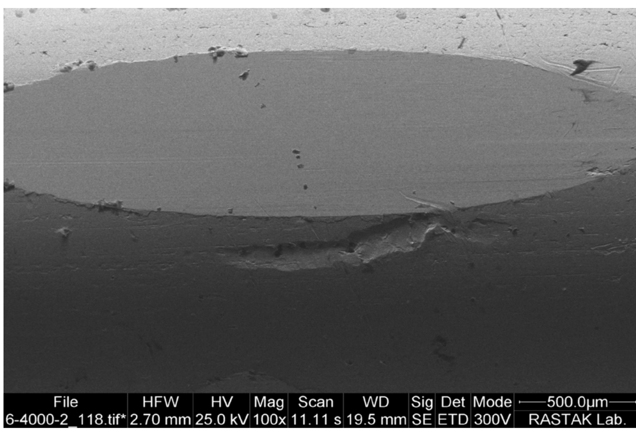


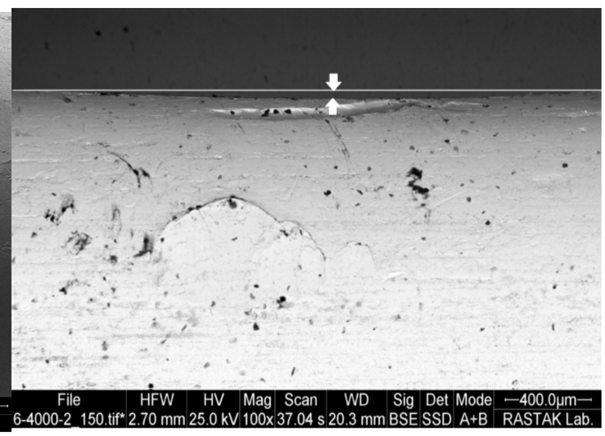

(16-1) (16-2)



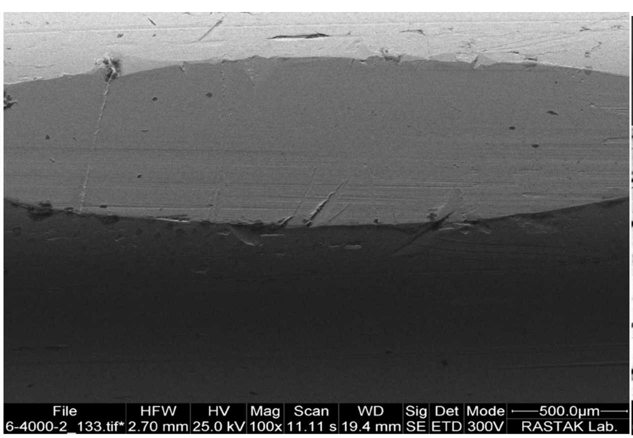



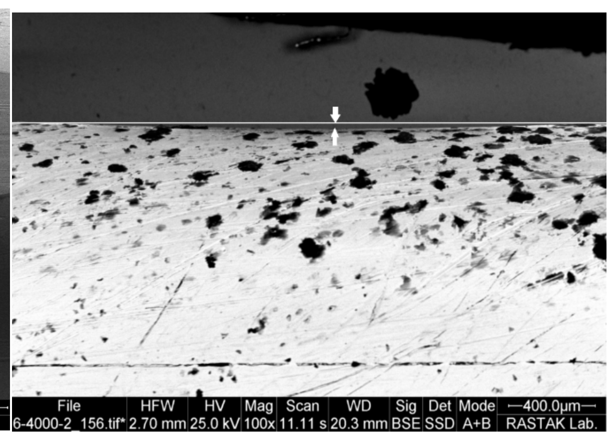

(16-3) (16-4)



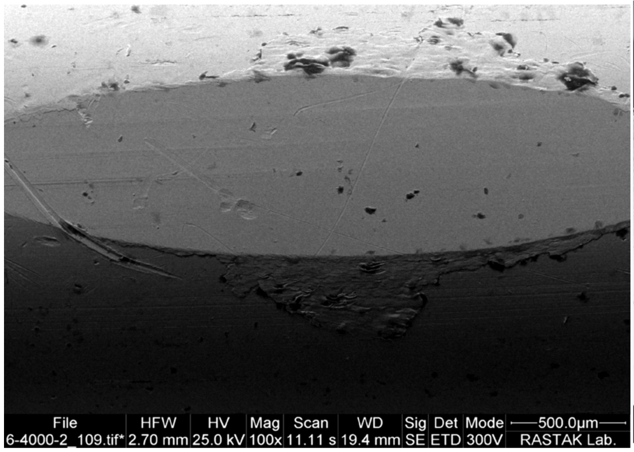




(16-5) (16-6)

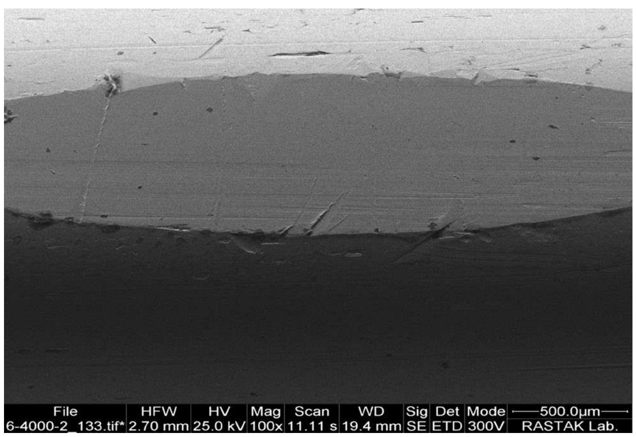


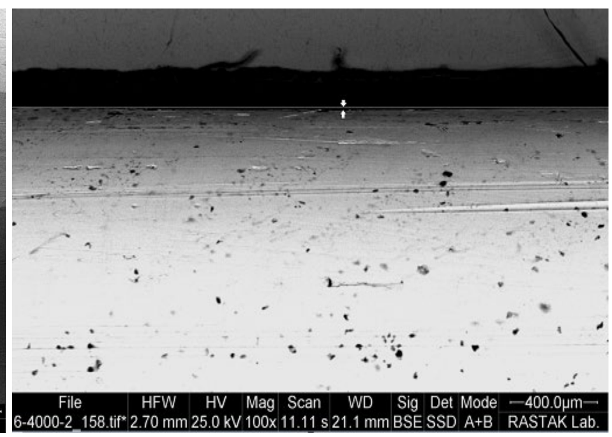




(16-7) (16-8)



(16-9) (16-10)





(16-11) (16-12)

Figure 16. The wear depth of copper pins in the presence of: (16-1,16-2) pure fluid [36], (16-3,16-4) nanofluid with 0.05 wt.% of MWCNTs , (16-5,16-6) nanofluid with 0.1 wt.% of MWCNTs, (16-7,16-8) nanofluid with 0.2 wt.% of MWCNTs, (16-9,16-10) nanofluid with 0.3 wt% of MWCNTs, (16-11,16-12) nanofluid with 0.4 wt.% of MWCNTs.

The average friction coefficient inside the copper tube with applying nanofluids as working fluids in the range of 0.05 wt.% to 0.4 wt.% of $TiO_2$ and MWCNTs nano additives was calculated. Also, the variation of the average friction coefficient inside the copper tube with the various velocity inlet of nanofluids that in the form experimental and simulation data is presented in Figure 17. The simulation data and experimental data are closer together or show a minor deviation that the maximum deviation is 0.051. With increasing velocity inlet of lubricants led to an enhancement in the Reynolds number, which led to a decline in the average friction coefficient. The average friction coefficient inside the copper tube with applying MWCNTs/turbine meter oil as a working fluid is a little more than the average friction coefficient of inside the copper tube with applying $TiO_2$/turbine meter oil as a working fluid that the maximum difference between them is 0.053 at the velocity inlet of 0.069 m/s.

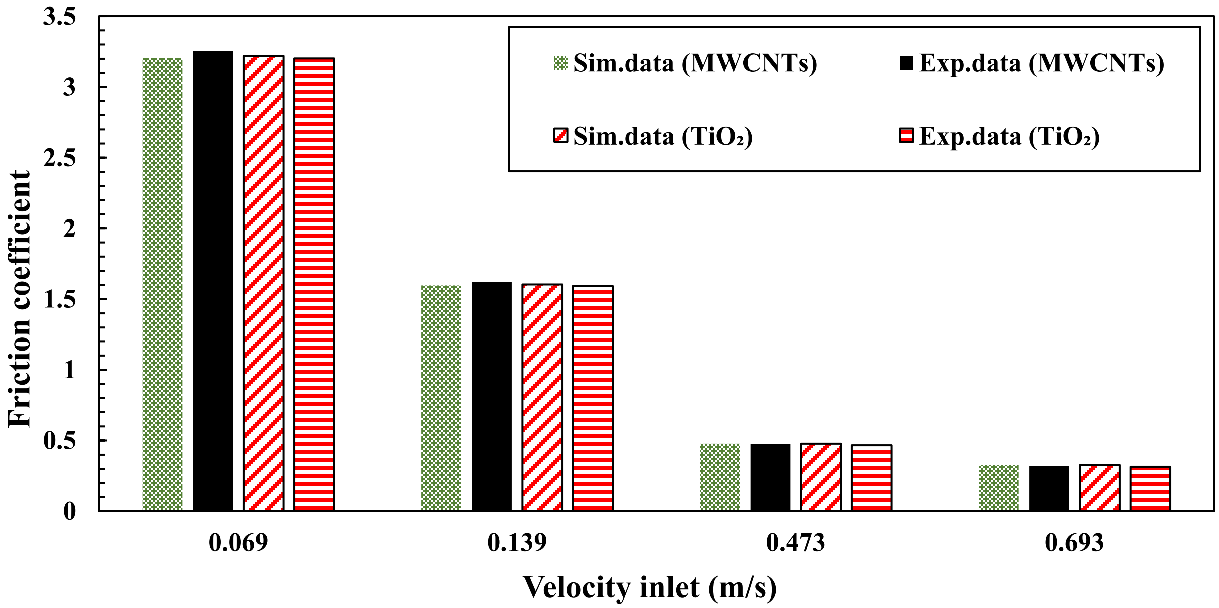



Figure 17. Comparison of experimental and simulation data of the average friction coefficient of the nanofluids in various values of velocity inlet in the range of 0.05 to 0.4 wt.% of $TiO_2$ and MWCNTs nano additives

The average friction coefficient inside the copper tube with applying nanofluid as a working fluid in the range of 0.069 m/s to 0.698 m/s velocity inlet of  nanofluid was calculated. Also, the variation of the average friction coefficient inside the copper tube with the addition of $TiO_2$ and MWCNTs nano additives with different mass fraction to pure oil that in the form experimental and simulation data are presented in Figure 18. The simulation data and experimental data for this test are closer together or indicate a minor deviation that the maximum deviation is 0.036. The addition of the mass fraction of $TiO_2$ and MWCNTs nano additives to the pure oil cause to increase in the average friction coefficient compared with the base oil. The maximum increase of the average friction coefficient (i.e., 9.36% and 6.14%, respectively) was obtained by increasing MWCNTs and $TiO_2$ nanoparticles to 0.3 wt.% and 0.4 wt.% to the pure oil, respectively. Increasing concentration of nano additives cause to increases in the viscosity of nano lubricant and pressure drop, which increases the friction coefficient in the same conditions.

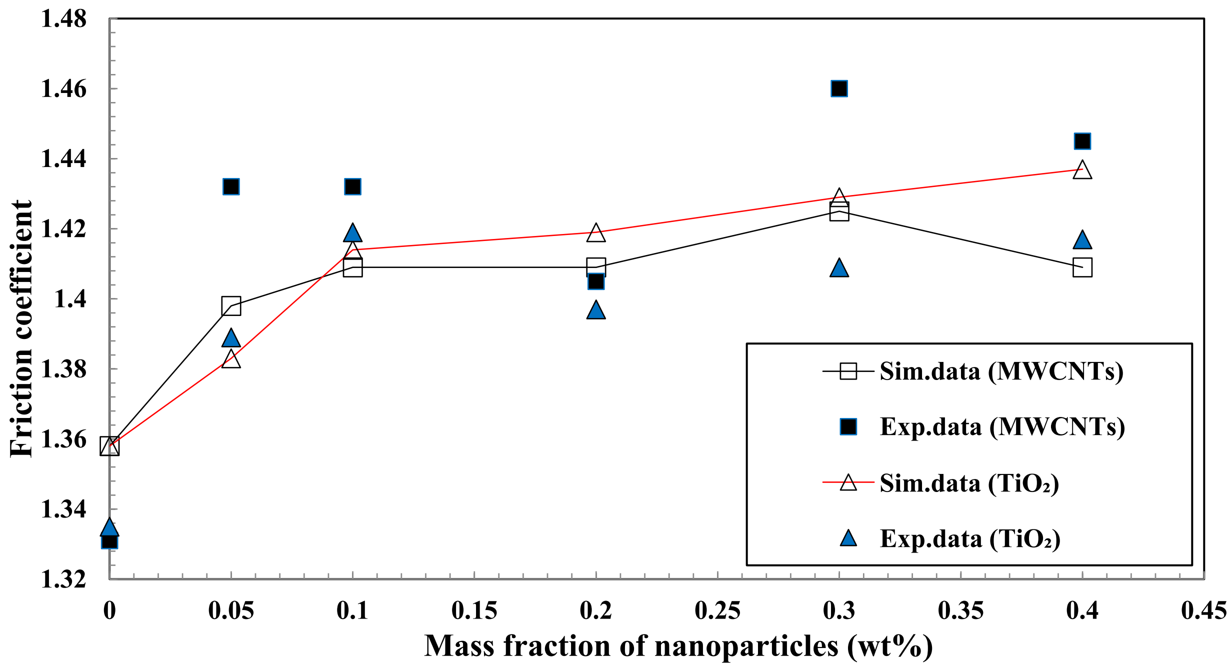



Figure 18. Comparison of experimental and simulation data of the average friction coefficient of the nanofluids in the different mass fraction of $TiO_2$ and MWCNTs nano additives in the range of 0.069 m/s to 0.698 m/s velocity inlet

Figures 19 and 20 illustrate the simulation data and experimental data for the pressure drop changes of the nano lubricant with the addition of $TiO_2$ and MWCNTs nano additives in the mass fraction of 0.05 wt.%, 0.1 wt.%, 0.2 wt.%, 0.3 wt.%, and 0.4 wt.% in the various velocity inlet boundary conditions. The simulation data and experimental data for the pressure drop are closer together and indicate a minor error that the maximum error is less than 10%. Increasing of MWCNTs and $TiO_2$ to the base oil causes to increase in the pressure drop compared to the base oil. Also, the increasing of the velocity inlet increases in the pressure drop compared to the pure lubricant, but the effect of increasing the velocity inlet of the nanofluids on the pressure drop is greater than the effect of adding nanoparticles to the pure fluids on the pressure drop. The maximum value of pressure drop of MWCNTs/turbine meter oil nanofluid with 0.3 wt.% of MWCNTs at the velocity inlet of 0.698 m/s was 7706.88(Pa). The maximum value of pressure drop of $TiO_2$/turbine meter oil nanofluid with 0.4 wt.% of $TiO_2$ at the velocity inlet of 0.698 m/s was 7706.89(Pa).

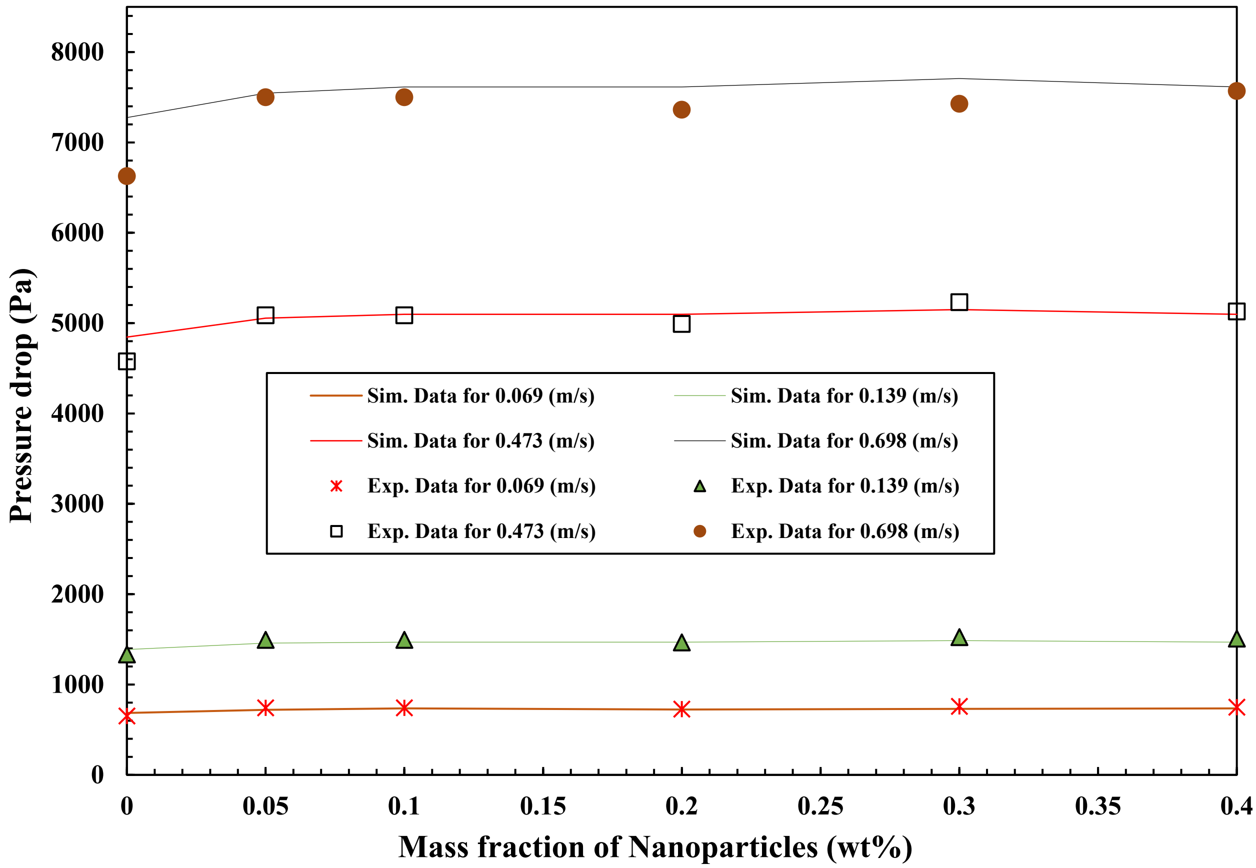



Figure 19. Comparison of experimental and simulation data of the pressure drop of the nanofluids in different mass fraction of MWCNTs nano additives

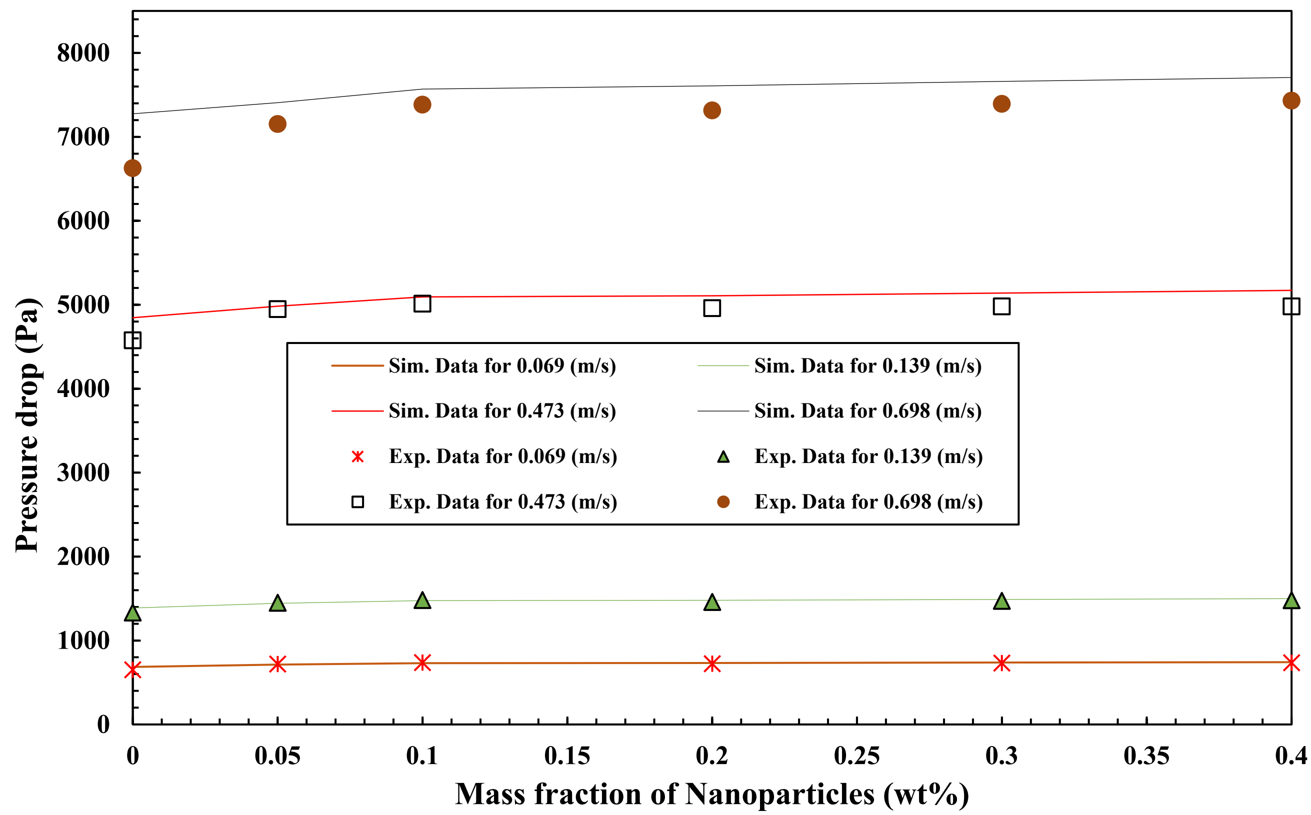



Figure 20. Comparison of experimental and simulation data of the pressure drop of the nanofluids in different mass fraction of $TiO_2$ nano additives

## 5. Conclusion

The impact of MWCNT/turbine meter oil nano lubricant and $TiO_2$/turbine meter oil nano lubricants with the different mass fraction of MWCNTs and $TiO_2$ (0.05 wt.% - 0.4 wt%) and temperature measuring range from 30 °C to 100 °C on the average friction coefficient, pressure drop, pour point, flash point, relative viscosity, kinematic viscosity, viscosity index and average friction coefficient were investigated. Also, The pressure drop and the average friction coefficient inside the copper tube were simulated and compared with experimental results. From the obtained experimental and simulation results, the following conclusions are made:

1. With the addition of $TiO_2$ and MWCNTs nano additives to the pure lubricant, the kinematic viscosity of the nano lubricants in different percentages of nano additives relative to the pure lubricant enhanced at all temperature ranges.

2. The correlation outputs and experimental data of relative viscosity are closer together or show a minor deviation that calculation of Margin of deviation indicates the maximum deviation margin was 1%.

3. According to the results, the wear depth of copper pins with increasing of MWCNTs to pure lubricant has been improved compared with increasing of $TiO_2$ nano additive to pure lubricant.

4. The average friction coefficient inside the copper tube with applying MWCNTs/turbine meter oil as a working fluid is a little more than the average friction coefficient of inside the copper tube with applying $TiO_2$/turbine meter oil as a working fluid that the maximum difference between them is 0.053 at the velocity inlet of 0.069 m/s.

5. Nano lubricants with 0.1 wt.% of $TiO_2$ and 0.4 wt.% of MWCNTs nano additives illustrated the maximum improvement in the pour point temperature with decrease 1.2 °C and 2.6 °C compared to the pour point temperature of pure oil, respectively.

6. Nano lubricants with 0.4 wt.% of $TiO_2$ and 0.3 wt.% of MWCNTs nano additives illustrated the maximum percentage of increase the average friction coefficient with increasing of 6.14% and 9.36% compared to the pure lubricant, respectively.

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## Author Contribution

H. Pourpasha is done the experiments and drafted the manuscript text and provide the figures and tables as his M.S. final project. S. Zeinali Heris is supervisor of M.S. thesis and all experiments is done under his supervision and manuscript text, figures and tables are rewritten based on his comments. Y. Mohammadfam is checked all manuscript and commented for improving it and also proposed to add some new experimental results to manuscript.

## Additional Information

**Competing Interests:** The authors declare no competing interests.

**Figure captions and tables:**

Table 1. Nano additives characteristics

Table 2. Oil characteristics

Table 3: Mesh independence analysis mesh independence analysis in three different mesh size for turbine meter oil as the operating fluid with a velocity inlet of 0.069 [35]

Table 4: Comparison of the kinematic viscosity for $TiO_2$/turbine meter oil and MWCNTs/turbine meter oil lubricants at different temperatures.

Figure 1. Schematic of the experimental system

Figure 2. Schematic of the wear apparatus

Figure 3. Schematic and mesh diagram of copper tube

Figure 4. SEM images of the $TiO_2$ nanoparticles [36].

Figure 5. SEM images of the MWCNTs nanoparticles [35].

Figure 6. DLS images of the $TiO_2$ nanoparticles.

Figure 7. DLS images of the MWCNTs nanoparticles [35].

Figure 8. Comparison of the kinematic viscosity of $TiO_2$/turbine meter oil and MWCNTs/turbine meter oil nanofluids in different mass fraction at 40°C and 100°C.

Figure 9. Comparison of viscosity index of $TiO_2$/turbine meter oil and MWCNTs/turbine meter oil nanofluids.

Figure 10. Variation of relative viscosity of MWCNTs/turbine meter nanofluids in different mass fraction

Figure 11. Variation of relative viscosity of $TiO_2$/turbine meter nanofluids in different mass fraction

Figure 12. Variation of relative viscosity of $TiO_2$/turbine meter and MWCNTs/turbine meter oil nanofluids in different mass fraction

Figure 13. Comparison of pour point of $TiO_2$/turbine meter oil and MWCNTs/turbine meter oil nanofluids in different mass fraction

Figure 14. Comparison of flash point of $TiO_2$/turbine meter oil and MWCNTs/turbine meter oil nanofluids in different mass fraction.

Figure 15. Comparison of the wear depth of copper pins with the addition of MWCNTs and$TiO_2$ to the pure oil

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Figure 17. Comparison of experimental and simulation data of the average friction coefficient of the nanofluids in various values of velocity inlet in the range of 0.05 to 0.4 wt.% of $TiO_2$ and MWCNTs nano additives

Figure 18. Comparison of experimental and simulation data of the average friction coefficient of the nanofluids in the different mass fraction of $TiO_2$ and MWCNTs nano additives in the range of 0.069 m/s to 0.698 m/s velocity inlet

Figure 19. Comparison of experimental and simulation data of the pressure drop of the nanofluids in different mass fraction of MWCNTs nano additives

Figure 20. Comparison of experimental and simulation data of the pressure drop of the nanofluids in different mass fraction of $TiO_2$ nano additives

# Figures

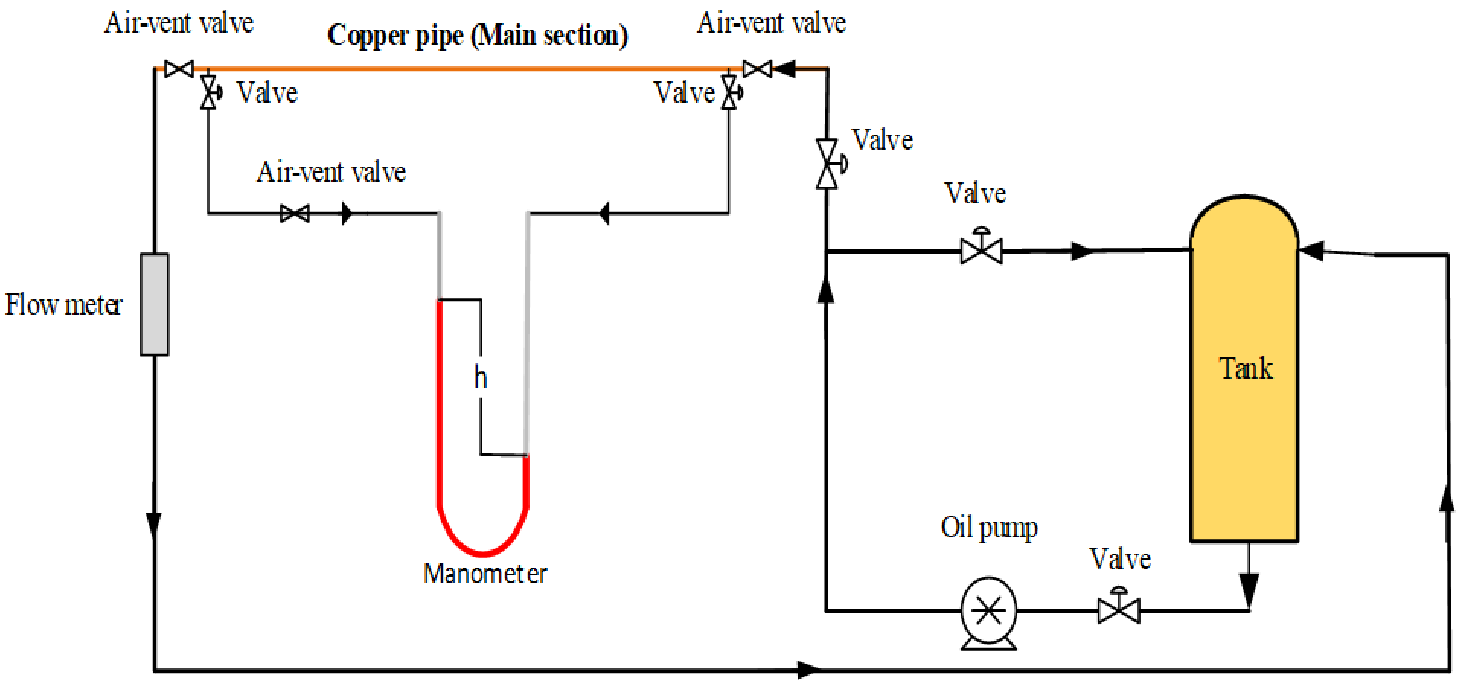
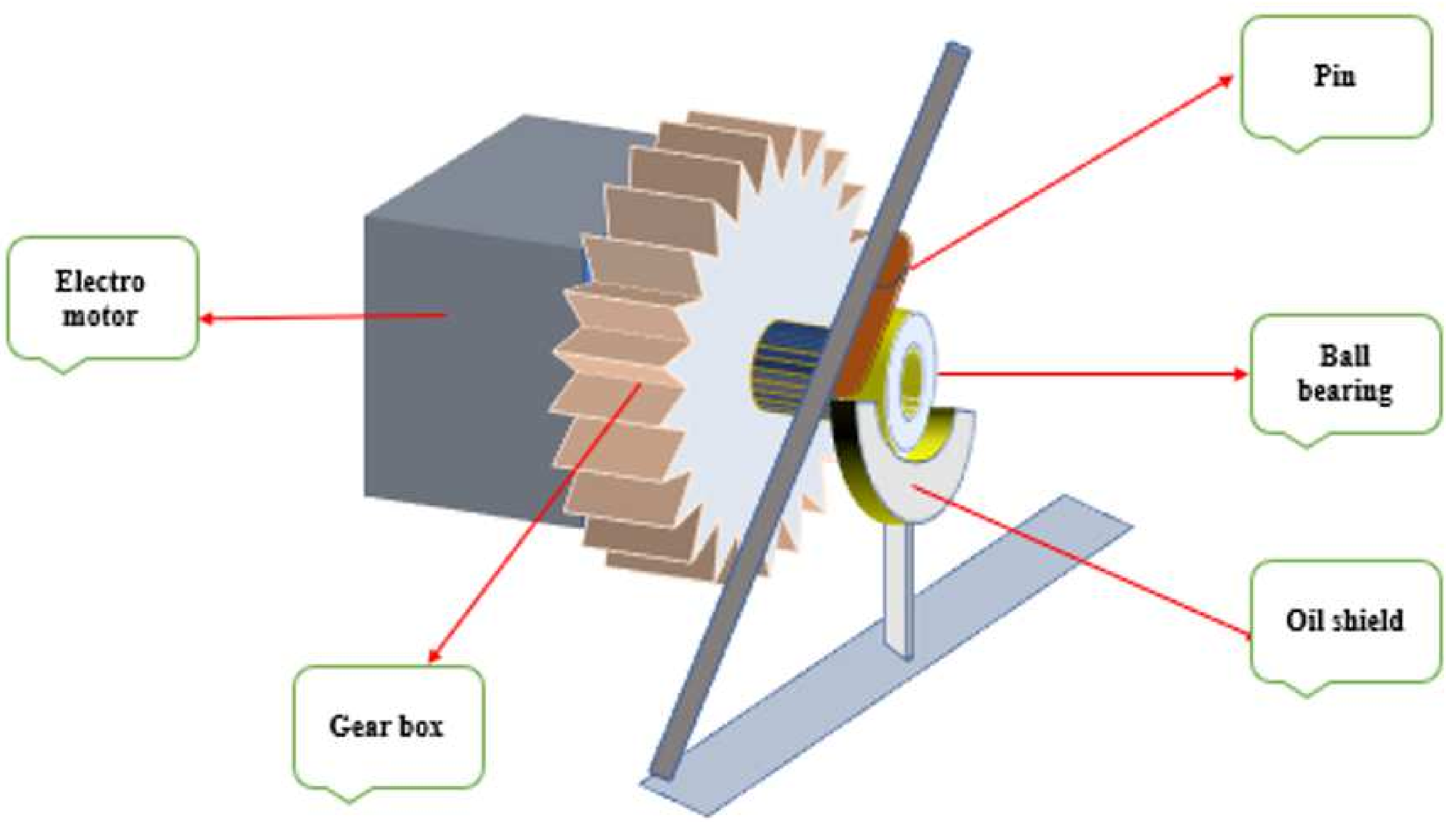


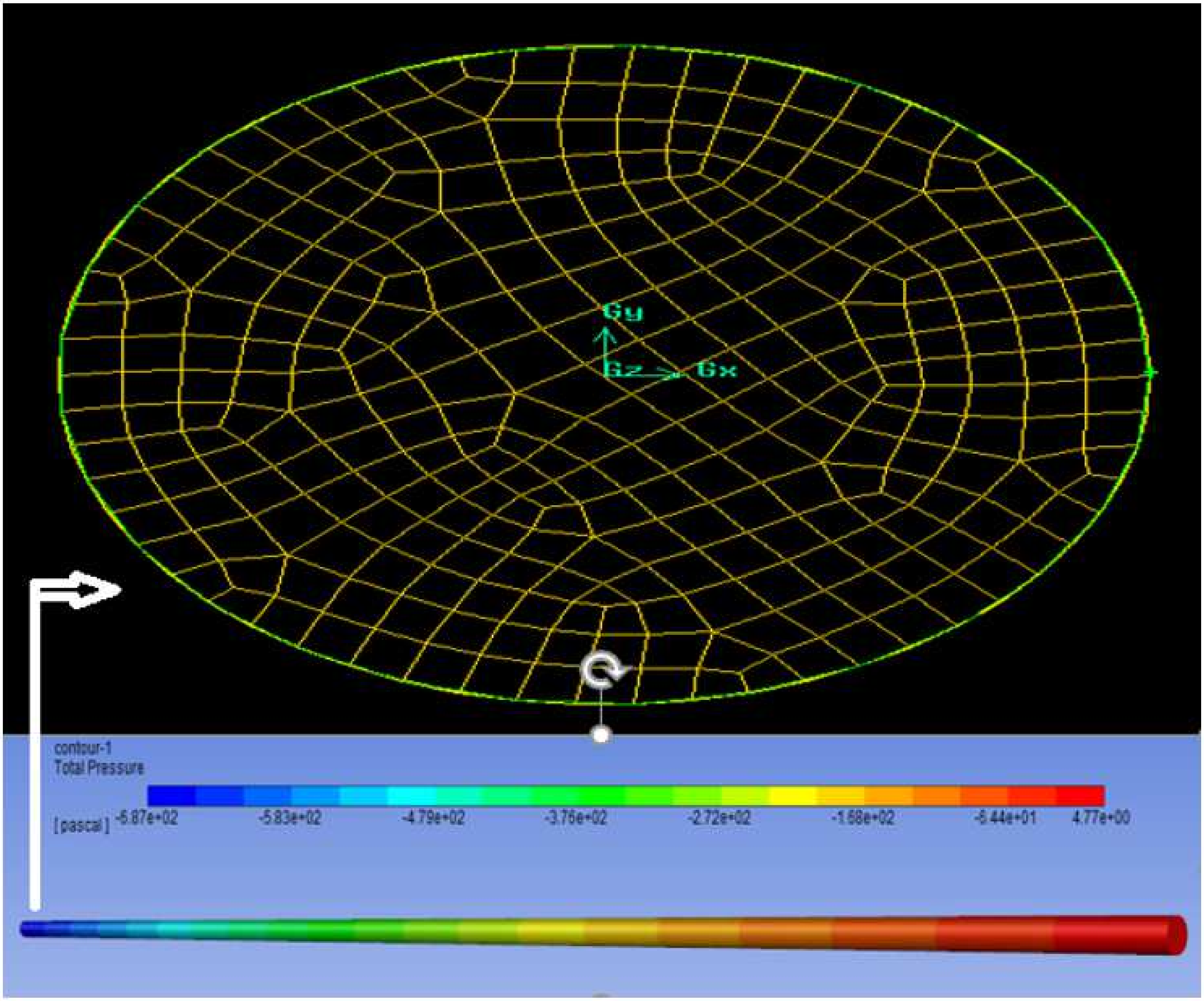

**Figure 1**

Schematic of the experimental system



## Figure 2

Schematic of the wear apparatus




## Figure 3

Schematic and mesh diagram of copper tube

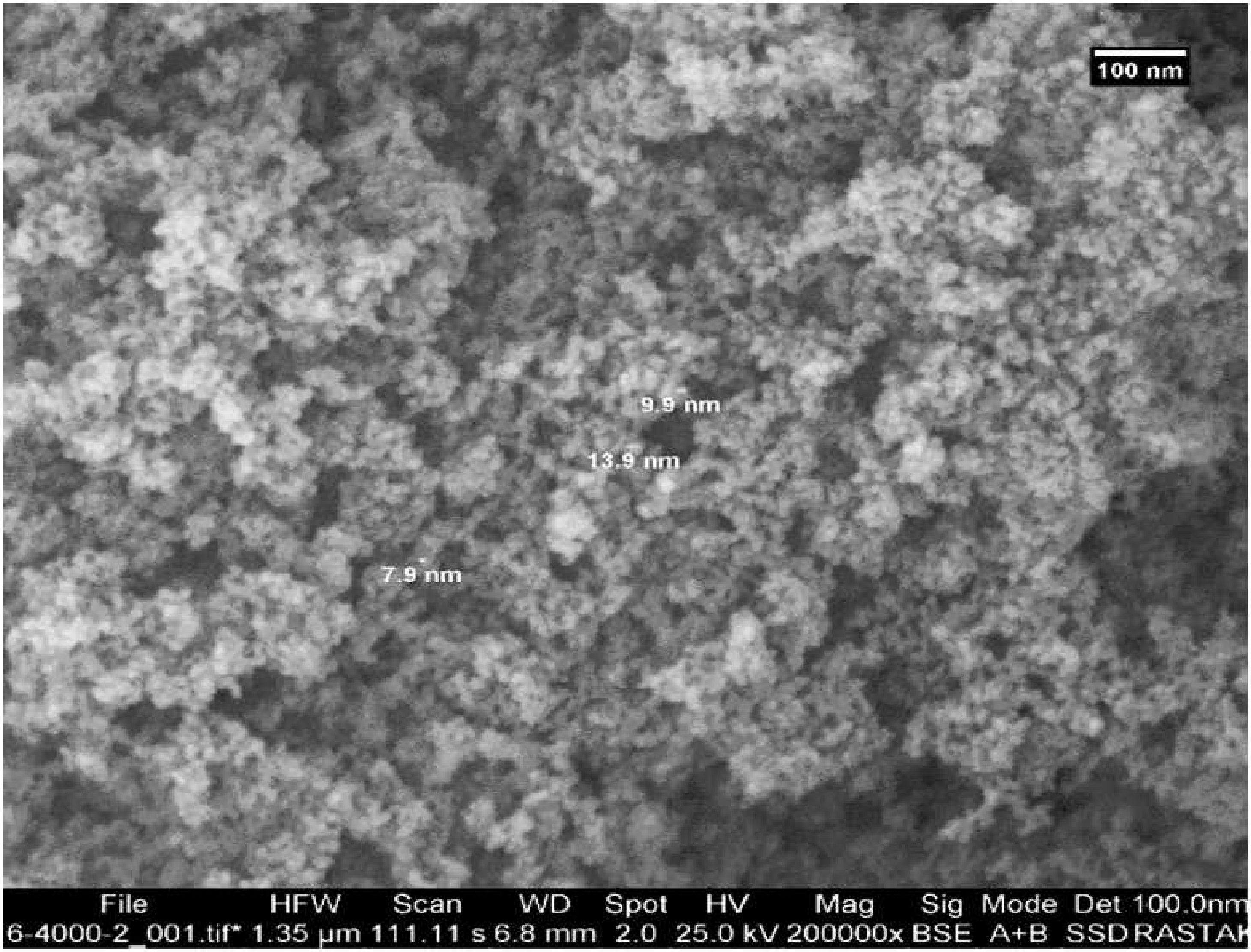



**Figure 4**

SEM images of the TiO2 nanoparticles [36].

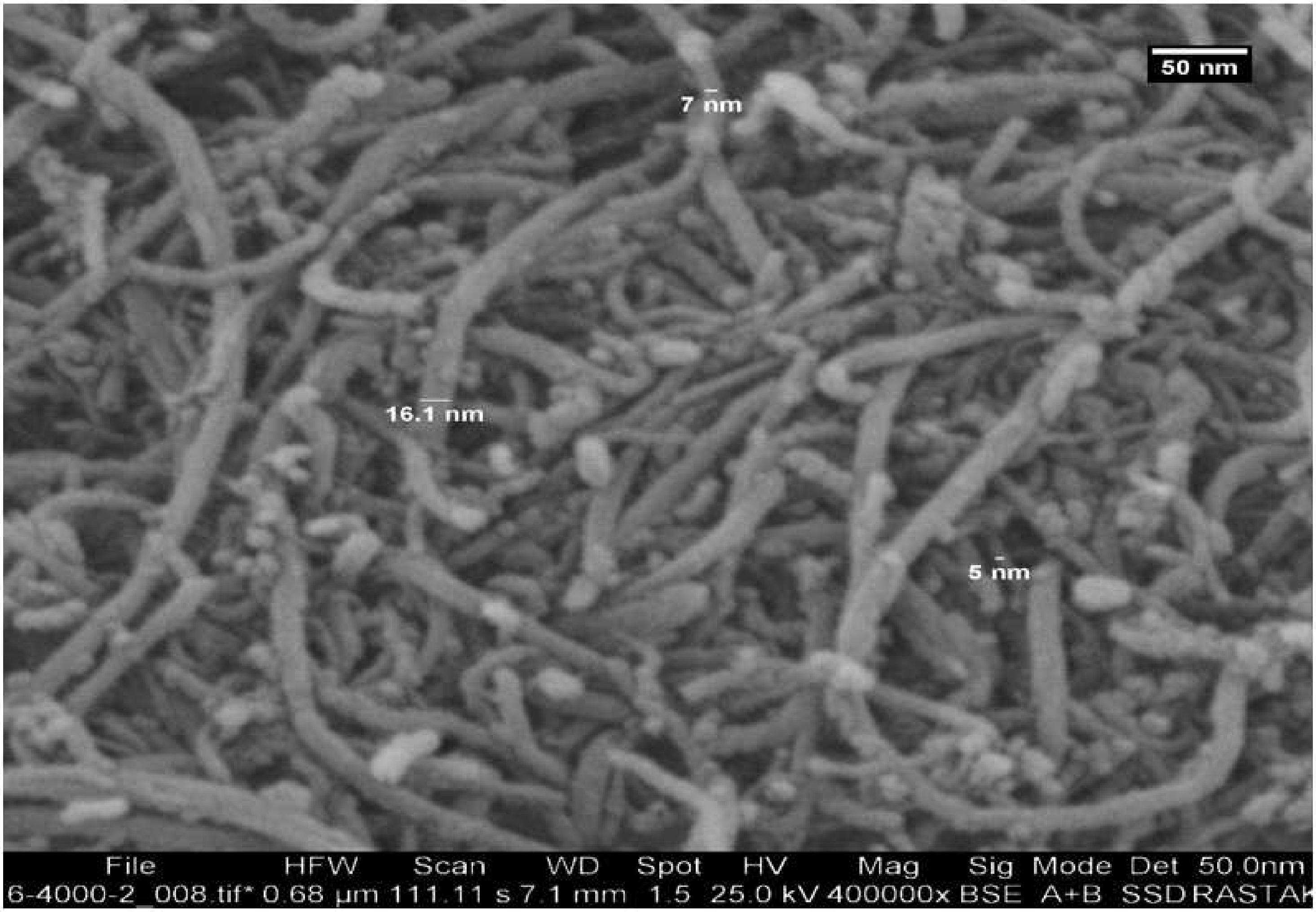



**Figure 5**

SEM images of the MWCNTs nanoparticles [35].

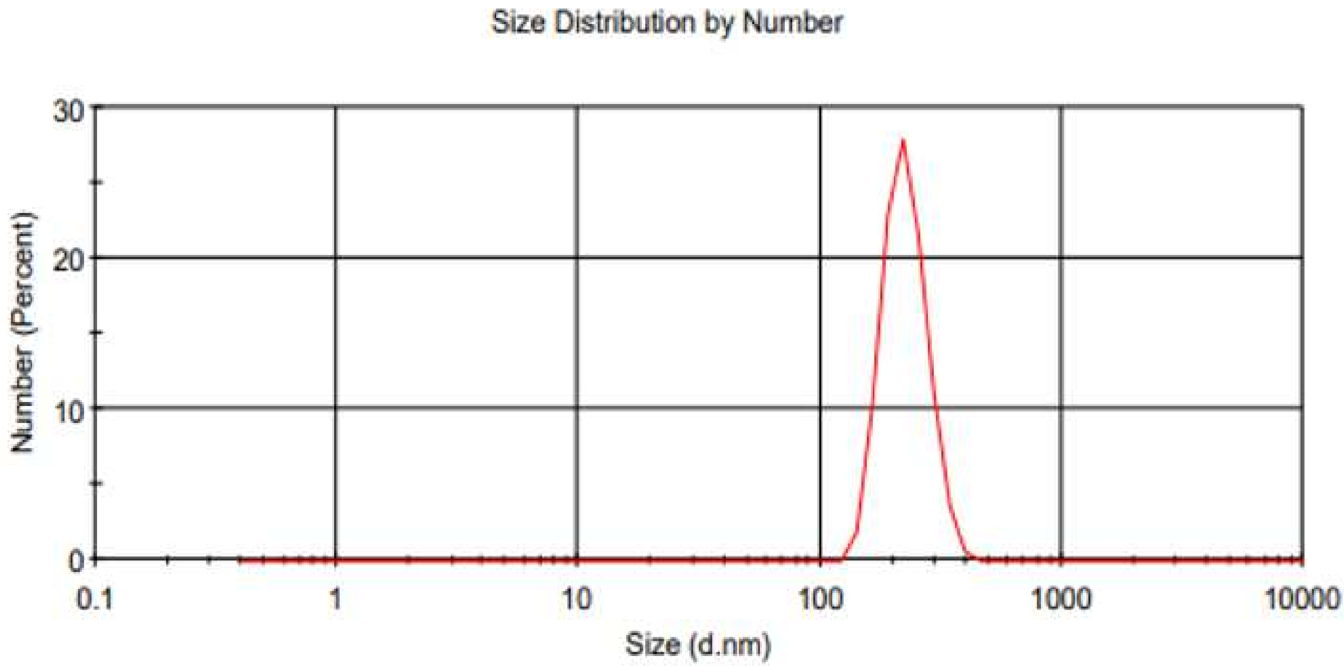



**Figure 6**

DLS images of the $TiO_2$ nanoparticles.

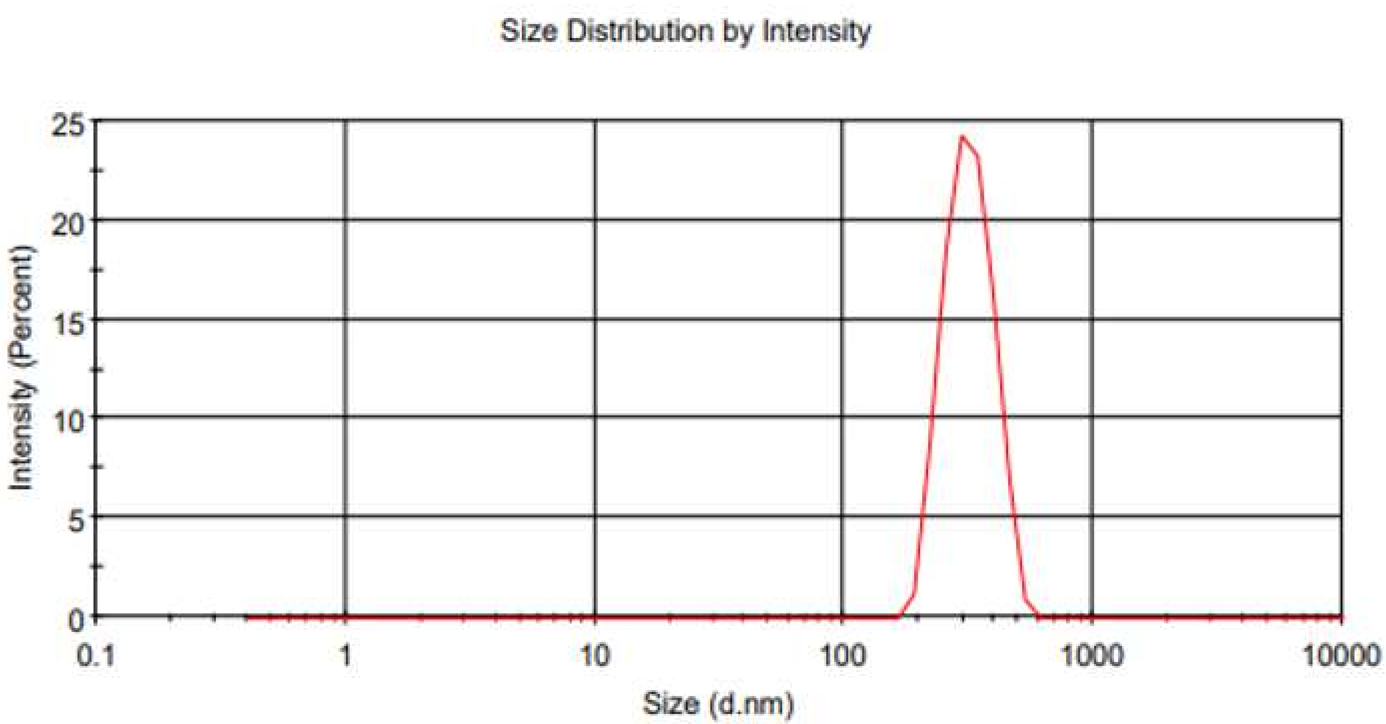
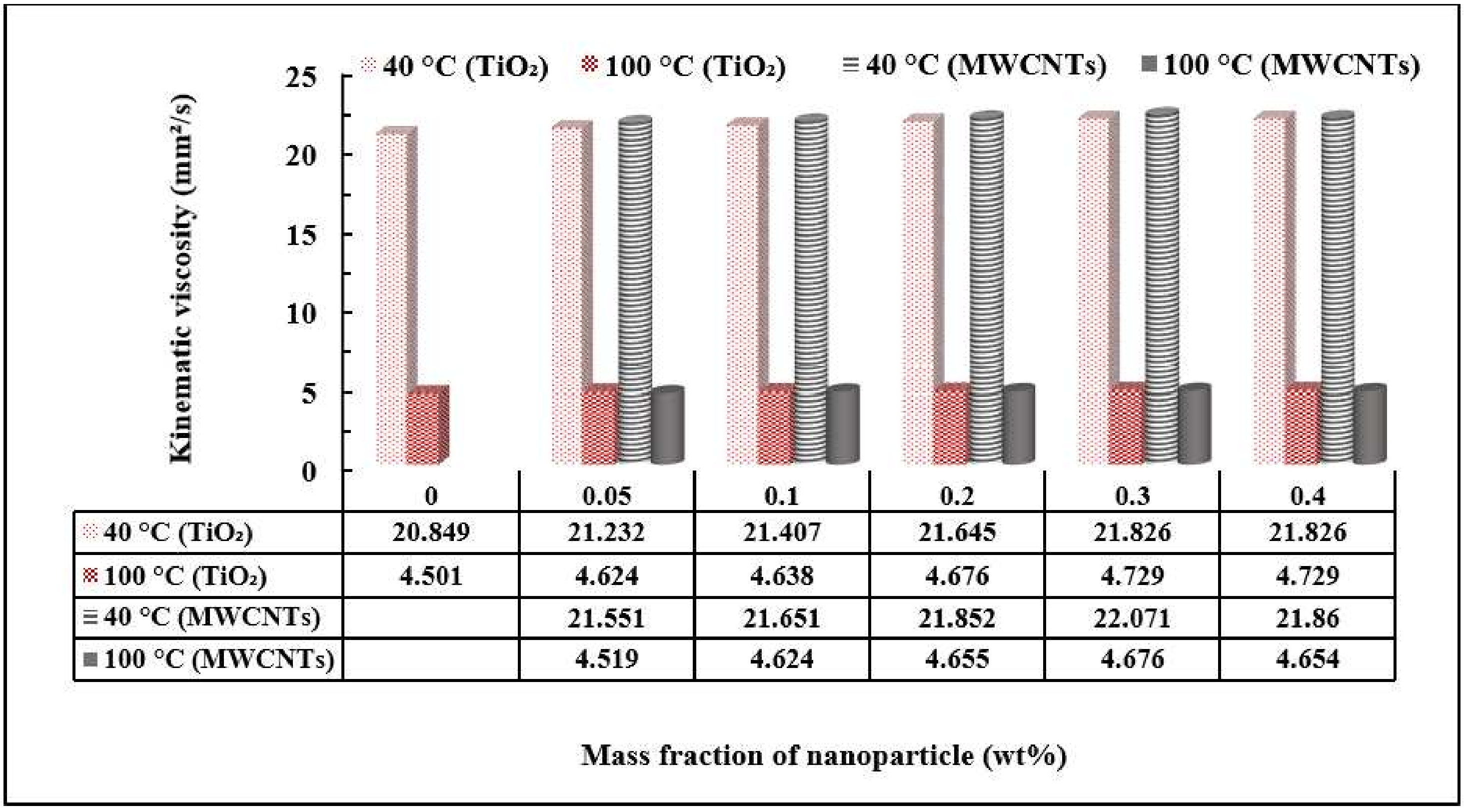



**Figure 7**

DLS images of the MWCNTs nanoparticles [35].




## Figure 8

Comparison of the kinematic viscosity of TiO2/turbine meter oil and MWCNTs/turbine meter oil nanofluids in different mass fraction at 40°C and 100°C.

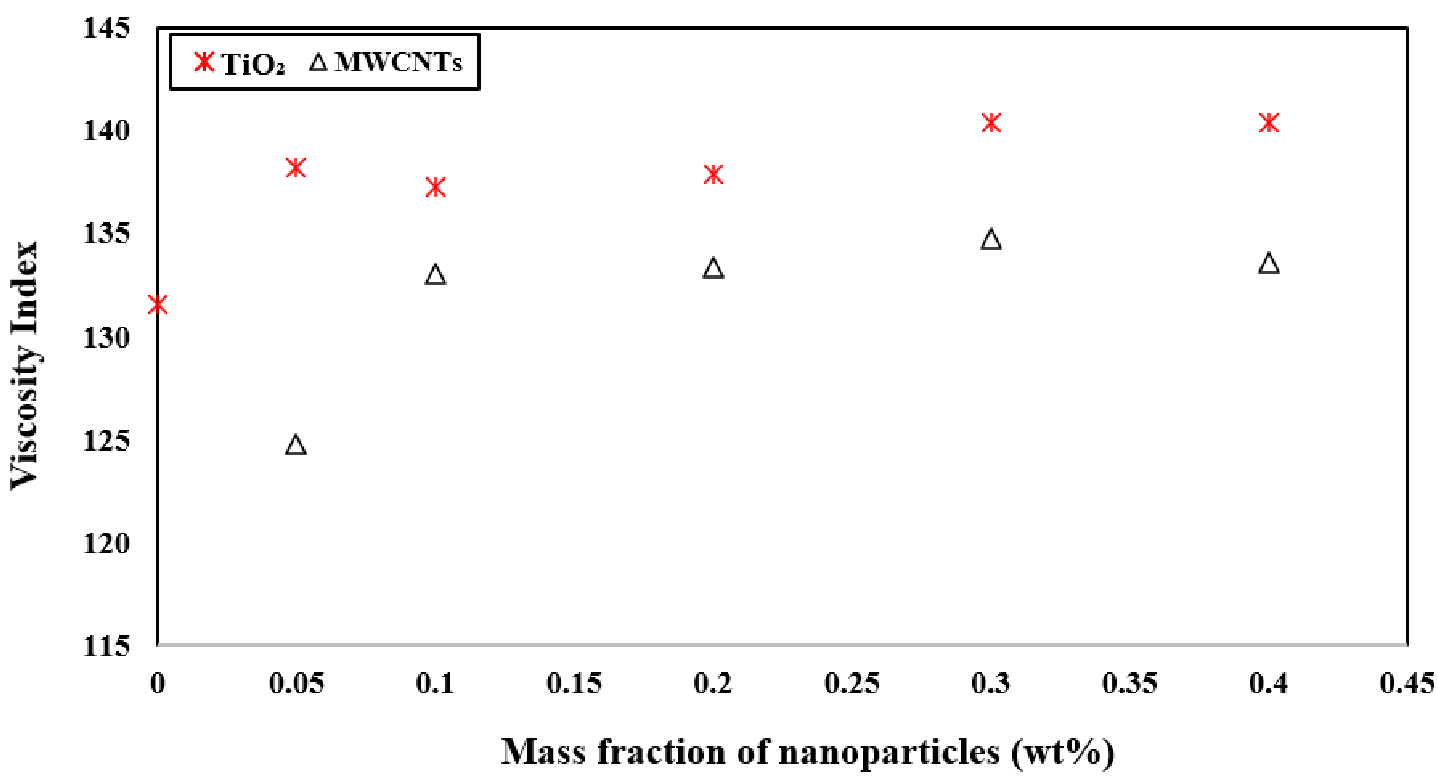


Figure 9

Comparison of viscosity index of TiO2/turbine meter oil and MWCNTs/turbine meter oil nanofluids.

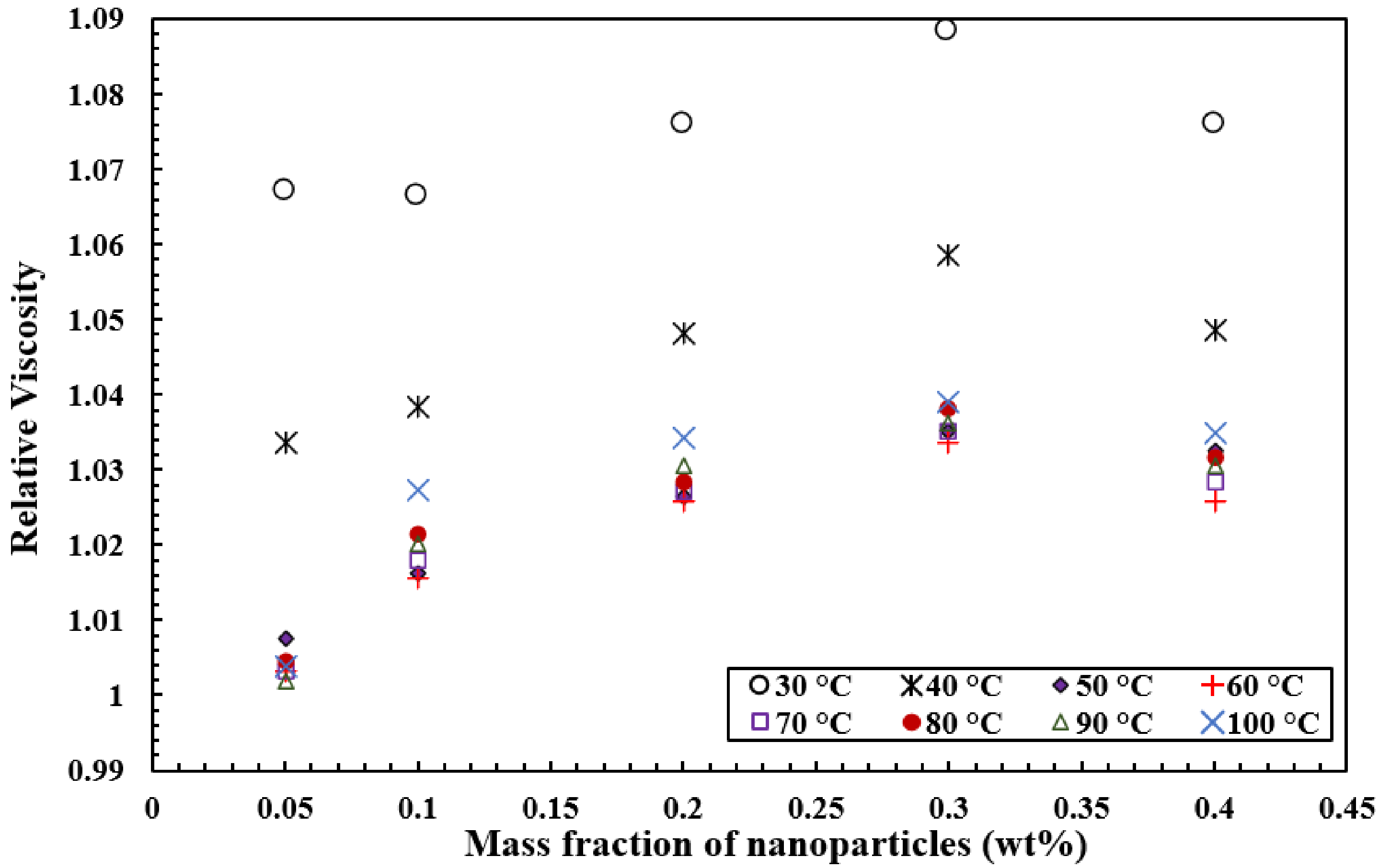



Figure 10

Variation of relative viscosity of MWCNTs/turbine meter nanofluids in different mass fraction

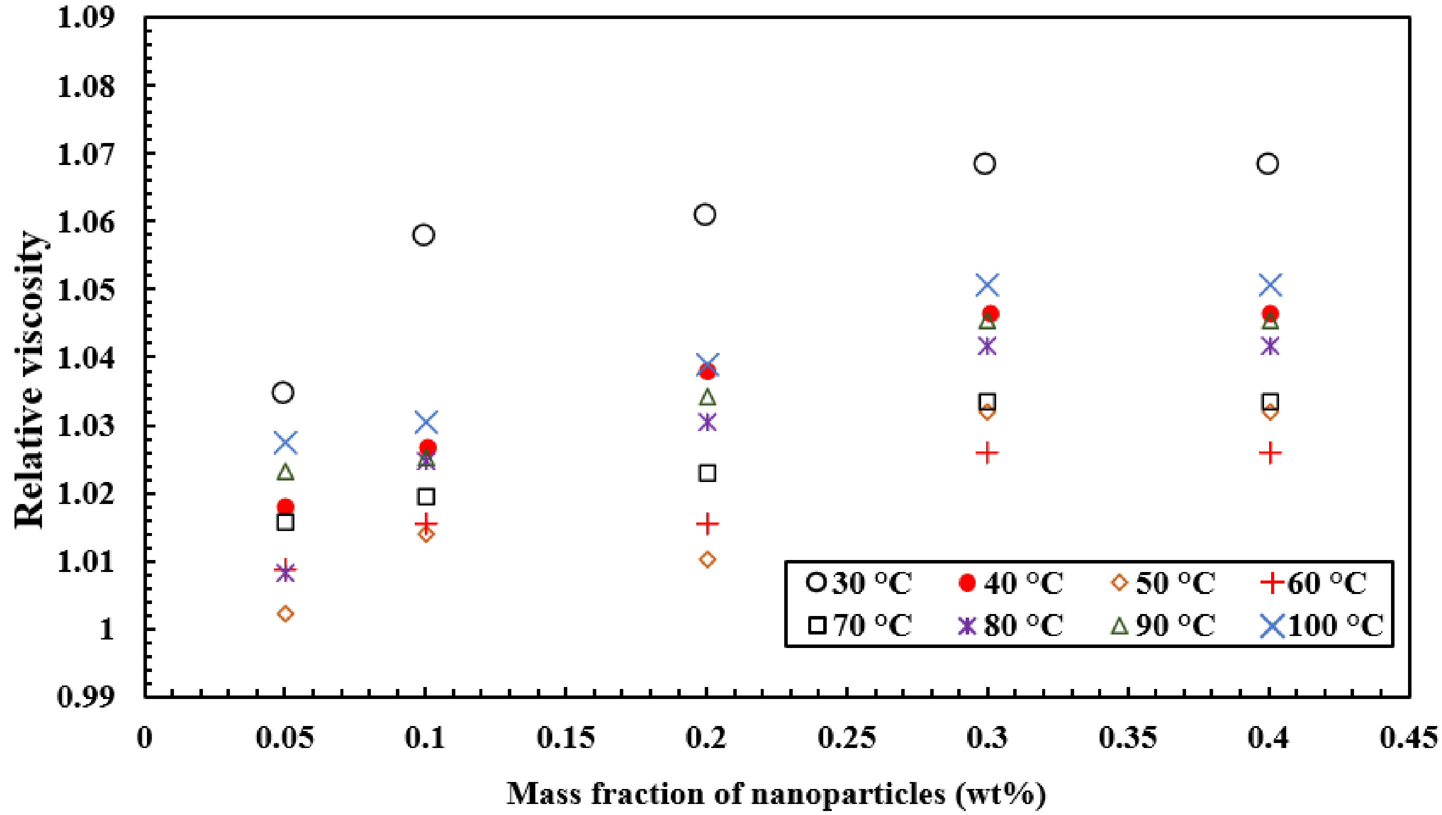
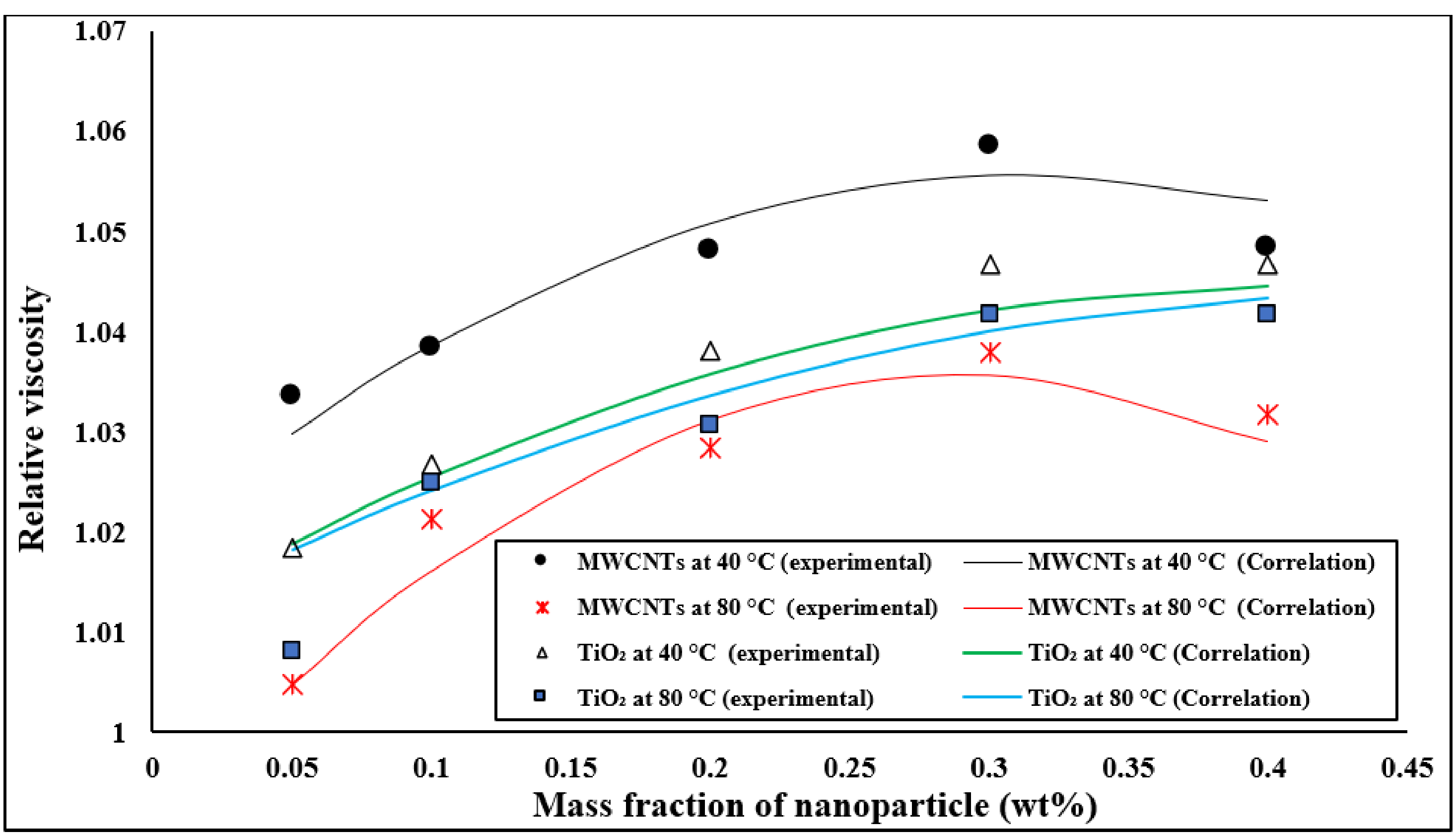


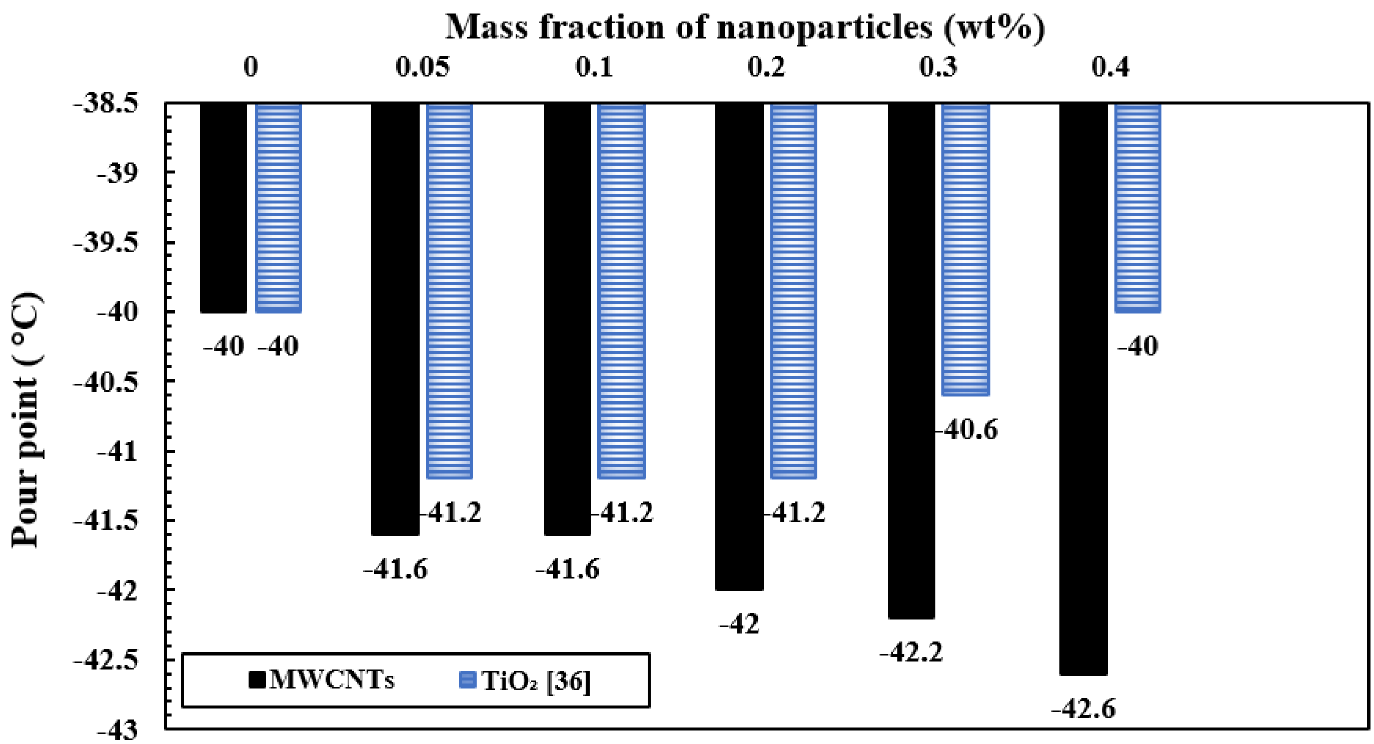

Figure 11

Variation of relative viscosity of TiO2/turbine meter nanofluids in different mass fraction



## Figure 12

Variation of relative viscosity of TiO2/turbine meter and MWCNTs/turbine meter oil nanofluids in different mass fraction




## Figure 13

Comparison of pour point of TiO2/turbine meter oil and MWCNTs/turbine meter oil nanofluids in different mass fraction

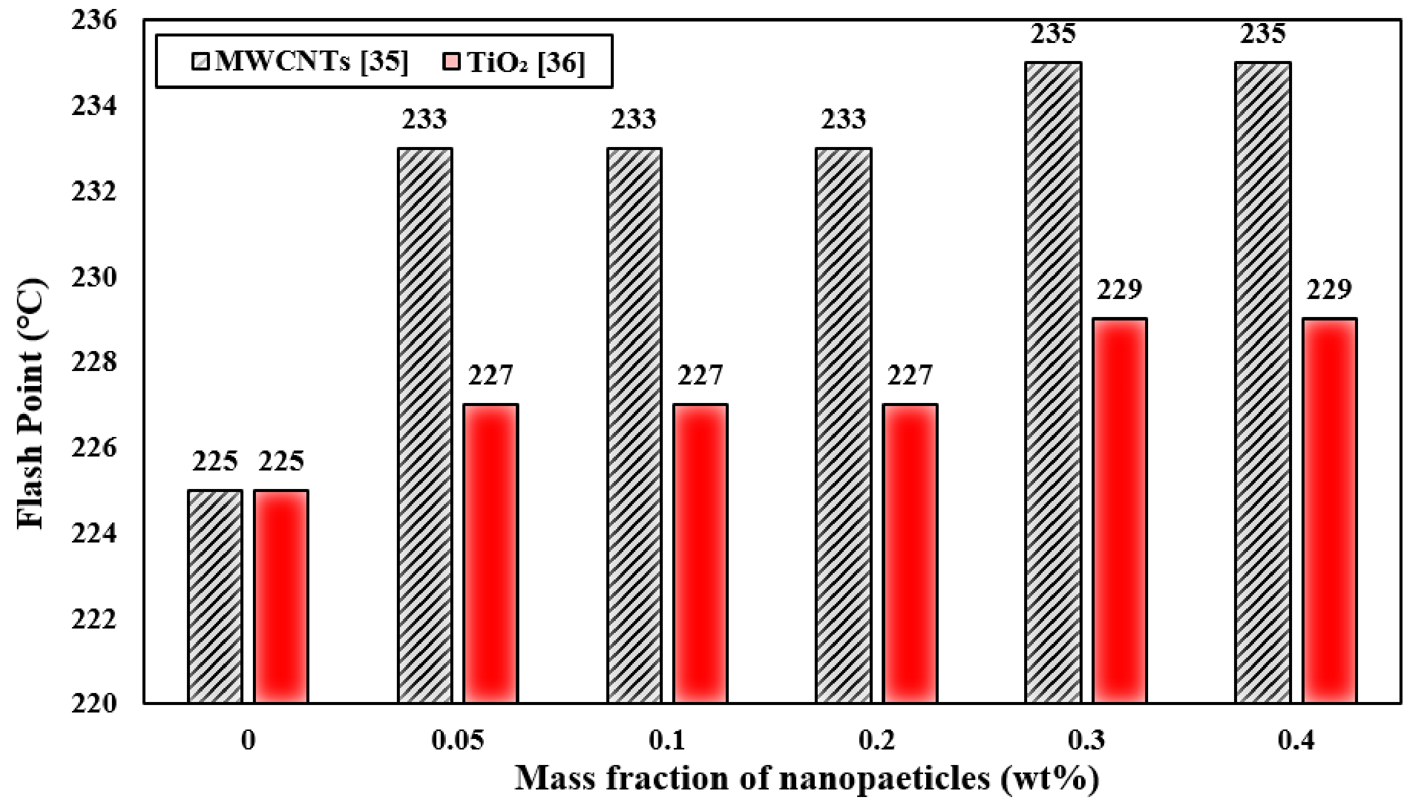
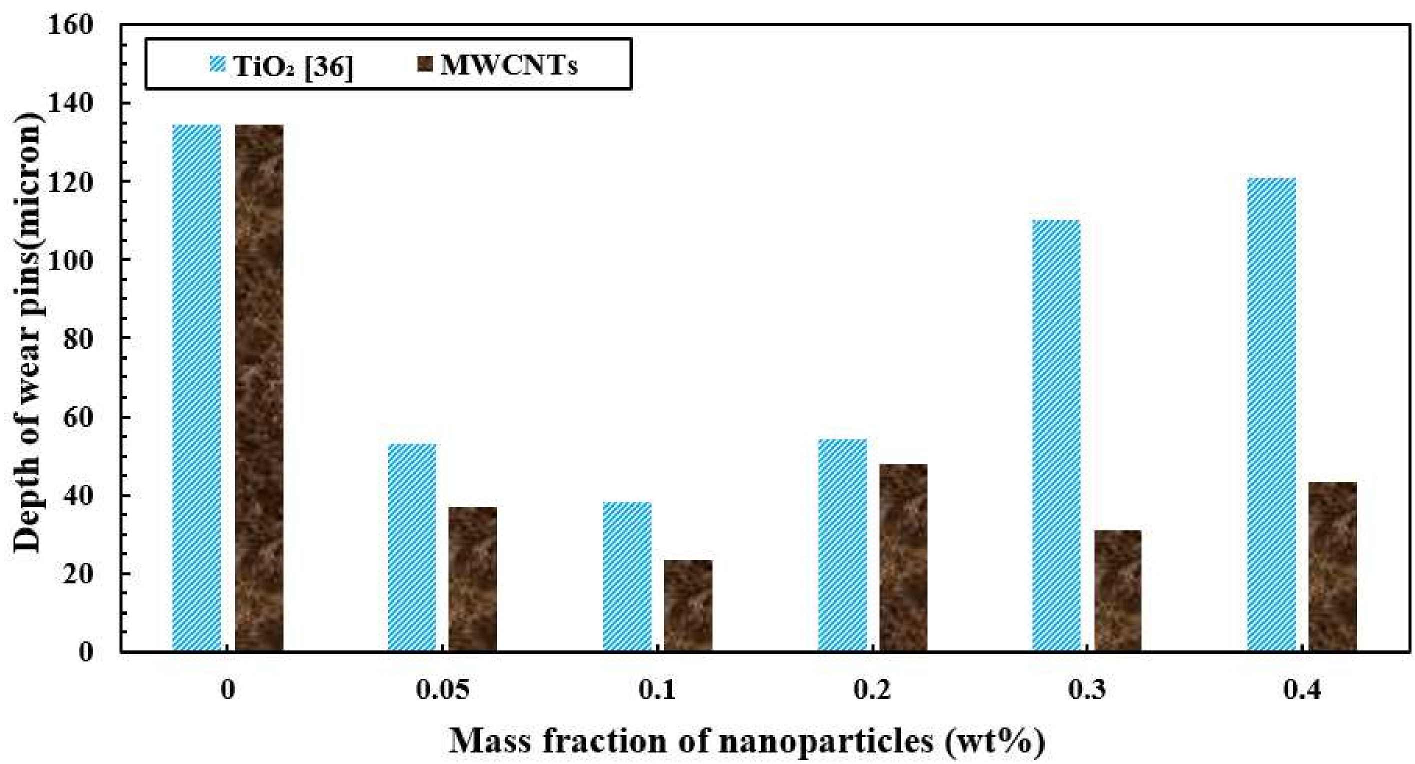


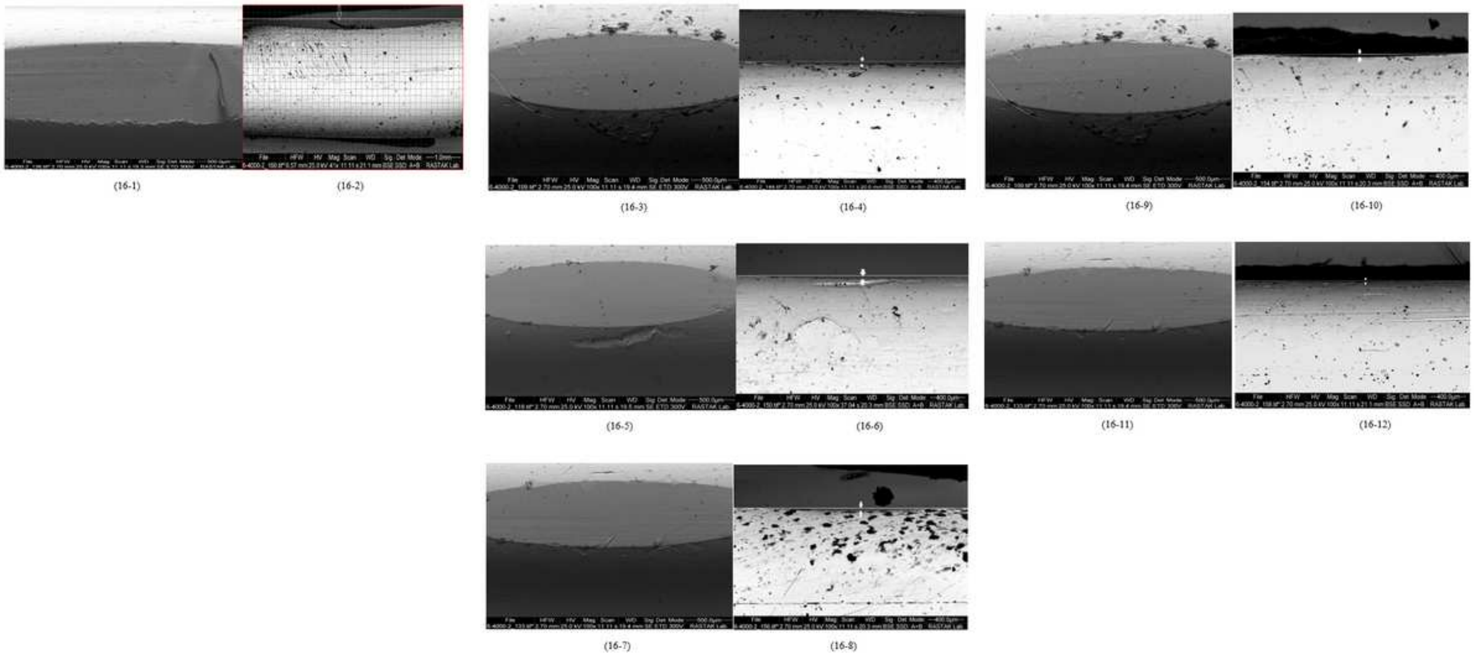

Figure 14

Comparison of flash point of TiO2/turbine meter oil and MWCNTs/turbine meter oil nanofluids in different mass fraction.



## Figure 15

Comparison of the wear depth of copper pins with the addition of MWCNTs andTiO2 to the pure oil




## Figure 16

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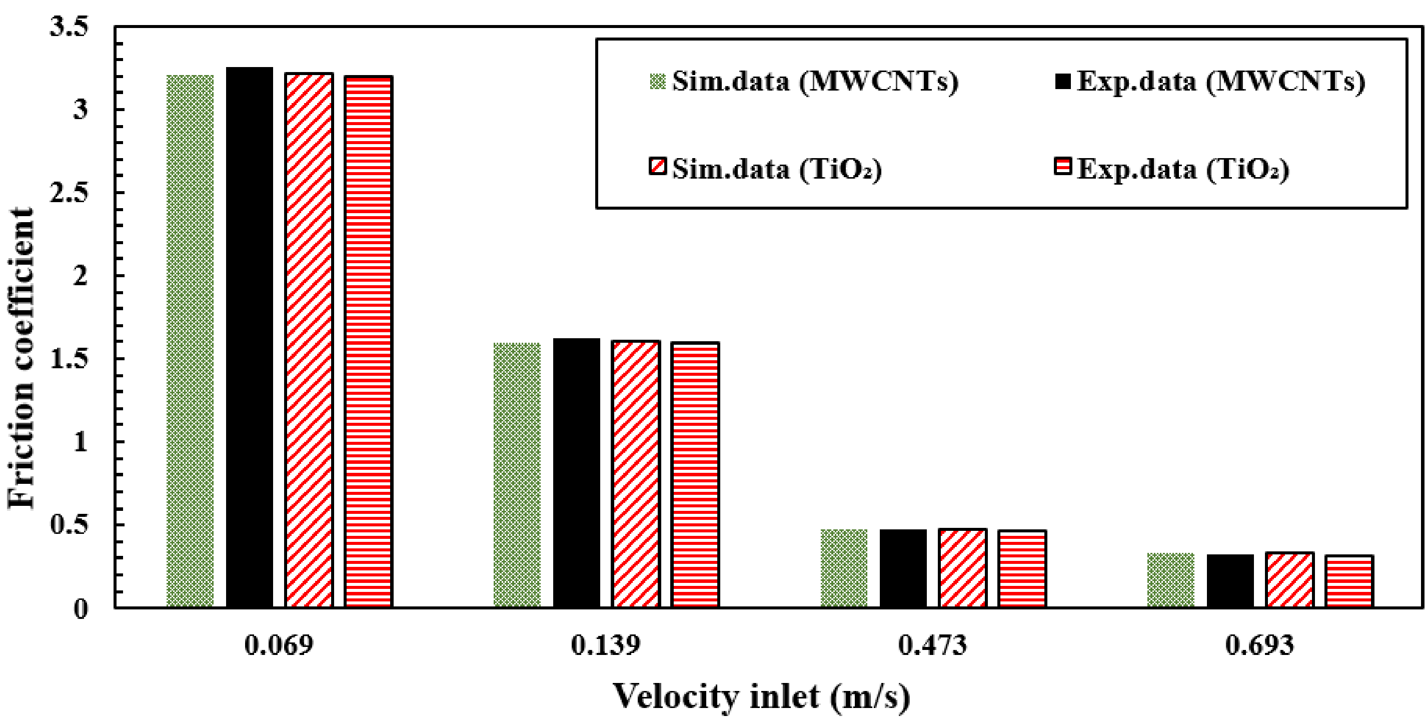
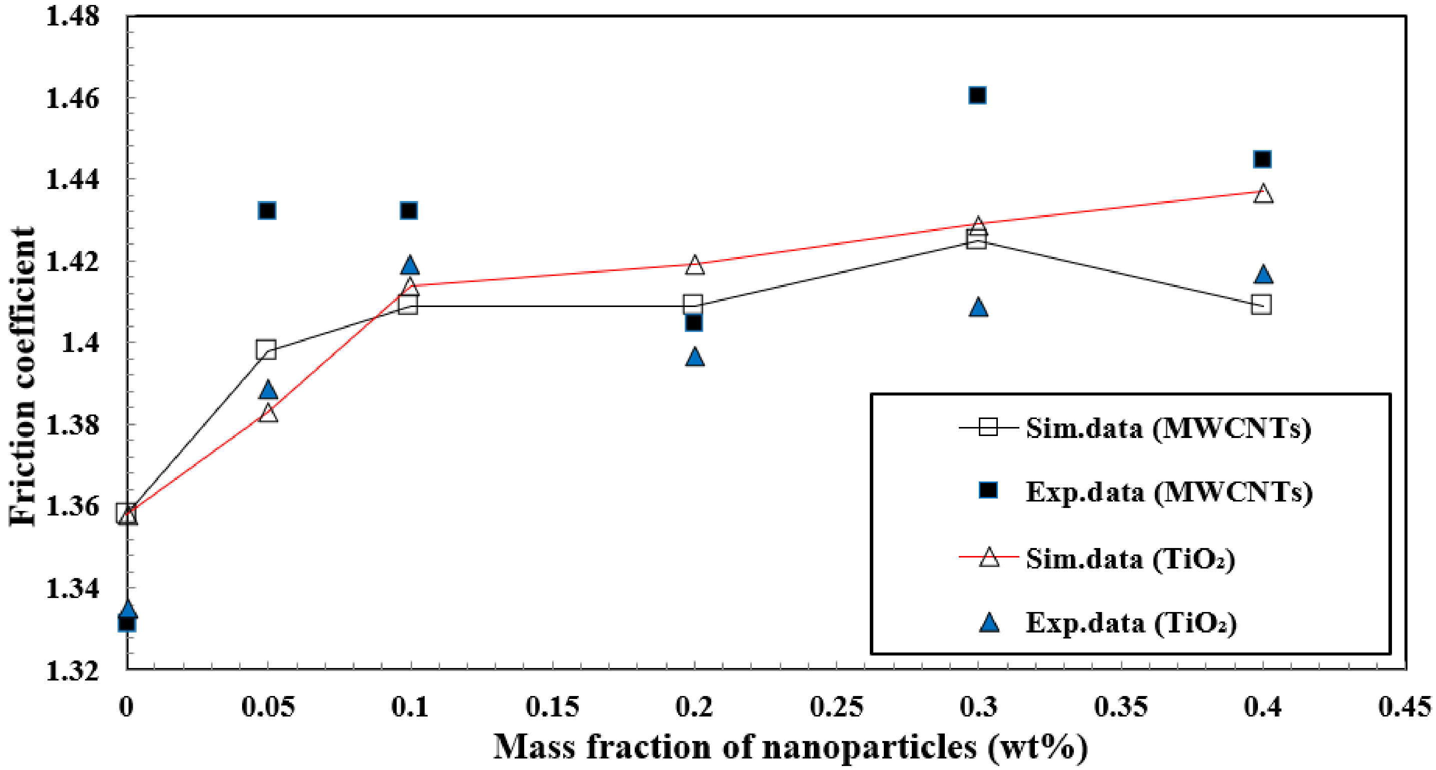


## Figure 17

Comparison of experimental and simulation data of the average friction coefficient of the nanofluids in various values of velocity inlet in the range of 0.05 to 0.4 wt.% of TiO2 and MWCNTs nano additives




## Figure 18

Comparison of experimental and simulation data of the average friction coefficient of the nanofluids in the different mass fraction of TiO2 and MWCNTs nano additives in the range of 0.069 m/s to 0.698 m/s velocity inlet

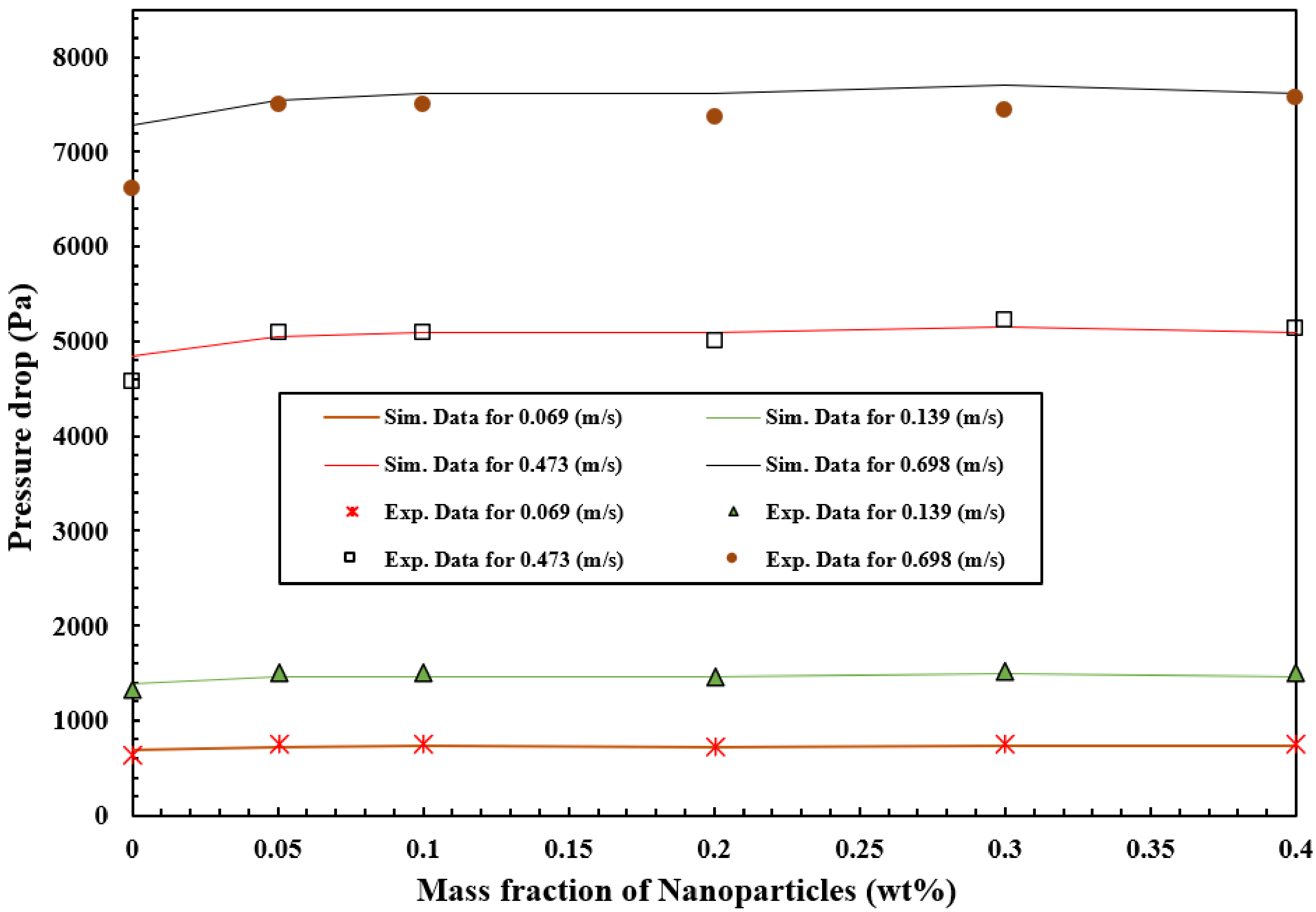
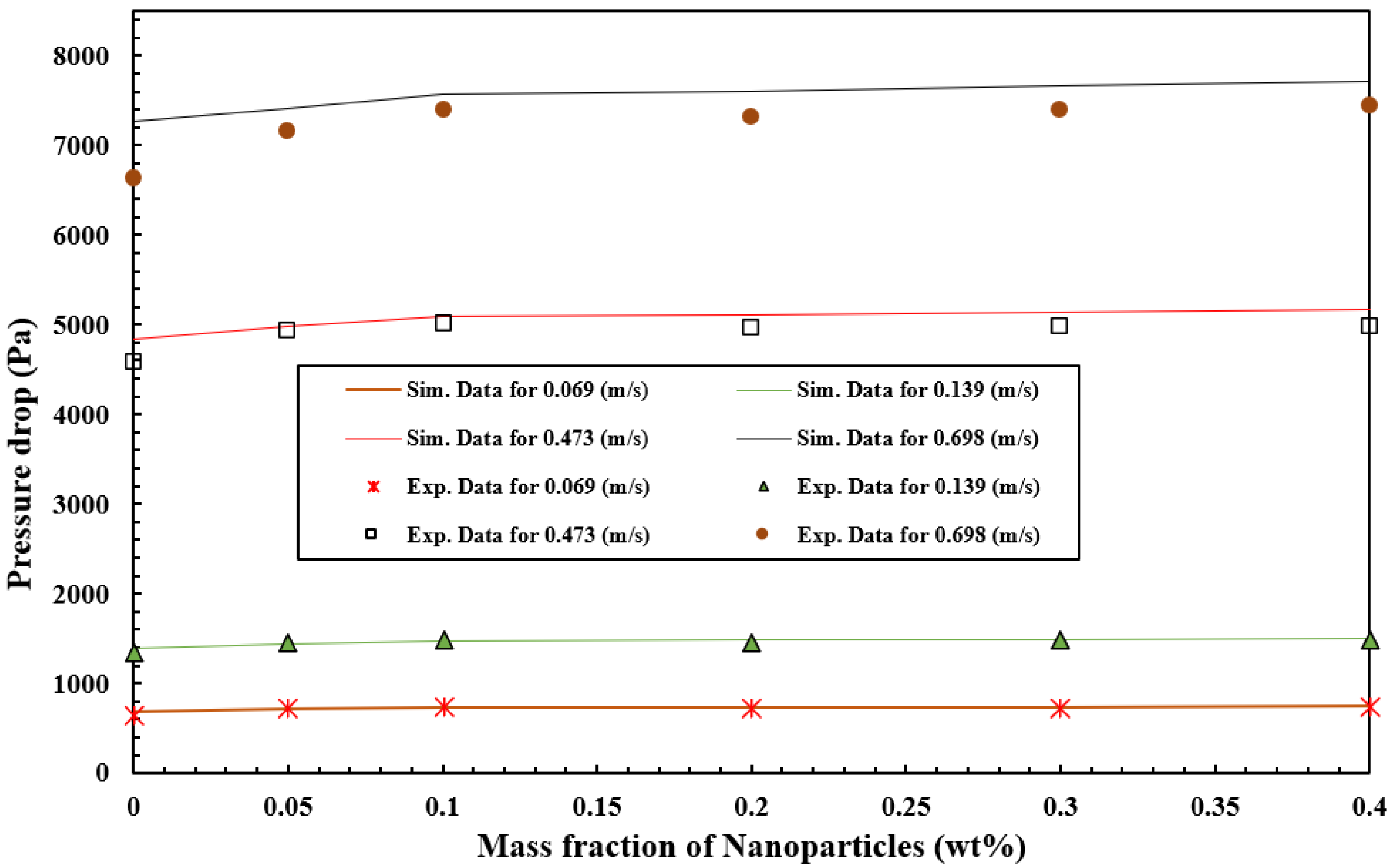



**Figure 19**

Comparison of experimental and simulation data of the pressure drop of the nanofluids in different mass fraction of MWCNTs nano additives




## Figure 20

Comparison of experimental and simulation data of the pressure drop of the nanofluids in different mass fraction of TiO2 nano additives