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## Numerical investigation of TiO<sub>2</sub> and MWCNTs turbine meter oil nanofluids: Flow and hydrodynamic properties

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24 concentration and the volume flow rates, sequentially. Additionally, with increasing the  
25 volume flow rate, the entrance length increased, and reaching the developed state was delayed.  
26 It is worth noting as the final finding of this study that increasing the NPs concentration resulted  
27 in decreasing the entrance length and the fast reaching of the developed state.

28 **Keywords:** Nanofluid; Lubricant; MWCNTs; TiO<sub>2</sub> nanoparticles; Gas turbine-meter; Pressure  
29 drop.

### 30 **Nomenclature**

31 Q Flow rate ( $\text{m}^3 \text{s}^{-1}$ )  
32 U Velocity ( $\text{m s}^{-1}$ )  
33 A Cross-section area ( $\text{m}^2$ )  
34 K Local energy dissipation coefficient  
35 g Gravitational acceleration ( $\text{m}^2 \text{s}^{-1}$ )  
36 Re Reynolds number  
37 L Length (m)  
38 wt Nanoparticle weight fraction (%)  
39 D Diameter (m)  
40 P Pressure ( $\text{kg m}^{-1} \text{s}^{-2}$ )  
41 F Coefficient of friction

### 42 **Greek letters**

43  $\mu$  Kinematic viscosity ( $\text{mm}^2 \text{s}^{-1}$ )  
44  $\rho$  Density ( $\text{kg m}^{-3}$ )

### 45 **Subscripts**

46 e Entrance

47 nf Nanofluid

48 bf Base fluid

## 49 **1. Introduction**

50 Tribology is the science of control and handling of wear, friction, and lubrication.  
51 Lubrication is a method of preventing friction and abrasion of moving surfaces that lump  
52 together. The friction is undesirable in most machines, so it is always attempted to be reduced  
53 or eliminated. Friction also causes erosion, noise, reducing durability, and heat generation of  
54 the equipment. Loss of energy is the most significant problem caused by wear and friction [1,  
55 2]. Good lubricant quality is required to reduce friction and improve the performance of parts  
56 of a machine or surfaces that are in contact with each other. Since most oils cannot be used  
57 directly or purely, they are mixed with certain additives to improve their viscosity and  
58 properties, most of which are nanomaterials [3-6]. Nanoparticles can enhance the tribological  
59 and anti-wear characteristics of oils by one of the following mechanisms (1) rolling effect,  
60 which can occur in the presence of small spherical nanoparticles rolling between the two  
61 contacting surfaces altering the sliding friction to rolling friction, (2) in the mending effect the  
62 mass loss will be compensated due to the incorporation of nanoparticles from the physical film,  
63 (3) nanoparticles polish the contact surface and decrease the surface roughness, and (4)  
64 nanoparticles protect the contacting surfaces by providing a stable tribo-film [7]. Nano  
65 lubricants are mainly used in the turbine meter to reduce friction and wear in bearings. Most  
66 turbine meters are equipped with a lubrication system that changes the oil pump's size based  
67 on the turbine meter's capacity. Constant lubrication of the turbine meter is required to achieve  
68 a longer service life.

69 Carbon nanotubes (MWCNTs) have attracted attention due to their remarkable properties,  
70 such as small size, high surface density, and weak covalent bonds, leading the plates to slip on

71 each other, reducing the friction of the contact plates in the lubrication system [8-13]. In  
72 addition, MWCNTs/nanofluid has excellent physicochemical and heat transfer properties viz.  
73 thermal conductivity, high thermal stability, high viscosity index, low pour point, and high  
74 flash point [14-23].

75 Titanium dioxide ( $\text{TiO}_2$ ) nanoparticles are used in many industries because of their excellent  
76 heat transfer, lubricity, optical, electrical, and catalytic properties. These applications include  
77 industrial pigments, environmental clean-up photocatalysts, skin protectors in sunscreens, and  
78 lubricants as additives [24-29]. Many investigations have shown the anti-friction  
79 characteristics of  $\text{TiO}_2$  nanoparticles due to their inherent anti-friction functionality, ease of  
80 synthesis, and low toxicity [30-33].

81 Different parameters of nanoparticles such as structure, functional surface groups, and  
82 concentrations affect the tribological properties of lubricants. The shape of the nanoparticles is  
83 another crucial parameter; the nanospheres experience more pressure at a given load than the  
84 nanoparticles because the former contact surface area is much smaller. Therefore, using layer  
85 nanoparticles can minimize the deformation of the wear surfaces [34-38]. Studies have shown  
86 that even a small concentration of nanoparticles can effectively improve the tribological  
87 properties. However, all the operating system parameters must be considered to find the  
88 optimum concentration for the minimum coefficient of friction [39-42]. Numerous studies have  
89 been conducted to investigate the effect of  $\text{TiO}_2$  nanoparticles and MWCNTs on the  
90 tribological properties of base fluid, which in most cases improved the performance of the  
91 lubricants and oils [43-50].

92 Heris et al. [51] investigated the thermal conductivity of turbine oil-based nanofluids inside  
93 a circular tube under laminar flow and constant flow rate. Three different nanofluids were  
94 prepared using  $\text{TiO}_2$ ,  $\text{CuO}$ , and  $\text{Al}_2\text{O}_3$  nanoparticles at different concentrations. The results  
95 showed an increase in heat transfer coefficient and Nusselt number with the addition of

96 nanoparticles. They also introduced a parameter as the ratio of nanofluid pressure drop to base  
97 fluid pressure drop and observed that this parameter was always greater than one. In other  
98 words, the addition of nanoparticles increased the pressure drop. Hosseinzadeh et al. [52]  
99 evaluated the effect of magnetic field and nanoparticle concentrations on heat transfer  
100 coefficient and friction in the presence of water and  $\text{Fe}_3\text{O}_4$  nanoparticles. The experiments were  
101 performed inside a horizontal tube with a diameter of 7 mm and a length of 1 meter in different  
102 Reynolds numbers. The results showed that the Nusselt number increased with the addition of  
103 nanoparticles and Reynolds numbers. Additionally, the same result was observed with  
104 increasing magnetic field strength. The presence of nanoparticles increased the coefficient of  
105 friction but increasing the intensity of the magnetic field had no significant effect on the  
106 coefficient of friction. Furthermore, increasing the Reynolds number decreased the coefficient  
107 of friction. Ahmad Ali et al. [53] conducted a study to assess the effect of  $\text{TiO}_2$  and  $\text{Al}_2\text{O}_3$   
108 nanoparticles on the thermophysical and tribological characteristics of engine oil. The  
109 outcomes revealed that the coefficient of friction decreased by 40~50% and the tire wear rate  
110 decreased by 20~30%. They concluded that adding nanoparticles could remarkably enhance  
111 the thermophysical and tribological properties of engine oil. Borda et al. [54] examined the  
112 effect of Cu nanoparticles on mineralized and synthesized oil-based esters considering different  
113 concentrations. Their findings exhibited that the addition of Cu nanoparticles did not have a  
114 good effect on friction and wear on the synthesized oil. However, adding these nanoparticles  
115 to mineral oil decreased the coefficient of friction and improved the wear properties, especially  
116 at 0.3 wt% of the nanoparticles. Laad et al. [55] added  $\text{TiO}_2$  nanoparticles to improve the  
117 lubricating oil properties. Nanofluids were prepared at different concentrations, 0.3, 0.4, and  
118 0.5 wt%. A pin-on-disc tribometer was used to perform abrasion and friction tests. The results  
119 showed that the coefficient of friction increased with increasing the nanoparticles  
120 concentration. They asserted that the addition of this nanoparticle could reduce the amount of

121 wear and coefficient of friction and improve the lubricant properties. Curà et al. [56] studied  
122 the effect of graphene nanoplates on the tribological performance of lubricants considering  
123 different concentrations. It was observed that the addition of the used nanoparticles could  
124 significantly improve the tribological features of the lubricants. Hussein et al. [57]  
125 experimentally examined the effect of MWCNT/water nanofluids on heat transfer attributes  
126 and pressure drop at diverse concentrations ranging from 0.075–0.25 wt%. The experiments  
127 were conducted inside a circular mini tube under a laminar flow condition. The results showed  
128 that as the nanoparticle concentration increased, the coefficient of friction, the coefficient of  
129 heat transfer, and pressure drop increased. A 10% increase in pressure drop was reported at the  
130 highest concentration of nanoparticles. The effect of adding MWCNTs and graphene  
131 nanoplatelets on the thermal properties of the diesel oil at different concentrations and flow  
132 rates were assessed by Naddaf et al. [58]. The outcomes confirmed that the thermal properties  
133 of the prepared nanofluids were dependent on the concentration of nanoparticles. They further  
134 reported that both the convective heat transfer coefficient and the pressure drop increased with  
135 the addition of nanoparticles. Mousavi et al. [59] investigated the thermophysical and  
136 rheological properties of MoS<sub>2</sub>/diesel oil-based nano lubricants. A pin-on-disc friction and  
137 wear tester was employed to evaluate the friction and anti-wear properties. The highest  
138 viscosity and viscosity index were observed at the highest concentration in the study, 0.7 wt%.  
139 Ajeel et al. [60] evaluated the simultaneous effect of corrugated walls and turbulent flow of  
140 nanofluids on thermohydraulic performance. The experiments were conducted at diverse  
141 Reynolds numbers ranging in 10,000–30,000 and a heat flux of  $10000 \frac{W}{m^2K}$ . Three different  
142 channel shapes were considered as a semicircular, wavy channel, trapezoidal wavy channel,  
143 and straight channel. The nanofluids were prepared in volumetric percentages of 1% and 2%  
144 of Al<sub>2</sub>O<sub>3</sub>. The results showed that the nanofluid flow inside the trapezoidal corrugated channel  
145 increased 63.54% of the heat transfer coefficient and 1.37 times the pressure drop compared to

146 the straight channel. Pourpasha et al. [61] assessed the effect of CNT on the thermophysical  
147 and tribological features of turbine oil meter nano lubricants. The thermophysical properties of  
148 lubricating oil such as viscosity index, kinematic viscosity, flash point, pressure drop, and  
149 coefficient of friction were measured. It was found that the addition of CNT could enhance  
150 lubrication characteristics and improve the thermophysical of the turbine meter oil nano  
151 lubricants.

152 Based on the performed literature survey, most studies in the field of heat transfer  
153 characteristics of nano lubricants announce a positive effect on the friction-reduction behavior  
154 and thermophysical characteristics considering different nano additives. However, in the  
155 previous investigations, none of the studies were conducted while considering TiO<sub>2</sub> and  
156 MWCNTs nanoparticles in the turbine meter oil. Furthermore, heat transfer characteristics and  
157 tribological behaviors of the TiO<sub>2</sub> and MWCNTs nano lubricants have not been well-  
158 understood. It is worth mentioning that different effective parameters such as concentration of  
159 nanoparticles, flow rates, and pressure drops were comprehensively studied in this study.

160 In this study, to the best of our knowledge, lubrication oil simulation has been measured  
161 inside the turbine for the first time. The velocity profiles, pressure drop values, coefficient of  
162 friction of the base fluid, and nano lubricants considering MWCNTs and TiO<sub>2</sub> nanoparticles  
163 considering different weight percentages and volume flow rates were comprehensively  
164 investigated.

## 165 **2. Experimental Section**

### 166 **2.1. Materials**

167 Table 1 lists the specifications of the gas turbine meter oil manufactured by Shell Oil  
168 Company, USA. The TiO<sub>2</sub> and MWCNTs were commercially purchased from SkySpring  
169 Nanomaterials, USA, and US Research Nanomaterials, USA, respectively. These data were



170 reported by Pourpasha et al. [61]. Table 2 represents the specifications of the used  
171 nanomaterials. Figures 1 and 2 represent the SEM images of TiO<sub>2</sub> nanoparticles and MWCNTs,  
172 respectively. The specification of nanofluids is listed in Table 3.

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**Table 1** Specifications of gas turbine meter oil.

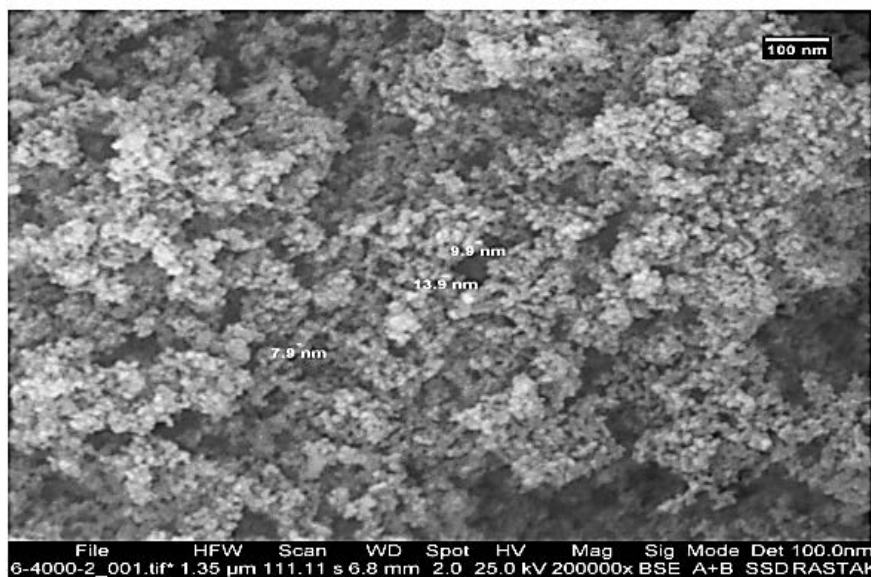
Properties	Unit	ASTM standard	Value
Density	Kg/m <sup>3</sup>	D1298	775
Viscosity at 40°C	cSt	D445	21.88
Viscosity at 100°C	cSt	D445	4.6
Viscosity index (VI)	–	D2270	130
Pour point	°C	D97	–40
Flash point	°C	D92	220

175

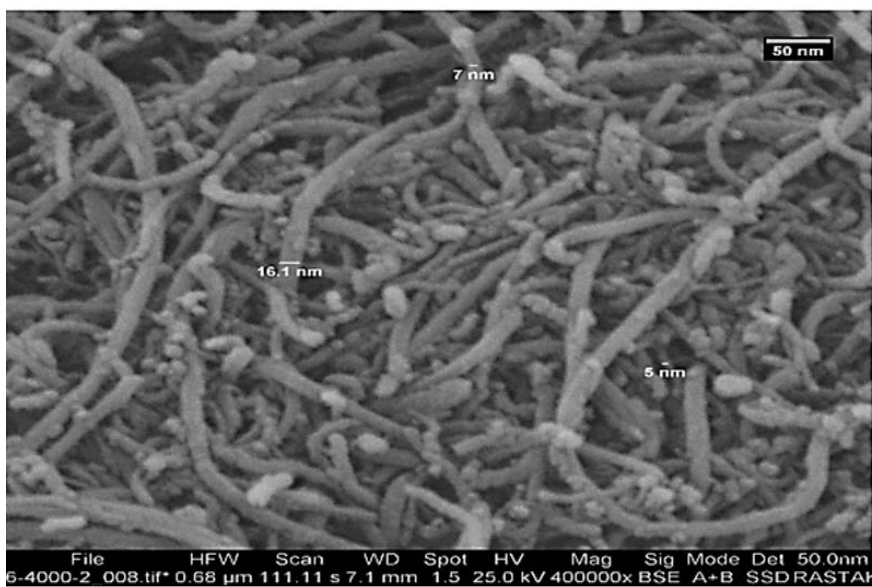
**Table 2** Physical properties of nanoparticles.

Nanoparticles	Morphology	Purity (%)	Average diameter (nm)	Density (kg/m <sup>3</sup> )	Color
TiO <sub>2</sub>	Spherical	99.5	10	4230	White
MWCNTs	Cylindrical	>95	13	2100	Black/Gray

176



**Fig. 1.** SEM image of TiO<sub>2</sub> nanoparticles.



**Fig. 2.** SEM image of MWCNTs.

**Table 3** Specifications of nanofluids.

Nanofluid	Density (kg/m <sup>3</sup> )	Viscosity at 40°C (cSt)
0 (Base oil)	775	21.88
0.1 wt% TiO <sub>2</sub>	776	21.407
0.2 wt% TiO <sub>2</sub>	776.4	21.645
0.3 wt% TiO <sub>2</sub>	777	21.826
0.1 wt% MWCNTs	775.8	21.651
0.2 wt% MWCNTs	776.4	21.852
0.3 wt% MWCNTs	777	22.071

## 184 2.2. Methods for experiment

185 The velocity inlet is essential information needed for modeling nanofluid flow through the  
 186 gas turbine meter conduit. The oil pathway and the pump were used to measure the velocity.  
 187 Figure 3 shows the oil inlet pathway for the velocity measurement system. A certain amount  
 188 of oil was pumped through the oil pump to the oil pathway to measure inlet velocity. The inlet  
 189 velocity was determined by measuring the time to complete oil outflow using equation 1.

$$Q = U \times A \quad (1)$$

190 where  $Q$  is the volume flow rate (m<sup>3</sup>/s),  $U$  is the velocity (m/s), and  $A$  is the cross-sectional  
 191 area (m<sup>2</sup>).



192

193

**Fig. 3.** Turbine meter oil inlet pathway for the velocity measurement system.

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### **2.3. The pressure drops from theoretical relationships**

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Two types of energy loss for pipes can be considered: first is the loss due to the change in the diameter of the pipes and the types of joints (minor loss). Second is the loss due to friction in the pipes (major loss), higher than the other. Factors such as changing the diameter of the pipes and the existence of different types of joints (knees, valves, and curvature in the pipes.) cause the deformation of the flow lines resulting in energy loss. The following formula can calculate this type of loss [62]:

$$h_f = K \frac{U^2}{g} \quad (2)$$

$$\Delta P = \rho g h_f \quad (3)$$

201

202

In the above relation,  $K$  is the local energy dissipation coefficient (the empirical coefficient obtained from the corresponding tables without dimension),  $U$  is the velocity (m/s) (the inlet

203 velocity),  $\Delta P$  is the pressure drop (Pa),  $\rho$  as density ( $kg/m^3$ ), and  $g$  is the gravitational  
204 acceleration ( $m^2/s$ ).

205 Depending on the shape and geometry, this type of pressure loss involves a pressure drop  
206 caused by the presence of a knee and a sudden change in the cross-sectional area. The  
207 coefficient of local energy loss resulting from the cross-sectional area change can be obtained  
208 from equation 4 [63]:

$$K = \left(1 - \frac{A_1}{A_2}\right)^2 \quad (4)$$

209 where  $A_1$  is a small cross-section and  $A_2$  is a large cross-section.

210 The simulation has been performed at a constant temperature without heat transfer, steady-  
211 state condition, and under the laminar flow condition. The frictional pressure drop is dependent  
212 on the friction between the fluid and the pipe, which is shown for a circular pipe with the  
213 Darcy-Weisbach relation.

$$\Delta P = F_D \times \frac{\rho L}{2} \times \frac{U^2}{D} \quad (5)$$

$$F_D = \frac{64}{Re} \quad (6)$$

$$Re = \frac{\rho U D}{\mu} \quad (7)$$

214 Where  $\Delta P$  is pressure drop [Pa],  $F_D$  is coefficient of friction,  $D$  is diameter [m],  $L$  length of  
215 pipe [m],  $\rho$  is density [ $kg/m^3$ ],  $U$  is velocity [m/s], and  $\mu$  is viscosity [kg/m.s].

#### 216 **2.4. Developing entrance length and developed flow and theoretical relationships**

217 For laminar flow, the hydrodynamic entrance length can be obtained from the following  
218 equation [64]:

219  $\frac{l_e}{D} = 0.058 Re$  (8)

220 where  $l_e$  is the entrance length and  $D$  is the diameter of the pipe.

### 221 3. Numerical simulation

#### 222 3.1. Simulation of nanofluids

223 As mentioned, this study aims to simulate the flow of nanofluids inside the oil pathway.  
224 Single-phase and general two-phase methods are used to model the flows involving  
225 nanoparticles. In the two-phase approach, nanofluids are considered two different liquid and  
226 solid phases with different momentums. The equations resulting from the two-phase theory are  
227 difficult to deal with and cannot be easily applied for nanofluids. In the single-phase approach,  
228 both the fluid phase and nanoparticles are considered a single homogeneous phase. Since the  
229 particles are ultrafine and become easily fluidized, all the equations of continuity, motion, and  
230 energy for pure fluid may be directly extended to nanofluids. In this study, due to the low  
231 concentration of nanoparticles and the experimental determination of properties such as  
232 viscosity and density, the homogeneous model has been used to simulate the nanofluid flow  
233 through the gas-turbine oil meter path.

#### 234 3.2. Governing Equations

235 The pressure drop is obtained from the continuity and momentum balance equations.  
236 Equations 5, 7, and 8 represent these equations.

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \vec{v}) = 0 \quad (7)$$

$$\frac{\partial}{\partial t} (\rho \vec{v}) + \nabla \cdot (\rho \vec{v} \vec{v}) = -\nabla P + \nabla \tau + \rho \vec{g} + \vec{F} \quad (8)$$

$$\frac{\Delta P}{L} = F_D * \frac{\rho}{2} * \frac{V^2}{D} \quad (9)$$

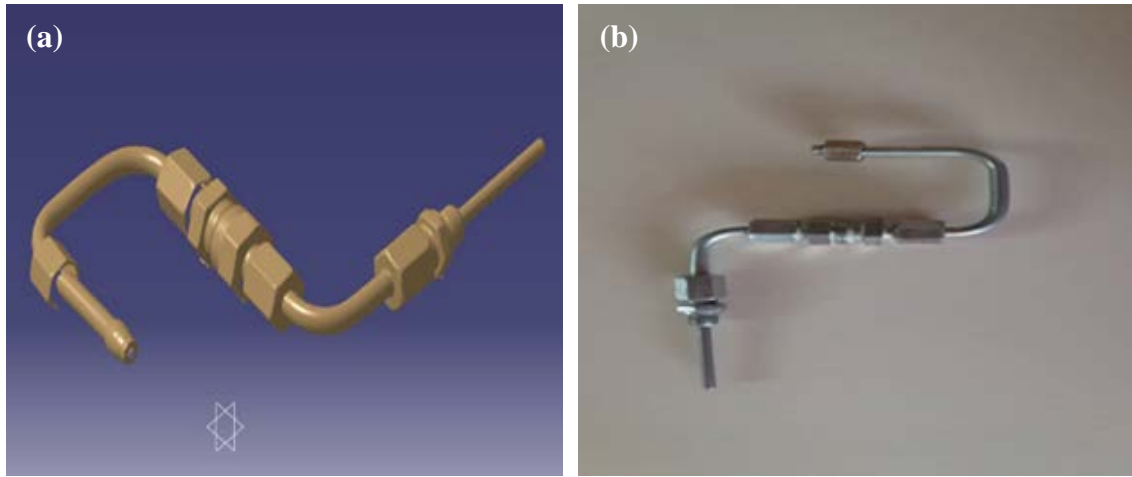
237 where  $P$  is the static pressure,  $\Delta P$  is a pressure drop,  $\rho \vec{g}$  and  $\vec{F}$  are the gravitational body  
238 force and exterior body forces,  $F_D$  is coefficient of friction, and  $D$  is diameter [63].

239 In the homogeneous model, the thermophysical properties of nanofluid such as viscosity  
240 and density must be used in continuity, momentum, and energy equations.

241 In the present study, experimental values of viscosity and density are given by Pourpasha et  
242 al. [61] were used in the continuity and momentum equations.

### 243 **3.3. Boundary conditions and needed information**

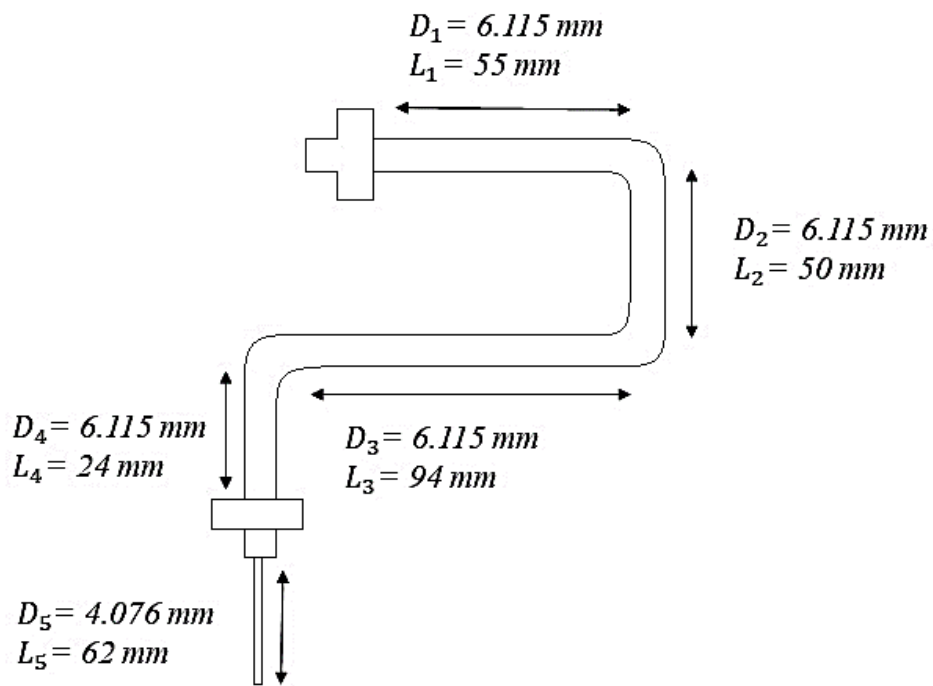
244 The purpose of this present study is to investigate the effect of MWCNTs and TiO<sub>2</sub>  
245 nanoparticles on the modeling of lubricant fluid flow within gas turbine meters. A lubrication  
246 system is necessary due to the high degree of wear and coefficient of friction of the bearings.  
247 In this regard, the lubricating oil pathway inside the gas turbine meters has been investigated  
248 and simulated. The CMM scanner scans the oil path in figure 4.. The condition used as the  
249 boundary condition is the inlet velocity is 0.00483, 0.0409, and 0.012 ( $m/s$ ). The dimension of  
250 the oil pathway is shown in figure 5. The oil pathway from part 1 to part 4 is iron, and part 5 is  
251 steel. The simulation is performed at a constant temperature without heat transfer, steady-state  
252 condition, and under the laminar flow condition.



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**Fig. 4.** (a) Scanned and (b) the real photo of the turbine meter oil pathway.



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**Fig. 5.** Dimension of oil pathway.

### 257 3.4. Numerical Analysis

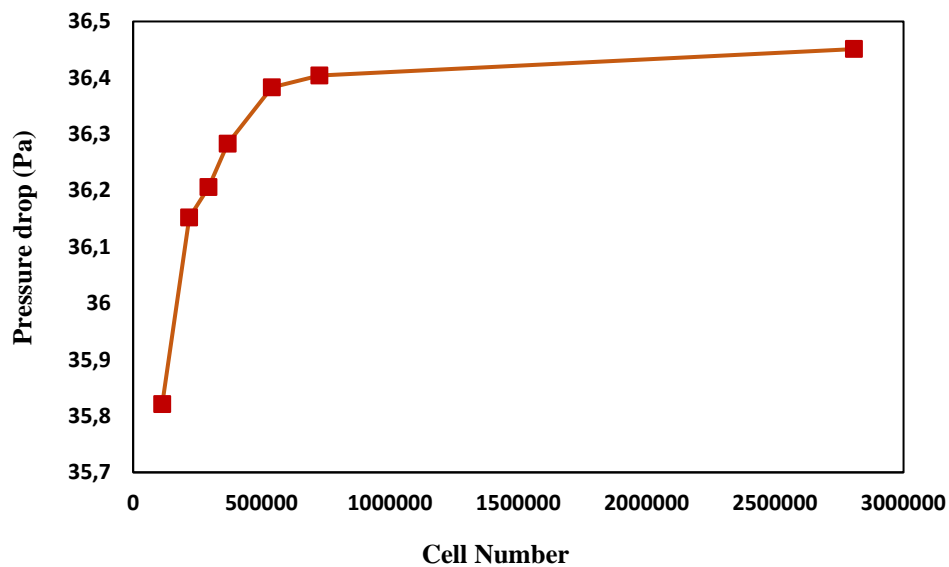
258 The oil pathway is meshed by Gambit software version 2. 4. 6 and the equations have been

259 solved by Fluent software version 19.1. ANSYS-FLUENT software has been used to solve the



260 governing equations discretized with a double-precision solver using the SIMPLEC algorithm.  
261 The convergence criteria for continuity, momentum, and energy equations were all set to  $10^{-6}$ .

262 For the mesh independence check, figure 6 is plotted, and given the optimal number of  
263 cells, 368462 is selected. The absolute convergence criteria for the continuum equation and the  
264 velocity equation with residuals below have been considered.



265

266 **Fig. 6.** Pressure drop variations versus cell number.

267

## 267 **4. Results**

### 268 **4.1. Results of TiO<sub>2</sub>/turbine meter oil nanofluids**

269 This section discusses the effect of increasing volume flow rate and mass percent of  
270 nanoparticles on pressure drop, coefficient of friction, and velocity profile. Furthermore, the  
271 effect of simultaneous mass percent of nanoparticles and volume flow rate on pressure drop  
272 and coefficient of friction are discussed. Different results are presented in Table 4 to compare  
273 the outlet velocity of the simulation and the theoretical relationships. The differences between  
274 experimental and numerical values of outlet velocities are 2.48%, emphasizing the accuracy

275 and correctness of the numerical simulation. Table 5 lists the pressure drop values of  
 276 TiO<sub>2</sub>/turbine meter oil nanofluid at volume flow rates of 0.14, 0.35, and 1.2  $\frac{cm^3}{s}$ . Figure 7 shows  
 277 the effect of TiO<sub>2</sub> concentration on the pressure drop variations as a function of flow rate.

278 **Table 4** The velocity values of modeling and theoretical relationships.

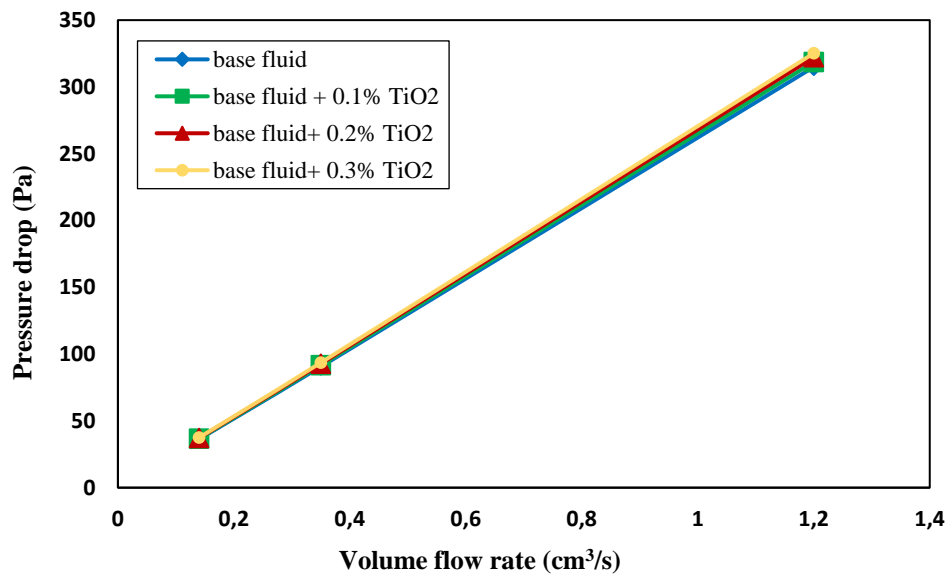
Fluid	Inlet velocity (m/s)	Modeling outlet velocity (m/s)	Theoretical outlet velocity (m/s)	Difference (%)
Base oil	0.00483	0.0106	0.01087	2.48

279

280 **Table 5** Modeling and theoretical pressure drop values of TiO<sub>2</sub> nanofluids at different flow rates.

Concentration (wt%)	Flow rate ( $\frac{cm^3}{s}$ )	Modeling pressure drop (Pa)	Theoretical pressure drop (Pa)	Difference (%)
0 (base oil)	0.14	36.28	36.44	0.439
	0.35	90.59	90.64	0.055
	1.2	314.91	310.74	1.342
0.1 TiO <sub>2</sub>	0.14	36.73	36.90	0.461
	0.35	91.68	92.60	0.994
	1.2	318.65	313.17	1.750
0.2 TiO <sub>2</sub>	0.14	37.15	37.31	0.429
	0.35	92.72	93.08	0.387
	1.2	322.20	316.80	1.705
0.3 TiO <sub>2</sub>	0.14	37.50	37.67	0.451
	0.35	93.60	93.62	0.021
	1.2	325.19	319.81	1.682

281



282

283 **Fig. 7.** The effect of TiO<sub>2</sub> concentration on the pressure drop variations as a function of flow rate.

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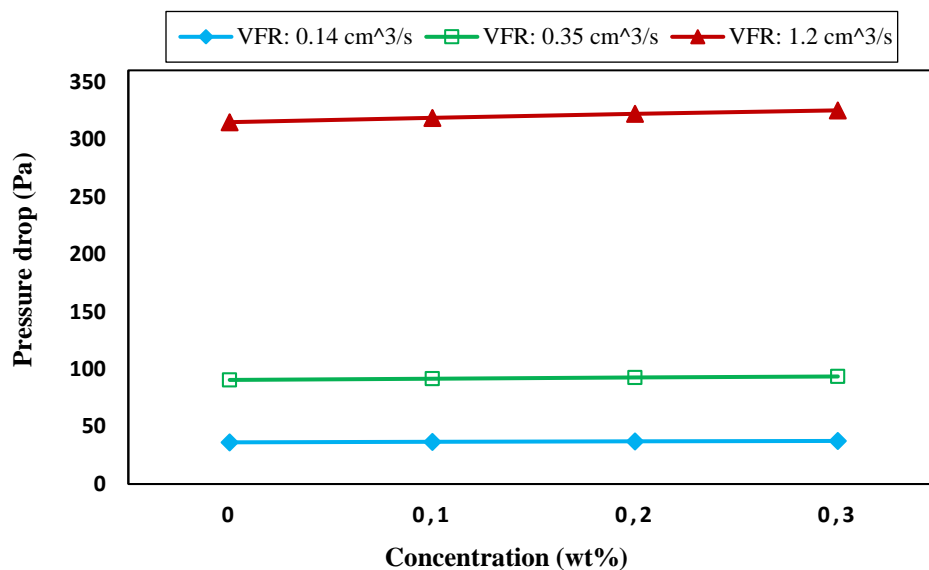
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The maximum difference between the values of the pressure drop obtained from the simulation and the theoretical pressure drop is 1.75%, indicating acceptable accuracy of the simulation. According to figure 7 and Table 5, it can be seen that by increasing the concentration of TiO<sub>2</sub> nanoparticles at a given volume flow rate, the pressure drop increased due to the increased viscosity. As the concentration of the nanoparticles increases, the interaction between the nanoparticles increases, which also increases the viscosity. According to equation 5, the increment of viscosity can lead to an increase in pressure drop. To illustrate, by increasing the concentration from 0.1 to 0.3 wt% at a flow rate of  $1.2 \frac{cm^3}{s}$ , the pressure drop reached 318.65 Pa from 325.19 Pa. The higher the flow rates and the concentrations, the more pressure drop. The reason for this variation can be due to the insignificant change in viscosity at lower concentrations since nanoparticles could not affect the viscosity. Other scholars have indicated similar results in the experimental investigation [57, 58].

Figure 8 exhibits pressure drop variation of TiO<sub>2</sub> nanofluids at different volume flow rates. According to figure 8 and Table 5, it can be seen that as the flow rate increased, pressure drop increased for all concentrations, as it is followed by the fluid velocity increase and the direct

299 relationship of pressure drop with fluid velocity (equation 5). Additionally, considering  
 300 equation 7, the Reynolds number is related to tube length, velocity, viscosity, and nanofluid  
 301 density. Given the constant length of the tube and minor changes in viscosity and density, the  
 302 leading cause of the pressure drop is related to an increase in flow rate. The highest pressure  
 303 drop rate at any given concentration is related to the highest flow rate. For instance, by  
 304 increasing the volume flow rate from 0.14 to  $1.2 \frac{cm^3}{s}$ , the pressure drop increased from 36.34  
 305 Pa to 318.65 Pa for 0.1 wt% TiO<sub>2</sub> nanofluid; thus, the volume flow rate has a significant effect  
 306 on the pressure drop. In a study conducted by Mousavi et al. [59], the pressure drop variations  
 307 of the prepared nanofluids in a tube were investigated. Their findings were consistent with the  
 308 modeling results.

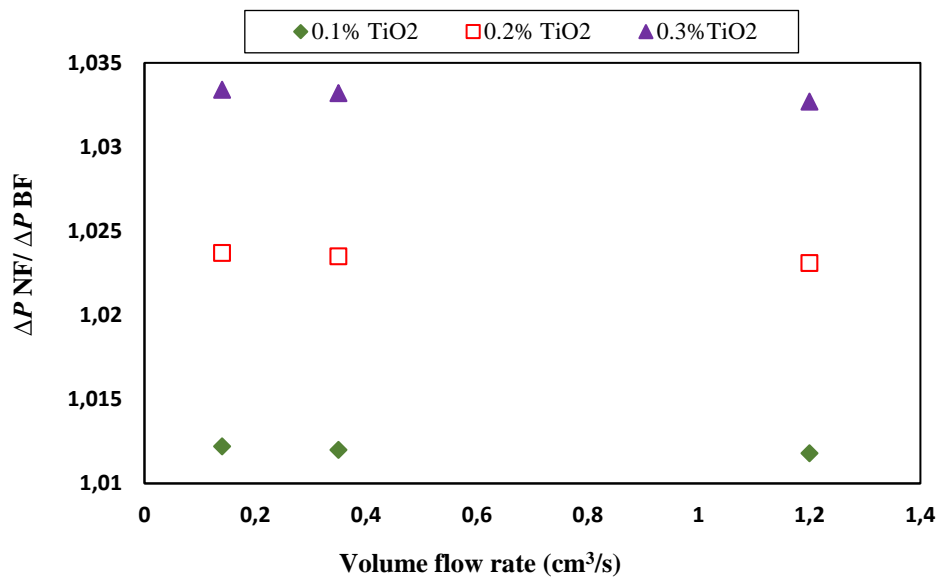


309

310 **Fig. 8.** Pressure drop variation of TiO<sub>2</sub> nanofluids at different volume flow rates.

311 Figure 9 represents the effect of volume flow rate on the pressure drop ratio of TiO<sub>2</sub>  
 312 nanofluids and pure oil. It can be seen that the increase in the volume flow rate of all prepared  
 313 TiO<sub>2</sub> nanofluids led to a decrease in the pressure drop of the nanofluid to the base fluid. As the  
 314 settling probability decreases; there will be a reduction in the high-volume flow rate, the ratio

315 of nanofluid pressure drop to base fluid pressure drop. By increasing the flow rate at the same  
 316 concentration, the number of nanoparticles per volume was reduced, leading to a decrease in  
 317 apparent viscosity. Also, this pressure drop ratio intensified with an increase in the  
 318 concentration of nanoparticles at given volume flow rates. Pourfarhang et al. [65] studied the  
 319 nanofluid flowing inside a car radiator and found that with increasing flow, the ratio of pressure  
 320 drop to the base fluid decreases, and this result is consistent with the outputs of the simulation.



321

322 **Fig. 9.** Pressure drop ratio of TiO<sub>2</sub> nanofluids to base oil at different flow rates.

323 To investigate the coefficient of friction variations (Darcy's Weisbach coefficient of  
 324 friction), the coefficient of friction of a pipe with a larger diameter was called  $F_1$ . The  
 325 coefficient of friction of a pipe with a smaller diameter was called  $F_2$ . Table 6 is provided to  
 326 compare the changes made on the coefficient of friction. Based on Table 6, the increase in the  
 327 concentration of nanoparticles led to an increase in the coefficient of friction. At higher  
 328 concentrations, the viscosity of the fluid and the coefficient of friction increased due to the  
 329 agglomeration of nanoparticles. It is also apparent that as the volume flow rate increases, the  
 330 coefficient of friction decreases since the coefficient of friction is inversely related to the fluid

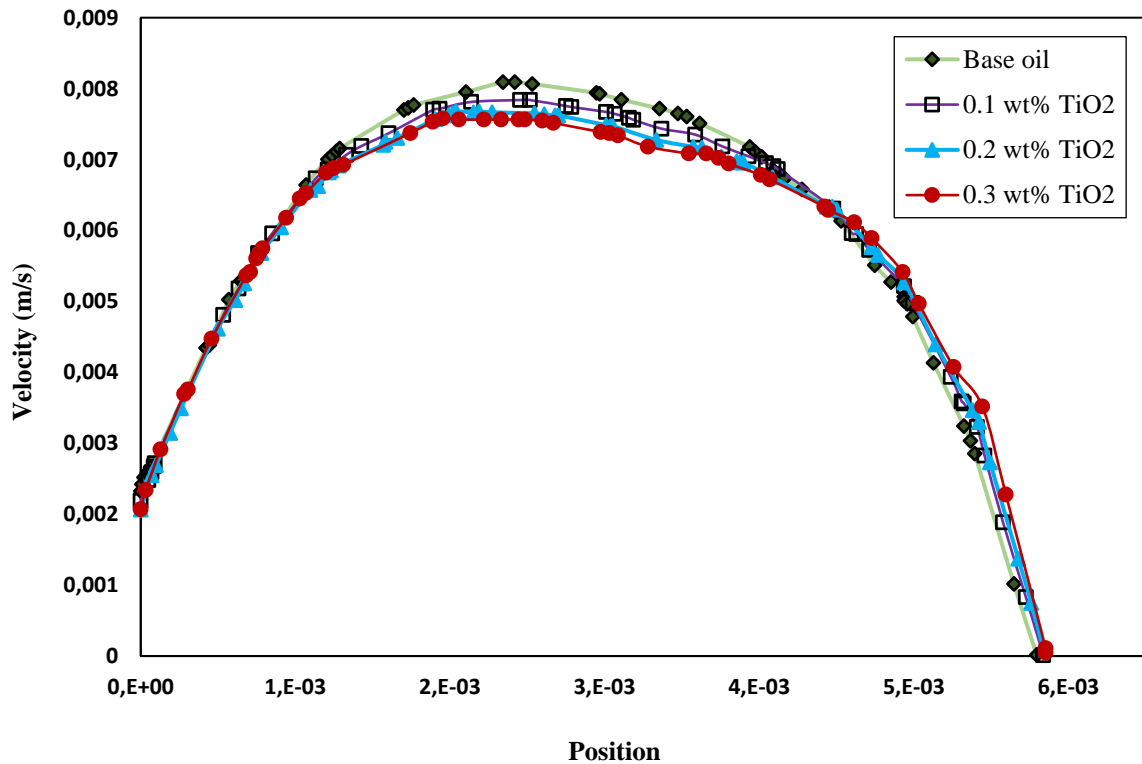
331 velocity (Eq. 5). Many researchers have also found that the coefficient of friction increases  
 332 with the increasing concentration of nanoparticles and decreases with the increasing flow rate  
 333 [1, 2, 59, 66].

334 **Table 6** Coefficient of friction at different concentrations and velocities of TiO<sub>2</sub> nanofluids.

Concentration (wt%)	Inlet velocity (m/s)	$F_1$	$F_2$
0 (base oil)	0.00483	45.88	31.37
	0.012	18.47	12.64
	0.0409	5.42	3.61
0.1 TiO <sub>2</sub>	0.00483	46.38	31.90
	0.012	18.67	12.78
	0.0409	5.48	3.78
0.2 TiO <sub>2</sub>	0.00483	46.89	32.00
	0.012	18.87	12.92
	0.0409	5.54	3.80
0.3 TiO <sub>2</sub>	0.00483	47.30	32.32
	0.012	19.04	13.03
	0.0409	5.59	3.83

335 Figure 10 shows the effect of adding TiO<sub>2</sub> nanoparticles on the velocity profile and reaching  
 336 the fully developed state. It shows the state of the velocity profile at the tube's inlet for the base  
 337 fluid and nanofluids containing 0.1, 0.2, and 0.3 wt% of TiO<sub>2</sub> nanoparticles at a volume flow  
 338 rate of  $0.14 \frac{cm^3}{s}$ . In addition, with the addition of TiO<sub>2</sub> nanoparticles and increasing the  
 339 concentration of nanoparticles, reaching the developed state occurs faster. Adding TiO<sub>2</sub>  
 340 nanoparticles led to an increase in viscosity; thus, considering equations 7 and 8, Reynolds

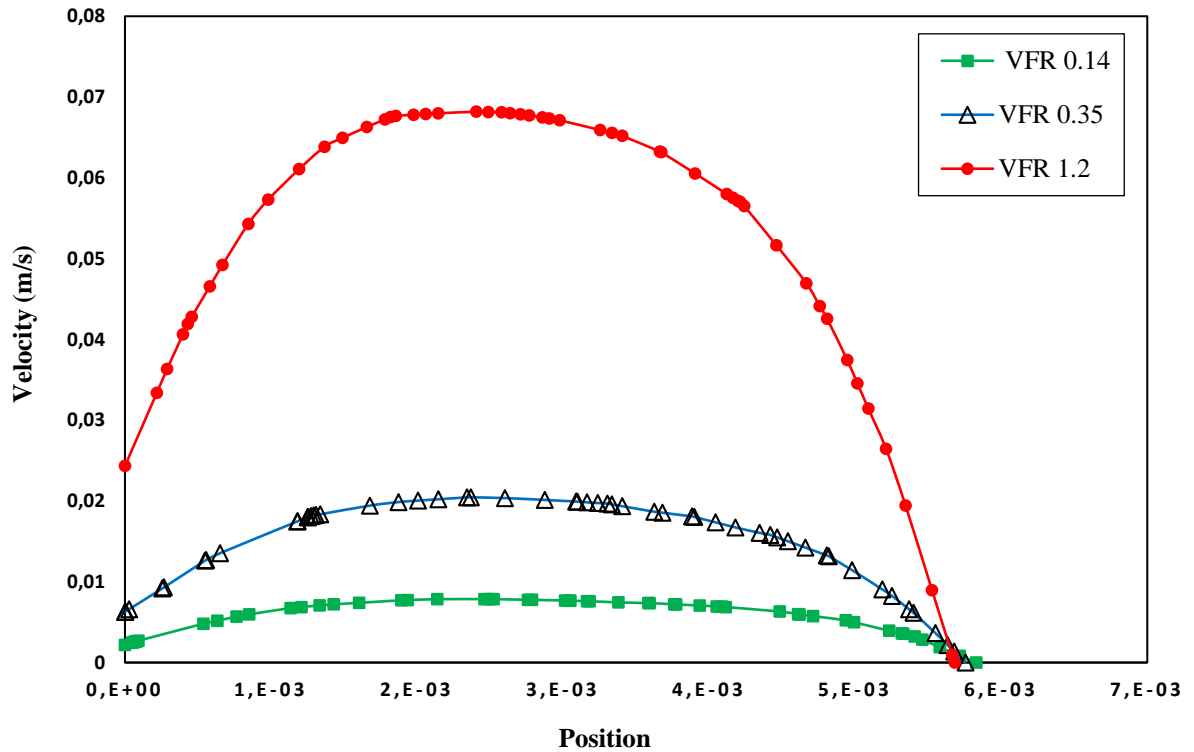
341 number and the entrance length decreased, and reaching the fully developed state occurred  
342 faster.



343

344 **Fig. 10.** Velocity profile of TiO<sub>2</sub> nanofluids at pipe inlet at a volume flow rate of 0.14 ( $\frac{cm^3}{s}$ ) and  
345 different concentrations.

346 Figure 11 exhibits the effect of volume flow rate of 0.2 wt% TiO<sub>2</sub> nanofluid on the velocity  
347 profile. It shows the velocity profile status at the inlet of the pipe containing 0.2 wt% of TiO<sub>2</sub>  
348 nanoparticles at different volume flow rates. It is observed that the increase of flow rate can  
349 delay reaching the developed state. Because with increasing flow, the velocity increases, and  
350 according to Equation 7, the Reynolds number increases. According to Equation 8, with  
351 increasing Reynolds number, the entrance length increases, and reaching the fully developed  
352 state is delayed. Gholinia et al. [67] examined the nanofluid flow inside a circular cylinder and  
353 observed that increasing the velocity caused the development state to be delayed.



354

355 **Fig. 11.** Velocity profile of 0.2 wt% TiO<sub>2</sub> nanofluids at pipe inlet considering different volume  
 356 flow rates.

357 **4.2. Results of MWCNTs/turbine meter oil nanofluid**

358 The effect of increasing the concentration of MWCNTs and volume flow rate on pressure  
 359 drop, coefficient of friction, and velocity profile are discussed in this section. Moreover, the  
 360 simultaneous effect of increasing the concentration of nanoparticles and volume flow rate on  
 361 pressure drop are scrutinized.

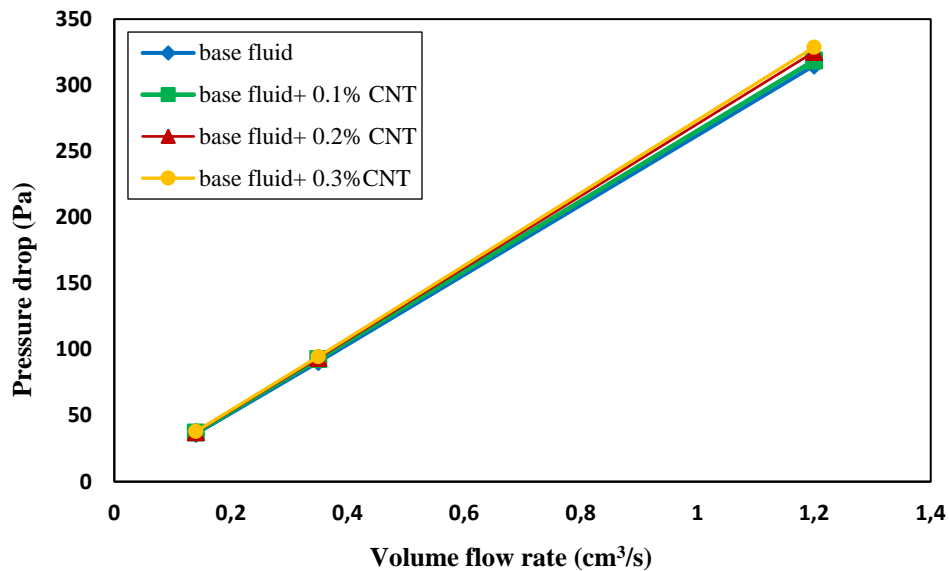
362 Table 7 lists the pressure drop values of MWCNTs nanofluids at different volume flow  
 363 rates. Figure 12 shows the effect of MWCNTs concentration on the variations of the pressure  
 364 drop as a function of flow rate.

365



366 **Table 7** Modeling and theoretical pressure drop values of MWCNTs nanofluids at different flow  
 367 rates.

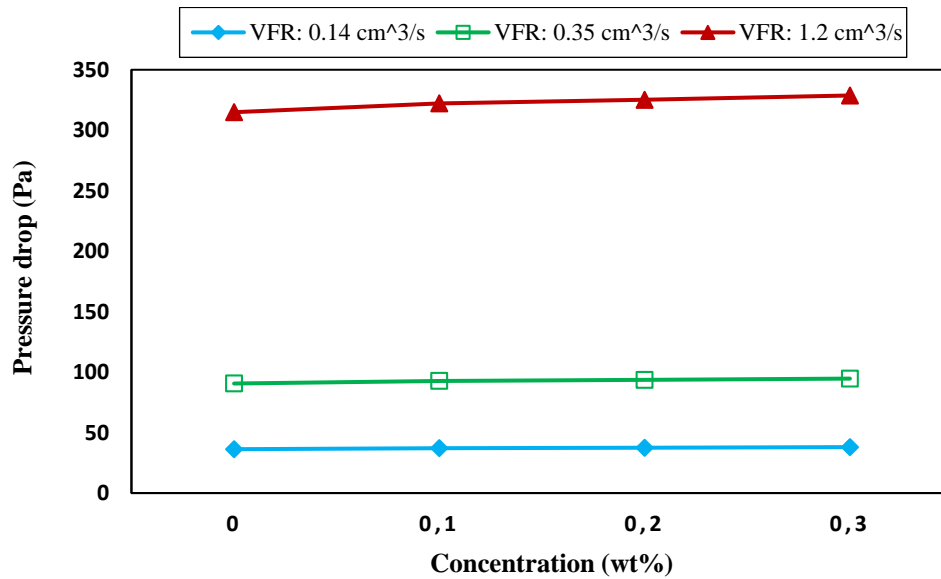
Concentration (wt%)	Flow rate ( $\frac{cm^3}{s}$ )	Modeling pressure drop (Pa)	Theoretical pressure drop (Pa)	Difference (%)
0 (base oil)	0.14	36.28	36.44	0.439
	0.35	90.59	90.64	0.055
	1.2	314.91	310.74	1.342
0.1 MWCNTs	0.14	37.14	37.32	0.482
	0.35	92.72	92.80	0.086
	1.2	322.19	318.63	1.117
0.2 MWCNTs	0.14	37.47	37.68	0.557
	0.35	93.60	93.69	0.096
	1.2	325.18	319.81	1.679
0.3 MWCNTs	0.14	38.00	38.18	0.471
	0.35	94.64	94.65	0.010
	1.2	328.73	323.41	1.645



368  
 369 **Fig. 12.** The effect of MWCNTs concentration on the pressure drop variations as a function of  
 370 flow rate.

371 According to Figure 12 and Table 7, the pressure drop of the nanofluid can be increased by  
372 increasing the concentration of MWCNTs at a given volume flow rate. The main reason for the  
373 increased viscosity is that as the concentration of MWCNTs increases, the collision between  
374 the MWCNTs increases because of increased random motion and increases viscosity. Due to  
375 the direct relationship of pressure drop with a viscosity (Eq. 5), pressure drop at higher  
376 percentages of MWCNTs shows a higher increase. At low concentrations of MWCNTs, the  
377 upward pressure drop of nanofluid is much lower than that of high nanofluid concentrations.  
378 In other words, at a low concentration of MWCNTs, the increase in pressure drop is not very  
379 noticeable due to the unremarkable change in viscosity of nanofluids at low concentrations.

380 Figure 13 shows pressure drop variation of MWCNTs nanofluids at different volume flow  
381 rates. According to Figure 13 and Table 7, it can be concluded that by increasing the volume  
382 flow rate, the pressure drop increases, since the increase in volume flow rate results in an  
383 increase in fluid velocity and the direct relationship between pressure drop and fluid velocity  
384 (Eq. 5). To illustrate, at a 0.3 wt% concentration of MWCNTs, the pressure drop was raised  
385 from 38 Pa to 94.64 Pa and then to 328.78 Pa. The results show the significant effect of  
386 increasing discharge on increasing pressure drop. In a study conducted by Hussein et al. [57]  
387 on a current-carrying nanofluid in a circular – mini - tube, they observed that with increasing  
388 flow rate, the pressure drop increased, which was quite similar to the simulation results.



389

390

**Fig. 13.** Pressure drop variation of MWCNTs nanofluids at different volume flow rates.

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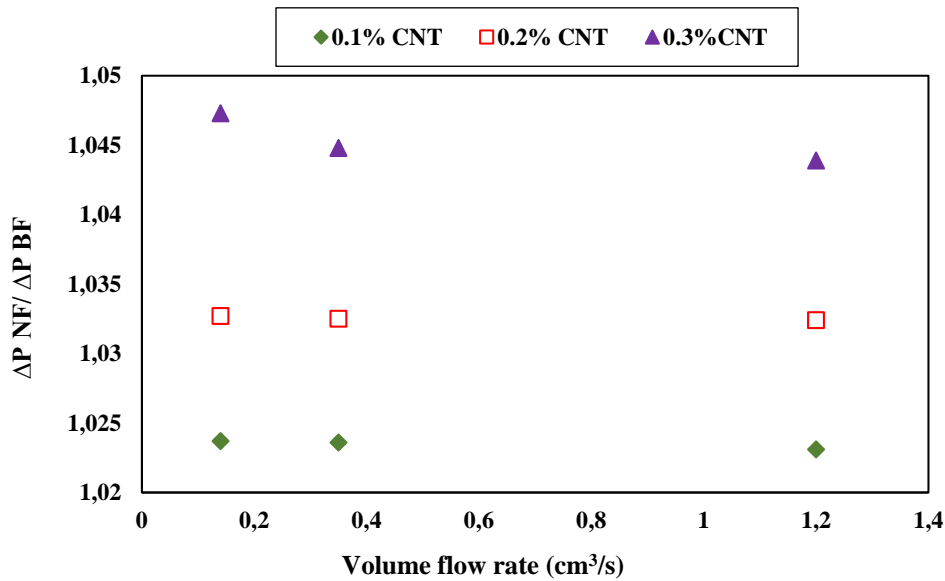
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Figure 14 exhibits the effect of volume flow rate and concentration of MWCNTs on pressure drop. It can be seen that by increasing the volume flow rate at all concentrations, the pressure drop of nanofluids to the base fluids decreased. As the volume flow rate increased, the rate of fluid coalescence increased, and the fluid dispersion became uniform. Since nanoparticles' effect was the least at the lowest concentration, nanofluid properties were close to base fluid properties, and the lowest proportion of pressure drop could be seen at the lowest nanoparticle concentration and the highest volume flow rates. Moreover, the probability of sedimentation decreases with the trend. As a result of the high-volume flow rate, the pressure drop rate relative to the base fluid decreased. Therefore, using nanofluids in high volume flow rates will cause less pressure drop and be more appropriate. In the research of Pourfarhang et al. [65] and Naddaf et al. [58], it was observed that the pressure drop ratio of nanofluid to the base fluid decreased with increasing flow rate.



403

404

**Fig. 14.** Pressure drop ratio of MWCNTs nanofluids to base oil at different flow rates.

405

Table 8 lists the coefficient of frictions at different concentrations of MWCNTs nanofluids.

406

Considering Table 8, as the concentration of MWCNTs increased, the coefficient of friction

407

increased. It is also apparent that as the volume flow rate increased, the coefficient of friction

408

decreased because the coefficient of friction is inversely related to the fluid velocity (Eq. 5).

409

Figure 15 presents the effect of adding MWCNTs on the velocity profile and reaching the

410

fully developed state. It shows the status of the velocity profile at tube inlet for base fluid and

411

nanofluids containing 0.1, 0.2, and 0.3 wt% of MWCNTs at a volume flow rate of  $0.35 \frac{cm^3}{s}$ . As

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can be seen, with the addition of MWCNTs and increasing the concentration of MWCNTs,

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reaching the developed state can be faster. The Reynolds number decreased with the addition

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of MWCNTs since they could increase the viscosity. According to Equation 8, with decreasing

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Reynold number, the entrance length decreases and reaches the fully developed state. The same

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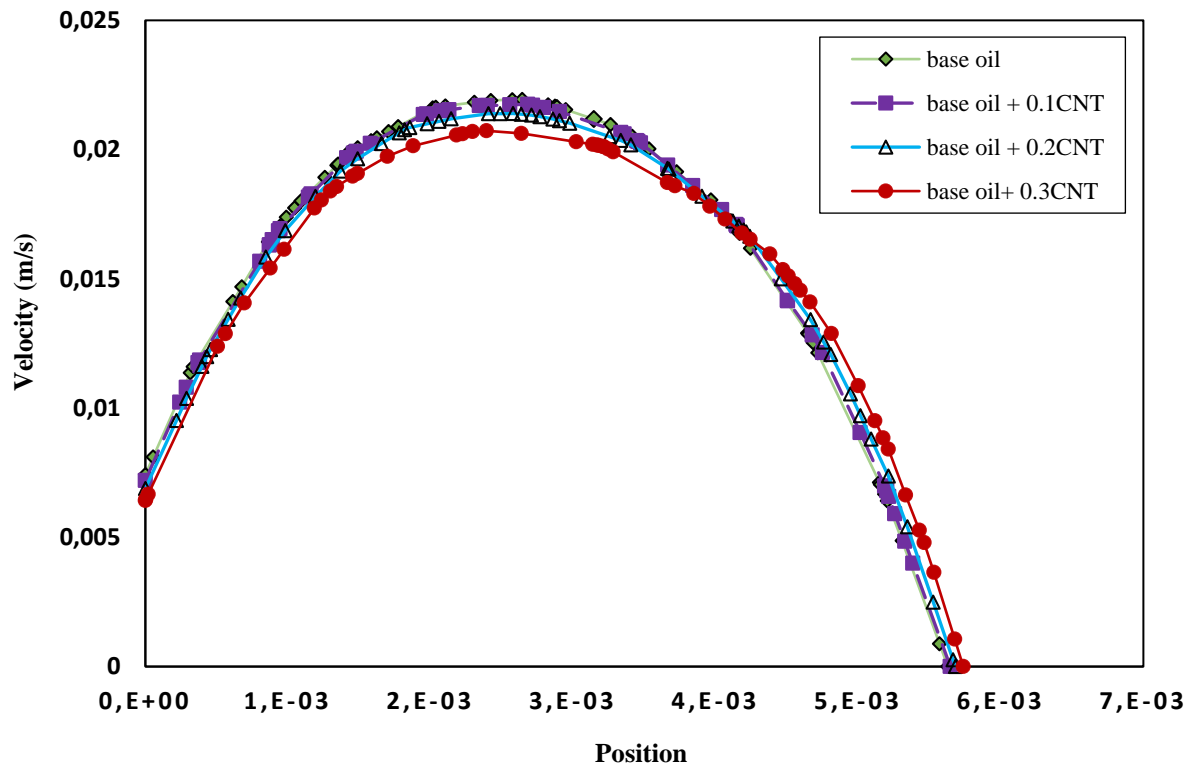
experimental results were reported in a study conducted by Bao et al. [68].

417

418

**Table 8** Coefficient of friction at different concentrations and velocities of MWCNTs nanofluids.

Concentration (wt%)	Inlet velocity (m/s)	$F_1$	$F_2$
0 (base oil)	0.00483	45.88	31.37
	0.012	18.47	12.64
	0.0409	5.42	3.61
0.1 MWCNTs	0.00483	46.96	32.08
	0.012	18.89	12.78
	0.0409	5.54	3.80
0.2 MWCNTs	0.00483	47.34	32.36
	0.012	19.05	12.93
	0.0409	5.59	3.83
0.3 MWCNTs	0.00483	47.83	32.70
	0.012	19.25	13.18
	0.0409	5.65	3.87



421

422

**Fig. 15.** Velocity profile at pipe inlet at a volume flow rate of  $0.35 \left(\frac{cm^3}{s}\right)$  and different

423

concentrations of MWCNTs.

424

Figure 16 shows the variations of the velocity profile at the inlet of the tube for nanofluids

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containing 0.1, 0.2, and 0.3 wt% of MWCNTs at a volume flow rate of  $0.35 \frac{cm^3}{s}$ . Increasing

426

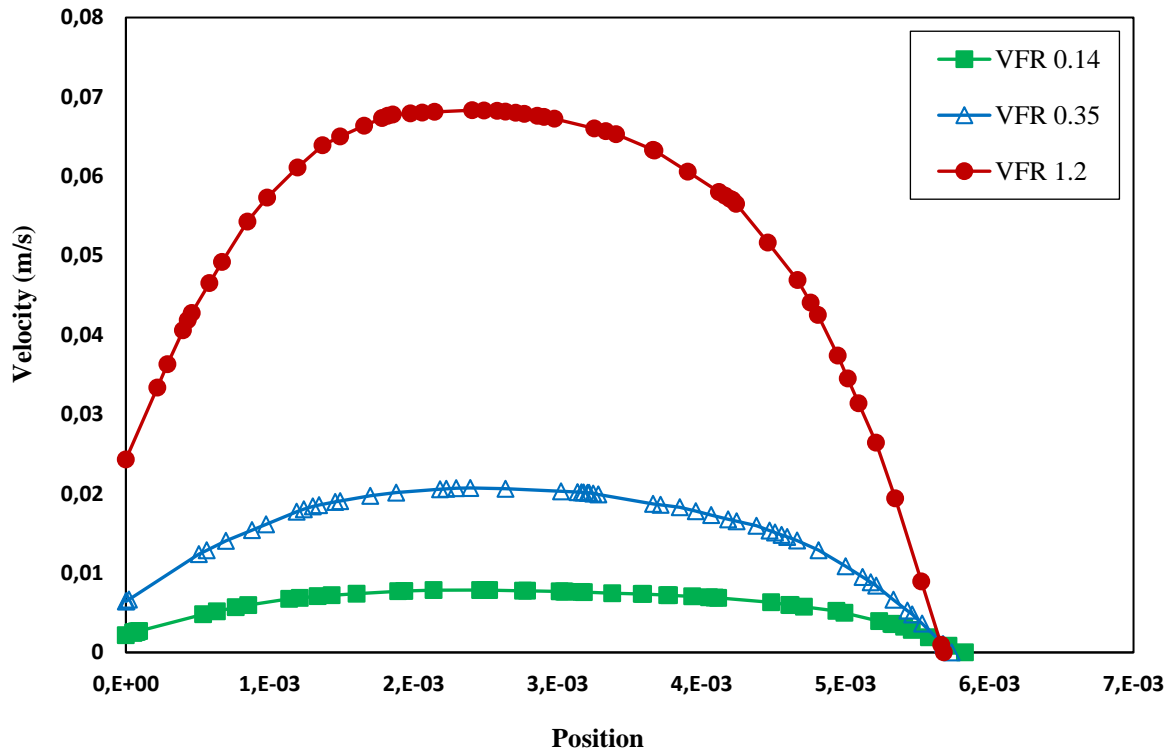
flow rate can delay the developed state because the velocity increases, and according to

427

Equation 7, the Reynolds number increases. According to Equation 8, with increasing Reynolds

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number, the entrance length increases, and reaching the developed state is delayed.



429

430 **Fig. 16.** Velocity profile of 0.3 wt% MWCNTs nanofluids at different volume flow rates.

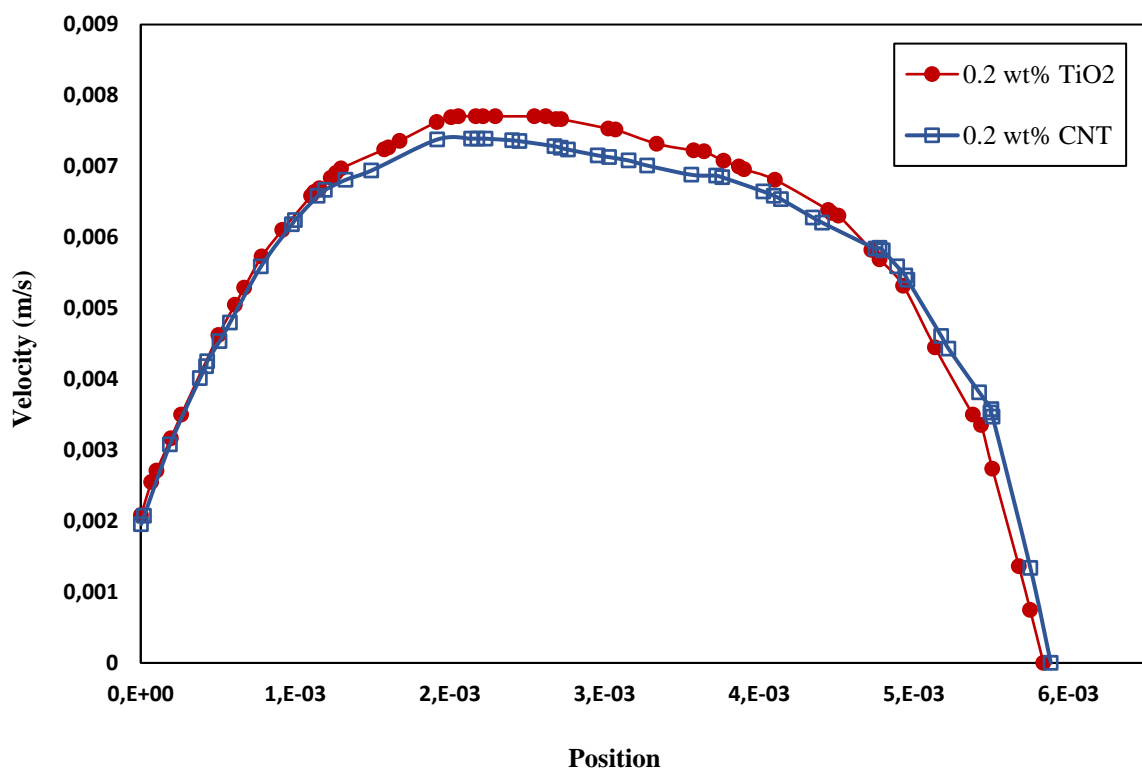
### 431 **4.3. Comparison of the results of TiO<sub>2</sub> and MWCNTs nanofluids**

432 Based on the acquired findings, it can be concluded that at a constant concentration of  
 433 nanoparticles, the MWCNTs/turbine meter oil nanofluid had a higher pressure drop and friction  
 434 coefficient than TiO<sub>2</sub>/turbine meter oil nanofluid. This phenomenon occurred due to the larger  
 435 dimensions of MWCNTs (13 nm) than the TiO<sub>2</sub> nanoparticles (10 nm). The number of particles  
 436 in the nanofluid containing MWCNTs was greater than the nanofluid containing TiO<sub>2</sub>  
 437 nanoparticles. Thus, increasing these particles' movement and random motion increased the  
 438 pressure drop of MWCNTs/turbine meter oil nanofluid. Additionally, due to the shape of the  
 439 MWCNTs, they were more likely to be agglomerated and be more viscous; accordingly, they  
 440 increased the pressure drop and coefficient of friction.

441 Figure 17 shows the velocity profile of nanofluids containing TiO<sub>2</sub> and MWCNTs at  
 442 different positions. It is observed that nanofluids containing MWCNTs developed faster than

443 nanofluids containing TiO<sub>2</sub>. Since the viscosity of MWCNTs/turbine meter oil was higher than  
444 that of TiO<sub>2</sub>/turbine meter oil, the Reynolds number was further reduced and developed faster.

445 Toghraei et al. [69] simulated the flow of a fluid containing platinum and copper  
446 nanoparticles into a nanochannel. They reported that since the size of platinum particles was  
447 larger than copper, the nanofluid containing platinum developed faster.



448  
449 **Fig. 17.** Velocity profile of 0.2 wt% TiO<sub>2</sub> and MWCNTs nanofluids at a flow rate of 0.14

450  $\frac{cm^3}{s}$  at different positions.

## 451 5. Conclusion

452 This simulation aimed to investigate the effect of MWCNTs and TiO<sub>2</sub> nanoparticles on the  
453 performance of the gas turbine meter oil. Moreover, the pressure drop and coefficient of friction  
454 of TiO<sub>2</sub>/turbine meter oil and MWCNTs/turbine meter oil nanofluids were studied.



455 With the increase of concentration of nanoparticles, the pressure drop increased due to the  
456 higher viscosity of the prepared nanofluids at higher concentrations. Furthermore, As the  
457 volume flow rate increased, the nanofluid pressure drop increased. It was further observed that  
458 the coefficient of friction increased with the increase of nanoparticles concentration at a  
459 constant volume flow rate. Considering each nanofluid, it was concluded that the coefficient  
460 of friction was inversely related to the volume flow rate. Concerning the physical  
461 characteristics of the pipe, it was reported that at higher concentrations of nanoparticles, a faster  
462 fully developed state occurred. Moreover, the MWCNTs/turbine meter oil nanofluids  
463 represented a higher coefficient of friction and pressure drops compared to the TiO<sub>2</sub>/turbine  
464 meter oil nanofluid.

#### 465 **Author contribution:**

466 **Atiyeh Aghaei Sarvari:** Investigation, Methodology, Conceptualization, Formal analysis,  
467 Writing original draft. **Saeed Zeinali Heris:** Supervision, Conceptualization, Formal analysis,  
468 Validation, Review & Editing. **Mousa Mohammadpourfard:**, Review & Editing. **Seyed**  
469 **Borhan Mousavi:**, Formal analysis, Writing original draft. **Patrice Estellé:** Validation,  
470 Review & Editing.

#### 471 **6. References**

- 472 [1] S. B. Mousavi, S. Z. Heris, and P. Estellé, "Experimental comparison between ZnO and  
473 MoS<sub>2</sub> nanoparticles as additives on performance of diesel oil-based nano lubricant,"  
474 *Scientific reports*, vol. 10, no. 1, pp. 1-17, 2020.
- 475 [2] S. B. Mousavi, S. Z. Heris, and P. Estellé, "Viscosity, tribological and physicochemical  
476 features of ZnO and MoS<sub>2</sub> diesel oil-based nanofluids: An experimental study," *Fuel*,  
477 vol. 293, p. 120481, 2021.

- 478 [3] Y. Singh, A. Sharma, N. K. Singh, and M. Noor, "Effect of SiC nanoparticles  
479 concentration on novel feedstock Moringa Oleifera chemically treated with  
480 neopentylglycol and their tribological behavior," *Fuel*, vol. 280, p. 118630, 2020.
- 481 [4] A. Boroomandpour, D. Toghraie, and M. Hashemian, "A comprehensive experimental  
482 investigation of thermal conductivity of a ternary hybrid nanofluid containing  
483 MWCNTs-titania-zinc oxide/water-ethylene glycol (80: 20) as well as binary and mono  
484 nanofluids," *Synthetic Metals*, vol. 268, p. 116501, 2020.
- 485 [5] D. Toghraie, N. Sina, N. A. Jolfaei, M. Hajian, and M. Afrand, "Designing an Artificial  
486 Neural Network (ANN) to predict the viscosity of Silver/Ethylene glycol nanofluid at  
487 different temperatures and volume fraction of nanoparticles," *Physica A: Statistical  
488 Mechanics and its Applications*, vol. 534, p. 122142, 2019.
- 489 [6] P. Barnoon, D. Toghraie, F. Eslami, and B. Mehmandoust, "Entropy generation  
490 analysis of different nanofluid flows in the space between two concentric horizontal  
491 pipes in the presence of magnetic field: single-phase and two-phase approaches,"  
492 *Computers & Mathematics with Applications*, vol. 77, no. 3, pp. 662-692, 2019.
- 493 [7] F. T. Hong, A. Schneider, and S. M. Sarathy, "Enhanced lubrication by core-shell TiO<sub>2</sub>  
494 nanoparticles modified with gallic acid ester," *Tribology International*, vol. 146, p.  
495 106263, 2020.
- 496 [8] A. Samadzadeh and S. Z. Heris, "Effect of stabilization method on the natural  
497 convection in an inclined cavity filled with MWCNTs/water nanofluids," *International  
498 Communications in Heat and Mass Transfer*, vol. 129, p. 105645, 2021.
- 499 [9] A. Samadzadeh, S. Z. Heris, I. Hashim, and O. Mahian, "An experimental investigation  
500 on natural convection of non-covalently functionalized MWCNTs nanofluids: effects  
501 of aspect ratio and inclination angle," *International Communications in Heat and Mass  
502 Transfer*, vol. 111, p. 104473, 2020.

- 503 [10] S. Z. Heris, M. Fallahi, M. Shanbedi, and A. Amiri, "Heat transfer performance of two-  
504 phase closed thermosyphon with oxidized CNT/water nanofluids," *Heat and Mass*  
505 *Transfer*, vol. 52, no. 1, pp. 85-93, 2016.
- 506 [11] M. H. Aghahadi, M. Niknejadi, and D. Toghraie, "An experimental study on the  
507 rheological behavior of hybrid Tungsten oxide (WO<sub>3</sub>)-MWCNTs/engine oil  
508 Newtonian nanofluids," *Journal of Molecular Structure*, vol. 1197, pp. 497-507, 2019.
- 509 [12] F. Soltani, D. Toghraie, and A. Karimipour, "Experimental measurements of thermal  
510 conductivity of engine oil-based hybrid and mono nanofluids with tungsten oxide  
511 (WO<sub>3</sub>) and MWCNTs inclusions," *Powder Technology*, vol. 371, pp. 37-44, 2020.
- 512 [13] P. Sreedevi and P. S. Reddy, "Entropy generation and heat transfer analysis of alumina  
513 and carbon nanotubes based hybrid nanofluid inside a cavity," *Physica Scripta*, vol. 96,  
514 no. 8, p. 085210, 2021.
- 515 [14] M. Doğan, A. Selek, O. Turhan, B. K. Kızılduman, and Z. Bicil, "Different functional  
516 groups functionalized hexagonal boron nitride (h-BN) nanoparticles and multi-walled  
517 carbon nanotubes (MWCNT) for hydrogen storage," *Fuel*, vol. 303, p. 121335, 2021.
- 518 [15] E. M. C. Contreras and E. P. Bandarra Filho, "HEAT TRANSFER PERFORMANCE  
519 OF AN AUTOMOTIVE RADIATOR WITH MWCNT NANOFLUID COOLING IN  
520 A HIGH OPERATING TEMPERATURE RANGE," *Applied Thermal Engineering*, p.  
521 118149, 2022.
- 522 [16] Z. Said, P. Sharma, L. S. Sundar, A. Afzal, and C. Li, "Synthesis, stability,  
523 thermophysical properties and AI approach for predictive modelling of Fe<sub>3</sub>O<sub>4</sub> coated  
524 MWCNT hybrid nanofluids," *Journal of Molecular Liquids*, vol. 340, p. 117291, 2021.
- 525 [17] W. He *et al.*, "Using of artificial neural networks (ANNs) to predict the thermal  
526 conductivity of zinc oxide–silver (50%–50%)/water hybrid Newtonian nanofluid,"  
527 *International Communications in Heat and Mass Transfer*, vol. 116, p. 104645, 2020.

- 528 [18] S.-R. Yan, D. Toghraie, L. A. Abdulkareem, A. a. Alizadeh, P. Barnoon, and M.  
529 Afrand, "The rheological behavior of MWCNTs–ZnO/Water–Ethylene glycol hybrid  
530 non-Newtonian nanofluid by using of an experimental investigation," *Journal of*  
531 *Materials Research and Technology*, vol. 9, no. 4, pp. 8401-8406, 2020.
- 532 [19] S. Rostami, D. Toghraie, B. Shabani, N. Sina, and P. Barnoon, "Measurement of the  
533 thermal conductivity of MWCNT-CuO/water hybrid nanofluid using artificial neural  
534 networks (ANNs)," *Journal of Thermal Analysis and Calorimetry*, vol. 143, no. 2, pp.  
535 1097-1105, 2021.
- 536 [20] P. S. Reddy and P. Sreedevi, "Flow and heat transfer analysis of carbon nanotubes based  
537 nanofluid flow inside a cavity with modified Fourier heat flux," *Physica Scripta*, vol.  
538 96, no. 5, p. 055215, 2021.
- 539 [21] P. S. Reddy, P. Sreedevi, and K. V. S. Rao, "Impact of heat generation/absorption on  
540 heat and mass transfer of nanofluid over rotating disk filled with carbon nanotubes,"  
541 *International Journal of Numerical Methods for Heat & Fluid Flow*, 2020.
- 542 [22] P. Sreedevi and P. Sudarsana Reddy, "Impact of Convective Boundary Condition on  
543 Heat and Mass Transfer of Nanofluid Flow Over a Thin Needle Filled with Carbon  
544 Nanotubes," *Journal of Nanofluids*, vol. 9, no. 4, pp. 282-292, 2020.
- 545 [23] P. Sudarsana Reddy, K. Jyothi, and M. Suryanarayana Reddy, "Flow and heat transfer  
546 analysis of carbon nanotubes-based Maxwell nanofluid flow driven by rotating  
547 stretchable disks with thermal radiation," *Journal of the Brazilian Society of*  
548 *Mechanical Sciences and Engineering*, vol. 40, no. 12, pp. 1-16, 2018.
- 549 [24] Z. S. Mahmoudabadi, A. Rashidi, and A. Tavasoli, "Synthesis of two-dimensional  
550 TiO<sub>2</sub>@ multi-walled carbon nanotube nanocomposites as smart nanocatalyst for ultra-  
551 deep oxidative desulfurization of liquid fuel: Optimization via response surface  
552 methodology," *Fuel*, vol. 306, p. 121635, 2021.

- 553 [25] Y. Singh, D. Singh, A. Singla, A. Sharma, and N. K. Singh, "Chemical modification of  
554 juliflora oil with trimethylolpropane (TMP) and effect of TiO<sub>2</sub> nanoparticles  
555 concentration during tribological investigation," *Fuel*, vol. 280, p. 118704, 2020.
- 556 [26] M. Valihesari, V. Pirouzfard, F. Ommi, and F. Zamankhan, "Investigating the effect of  
557 Fe<sub>2</sub>O<sub>3</sub> and TiO<sub>2</sub> nanoparticle and engine variables on the gasoline engine performance  
558 through statistical analysis," *Fuel*, vol. 254, p. 115618, 2019.
- 559 [27] J. Hou, H. Yang, B. He, J. Ma, Y. Lu, and Q. Wang, "High photocatalytic performance  
560 of hydrogen evolution and dye degradation enabled by CeO<sub>2</sub> modified TiO<sub>2</sub> nanotube  
561 arrays," *Fuel*, vol. 310, p. 122364, 2022.
- 562 [28] B. Ruhani, P. Barnoon, and D. Toghraie, "Statistical investigation for developing a new  
563 model for rheological behavior of Silica–ethylene glycol/Water hybrid Newtonian  
564 nanofluid using experimental data," *Physica A: Statistical Mechanics and Its  
565 Applications*, vol. 525, pp. 616-627, 2019.
- 566 [29] P. Sreedevi and P. S. Reddy, "Effect of magnetic field and thermal radiation on natural  
567 convection in a square cavity filled with TiO<sub>2</sub> nanoparticles using Tiwari-Das nanofluid  
568 model," *Alexandria Engineering Journal*, vol. 61, no. 2, pp. 1529-1541, 2022.
- 569 [30] S. Rostami, S. Mahdavi, M. Alinezhadfar, and A. Mohseni, "Tribological and corrosion  
570 behavior of electrochemically deposited Co/TiO<sub>2</sub> micro/nano-composite coatings,"  
571 *Surface and Coatings Technology*, vol. 423, p. 127591, 2021.
- 572 [31] W. H. Kan and L. Chang, "The mechanisms behind the tribological behaviour of  
573 polymer matrix composites reinforced with TiO<sub>2</sub> nanoparticles," *Wear*, vol. 474, p.  
574 203754, 2021.
- 575 [32] M. S. Park, C. S. Lee, J. H. Lee, D. Y. Ryu, and J. H. Kim, "Dissolution–precipitation  
576 approach for long-term stable low-friction composites consisting of mesoporous TiO<sub>2</sub>

- 577 nanospheres and carbon black in Poly (Vinylidene fluoride) matrix," *Tribology*  
578 *International*, vol. 145, p. 106187, 2020.
- 579 [33] A. Shahsavari, S. Khanmohammadi, D. Toghraie, and H. Salihepour, "Experimental  
580 investigation and develop ANNs by introducing the suitable architectures and training  
581 algorithms supported by sensitivity analysis: measure thermal conductivity and  
582 viscosity for liquid paraffin based nanofluid containing Al<sub>2</sub>O<sub>3</sub> nanoparticles," *Journal*  
583 *of Molecular Liquids*, vol. 276, pp. 850-860, 2019.
- 584 [34] I. Ali *et al.*, "Advances in carbon nanomaterials as lubricants modifiers," *Journal of*  
585 *molecular liquids*, vol. 279, pp. 251-266, 2019.
- 586 [35] Y. Singh, N. K. Singh, A. Sharma, A. Singla, D. Singh, and E. Abd Rahim, "Effect of  
587 ZnO nanoparticles concentration as additives to the epoxidized Euphorbia Lathyris oil  
588 and their tribological characterization," *Fuel*, vol. 285, p. 119148, 2021.
- 589 [36] M. Heidari, M. Tahmasebpour, A. Antzaras, and A. A. Lemonidou, "CO<sub>2</sub> capture and  
590 fluidity performance of CaO-based sorbents: Effect of Zr, Al and Ce additives in tri-,  
591 bi-and mono-metallic configurations," *Process Safety and Environmental Protection*,  
592 vol. 144, pp. 349-365, 2020.
- 593 [37] M. Heidari, M. Tahmasebpour, S. B. Mousavi, and C. Pevida, "CO<sub>2</sub> capture activity of  
594 a novel CaO adsorbent stabilized with (ZrO<sub>2</sub>+ Al<sub>2</sub>O<sub>3</sub>+ CeO<sub>2</sub>)-based additive under  
595 mild and realistic calcium looping conditions," *Journal of CO<sub>2</sub> Utilization*, vol. 53, p.  
596 101747, 2021.
- 597 [38] S. S. Seyedi, M. R. Shabgard, S. B. Mousavi, and S. Z. Heris, "The impact of SiC,  
598 Al<sub>2</sub>O<sub>3</sub>, and B<sub>2</sub>O<sub>3</sub> abrasive particles and temperature on wear characteristics of 18Ni  
599 (300) maraging steel in abrasive flow machining (AFM)," *International Journal of*  
600 *Hydrogen Energy*, 2021.

- 601 [39] Y. Singh and E. Abd Rahim, "Michelia Champaca: Sustainable novel non-edible oil as  
602 nano based bio-lubricant with tribological investigation," *fuel*, vol. 282, p. 118830,  
603 2020.
- 604 [40] S. K. Chaurasia, N. K. Singh, and L. K. Singh, "Friction and wear behavior of  
605 chemically modified Sal (Shorea Robusta) oil for bio based lubricant application with  
606 effect of CuO nanoparticles," *fuel*, vol. 282, p. 118762, 2020.
- 607 [41] B. A. Vardhaman, M. Amarnath, J. Ramkumar, and K. Mondal, "Enhanced tribological  
608 performances of zinc oxide/MWCNTs hybrid nanomaterials as the effective lubricant  
609 additive in engine oil," *Materials Chemistry and Physics*, vol. 253, p. 123447, 2020.
- 610 [42] B. Wang, Q. Fu, L. Sun, Y. Lu, and Y. Liu, "Improving the tribological performance of  
611 carbon fiber reinforced resin composite by grafting MWCNT and GNPs on fiber  
612 surface," *Materials Letters*, vol. 306, p. 130953, 2022.
- 613 [43] C. Almeida *et al.*, "Experimental Studies on Thermophysical and Electrical Properties  
614 of Graphene–Transformer Oil Nanofluid," *Fluids*, vol. 5, no. 4, p. 172, 2020.
- 615 [44] H. Akbarpour, A. Rashidi, M. Mirjalili, and A. Nazari, "Comparison of the conductive  
616 properties of polyester/viscose fabric treated with Cu nanoparticle and MWCNT s,"  
617 *Journal of Nanostructure in Chemistry*, vol. 9, no. 4, pp. 335-348, 2019.
- 618 [45] A. S. Al-Janabi, M. Hussin, and M. Abdullah, "Stability, thermal conductivity and  
619 rheological properties of graphene and MWCNT in nanolubricant using additive  
620 surfactants," *Case Studies in Thermal Engineering*, vol. 28, p. 101607, 2021.
- 621 [46] H. Rangaswamy, M. P. G. Chandrashekarappa, D. Y. Pimenov, K. Giasin, and S.  
622 Wojciechowski, "Experimental investigation and optimization of compression  
623 moulding parameters for MWCNT/glass/kevlar/epoxy composites on mechanical and  
624 tribological properties," *journal of materials research and technology*, vol. 15, pp. 327-  
625 341, 2021.

- 626 [47] M. Padhan, U. Marathe, and J. Bijwe, "Tribology of Poly (etherketone) composites  
627 based on nano-particles of solid lubricants," *Composites Part B: Engineering*, p.  
628 108323, 2020.
- 629 [48] R. de la Cruz Parejas, F. J. Moura, R. R. de Avillez, and P. R. de Souza Mendes, "Effects  
630 of Al<sub>2</sub>O<sub>3</sub>-NiO, TiO<sub>2</sub> and (Mg, Ni) O particles on the viscosity of heavy oil during  
631 aquathermolysis," *Colloids and Surfaces A: Physicochemical and Engineering Aspects*,  
632 vol. 625, p. 126863, 2021.
- 633 [49] A. M. Abdullah *et al.*, "Tailoring the viscosity of water and ethylene glycol based TiO<sub>2</sub>  
634 nanofluids," *Journal of Molecular Liquids*, vol. 297, p. 111982, 2020.
- 635 [50] V. V. Wanatasanapan, M. Abdullah, and P. Gunnasegaran, "Effect of TiO<sub>2</sub>-Al<sub>2</sub>O<sub>3</sub>  
636 nanoparticle mixing ratio on the thermal conductivity, rheological properties, and  
637 dynamic viscosity of water-based hybrid nanofluid," *Journal of Materials Research  
638 and Technology*, vol. 9, no. 6, pp. 13781-13792, 2020.
- 639 [51] S. Z. Heris, F. Farzin, and H. Sardarabadi, "Experimental comparison among thermal  
640 characteristics of three metal oxide nanoparticles/turbine oil-based nanofluids under  
641 laminar flow regime," *International Journal of Thermophysics*, vol. 36, no. 4, pp. 760-  
642 782, 2015.
- 643 [52] M. Hosseinzadeh, S. Z. Heris, A. Beheshti, and M. Shanbedi, "Convective heat transfer  
644 and friction factor of aqueous Fe<sub>3</sub>O<sub>4</sub> nanofluid flow under laminar regime," *Journal  
645 of Thermal Analysis and Calorimetry*, vol. 124, no. 2, pp. 827-838, 2016.
- 646 [53] M. K. A. Ali, H. Xianjun, R. F. Turkson, Z. Peng, and X. Chen, "Enhancing the  
647 thermophysical properties and tribological behaviour of engine oils using nano-  
648 lubricant additives," *RSC advances*, vol. 6, no. 81, pp. 77913-77924, 2016.



- 649 [54] F. L. G. Borda, S. J. R. de Oliveira, L. M. S. M. Lazaro, and A. J. K. Leiróz,  
650 "Experimental investigation of the tribological behavior of lubricants with additive  
651 containing copper nanoparticles," *Tribology International*, vol. 117, pp. 52-58, 2018.
- 652 [55] M. Laad and V. K. S. Jatti, "Titanium oxide nanoparticles as additives in engine oil,"  
653 *Journal of King Saud University-Engineering Sciences*, vol. 30, no. 2, pp. 116-122,  
654 2018.
- 655 [56] F. Curà, A. Mura, and F. Adamo, "Experimental investigation about tribological  
656 performance of grapheme-nanoplatelets as additive for lubricants," *Procedia Structural  
657 Integrity*, vol. 12, pp. 44-51, 2018.
- 658 [57] A. A. Hussien, N. M. Yusop, M. Z. Abdullah, A.-N. Moh'd A, and M. Khavarian,  
659 "Study on convective heat transfer and pressure drop of MWCNTs/water nanofluid in  
660 mini-tube," *Journal of Thermal Analysis and Calorimetry*, vol. 135, no. 1, pp. 123-132,  
661 2019.
- 662 [58] A. Naddaf, S. Z. Heris, and B. Pouladi, "An experimental study on heat transfer  
663 performance and pressure drop of nanofluids using graphene and multi-walled carbon  
664 nanotubes based on diesel oil," *Powder Technology*, vol. 352, pp. 369-380, 2019.
- 665 [59] S. B. Mousavi, S. Z. Heris, and M. G. Hosseini, "Experimental investigation of  
666 MoS<sub>2</sub>/diesel oil nanofluid thermophysical and rheological properties," *International  
667 Communications in Heat and Mass Transfer*, vol. 108, p. 104298, 2019.
- 668 [60] R. K. Ajeel and W.-I. Salim, "Experimental assessment of heat transfer and pressure  
669 drop of nanofluid as a coolant in corrugated channels," *Journal of Thermal Analysis  
670 and Calorimetry*, pp. 1-13, 2020.
- 671 [61] H. Pourpasha, S. Z. Heris, O. Mahian, and S. Wongwises, "The effect of multi-wall  
672 carbon nanotubes/turbine meter oil nanofluid concentration on the thermophysical  
673 properties of lubricants," *Powder Technology*, vol. 367, pp. 133-142, 2020.

- 674 [62] E. S. Menon, *Working Guide to Pump and Pumping Stations: Calculations and*  
675 *Simulations*. Gulf Professional Publishing, 2009.
- 676 [63] M. Kutz, *Mechanical Engineers' Handbook, Volume 4: Energy and Power*. John Wiley  
677 & Sons, 2015.
- 678 [64] M. Everts and J. P. Meyer, "Laminar hydrodynamic and thermal entrance lengths for  
679 simultaneously hydrodynamically and thermally developing forced and mixed  
680 convective flows in horizontal tubes," *Experimental Thermal and Fluid Science*, vol.  
681 118, p. 110153, 2020.
- 682 [65] P. Samira, Z. H. Saeed, S. Motahare, and K. Mostafa, "Pressure drop and thermal  
683 performance of CuO/ethylene glycol (60%)-water (40%) nanofluid in car radiator,"  
684 *Korean journal of chemical engineering*, vol. 32, no. 4, pp. 609-616, 2015.
- 685 [66] S. B. Mousavi and S. Z. Heris, "Experimental investigation of ZnO nanoparticles  
686 effects on thermophysical and tribological properties of diesel oil," *International*  
687 *Journal of Hydrogen Energy*, vol. 45, no. 43, pp. 23603-23614, 2020.
- 688 [67] M. Gholinia, S. Gholinia, K. Hosseinzadeh, and D. Ganji, "Investigation on ethylene  
689 glycol nano fluid flow over a vertical permeable circular cylinder under effect of  
690 magnetic field," *Results in Physics*, vol. 9, pp. 1525-1533, 2018.
- 691 [68] L. Bao, C. Zhong, P. Jie, and Y. Hou, "The effect of nanoparticle size and nanoparticle  
692 aggregation on the flow characteristics of nanofluids by molecular dynamics  
693 simulation," *Advances in Mechanical Engineering*, vol. 11, no. 11, p.  
694 1687814019889486, 2019.
- 695 [69] D. Toghraie, M. Mokhtari, and M. Afrand, "Molecular dynamic simulation of copper  
696 and platinum nanoparticles Poiseuille flow in a nanochannels," *Physica E: Low-*  
697 *dimensional Systems and Nanostructures*, vol. 84, pp. 152-161, 2016.
- 698