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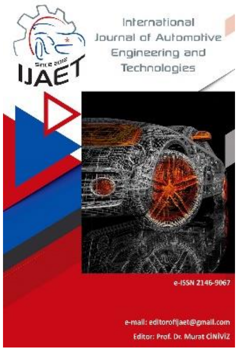

Original Research Article

Experimental investigation of heat transfer performance of different nanofluids in engine cooling system

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ABSTRACT

Cooling systems are needed for internal combustion engines to operate efficiently. The fluid traditionally used to transfer heat in cooling systems is a mixture of ethylene glycol (EG) and water (W). These fluids generally exhibit an effect that extends the operating temperature range and limits the heat output. On the other hand, nanofluids are known to increase the thermal capacity of liquid suspensions and have been studied in many experimental and numerical studies. This study examines the effects of nanofluids instead of currently used EG-Water on an actual vehicle. Three different nanofluids (TiO_2, Al_2O_3, and SiO_2) were used, and the concentration ratios of these fluids were determined as 0.1% and 0.2%. A real vehicle engine cooling system with a volume of 1400 cm^3 operating at an average of 2000 rpm was used in the studies. Fluids that are widely studied in the literature were taken into account when selecting nanofluids. The results showed that SiO_2 achieved the highest performance, with an increase of 15% compared to the base fluid. On the other hand, it was observed that increasing the concentration value of TiO_2 exhibited a lower performance increase compared to other nanofluids. Finally, it has been observed that the operating temperature range of nanofluids affects.

Keywords: Cooling system; Experimental; Heat transfer rate; Internal combustion engine; Nanofluid

1. Introduction

The rapid development and change in the automotive industry have led to increased thermal loads and hence the need for higher cooling rates [1]. If the cooling system cannot provide sufficient cooling to keep the engine within a well-defined temperature range, performance and durability will decrease, and emissions will increase. Although increasing the radiator size is a solution here, this causes an increase in the vehicle's weight and, therefore, more fuel consumption [2]. Considering today's environmental concerns, the costs of increased fuel consumption and the additional emission caused by excessive fuel consumption are highly undesirable [3]. Traditional methods, such as the development of fins and the addition of microchannels, have already been extended to their limits [4].

On the other hand, ethylene glycol (EG)-Water (W) mixtures are used as heat transfer fluid in engines [1]. Mixing EG with the engine coolant is an indispensable solution for using vehicles in all climatic conditions. However, heat transfer is limited in heating-cooling processes using traditional fluids, such as EG-W, due to the fluids' limited thermal properties [5]. Therefore, improving the thermal properties of the heat transfer fluid can be offered as a solution since the radiator design parameters have reached their limits [6]. In this context, it is a helpful approach to use nanofluid (NF) as a heat transfer fluid in cooling systems [7]. The literature has reported that the use of nanofluids in different areas, such as ground heat exchangers [8], solar thermal collectors [9], or mini-duct coolers [10], gives successful results. Nanomaterials have even been successfully applied to coat radiator fins [11]. Investigating the use of NFs in automobile radiators is given in Table 1. These studies have observed increased heat transfer using NFs at different mixing ratios.

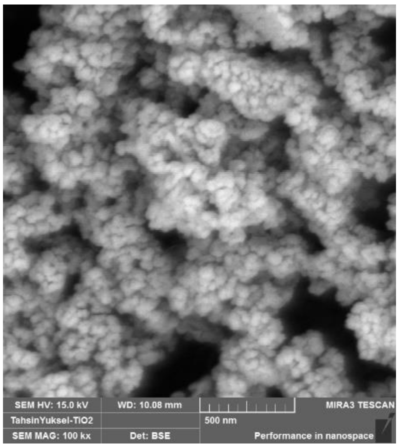
As seen from the studies given in Table 1, it can be said that using nanofluids in radiators increases the heat transfer rate. Thanks to the increase in heat transfer rate, the required cooling amount can be achieved with a smaller radiator [12]. More compact and lighter radiators provide both an increase in vehicle performance and a decrease in fuel consumption by decreasing weight [5, 13, 14]. The concentration ratio of nanoparticles mixed in the heat transfer fluid also affects the heat transfer. Studies carried out by adding nanoparticles at different volumetric concentrations into EG-W have indicated that as the density of nanoparticles increases, the volumetric concentration of nanoparticles increases; however, as the temperature increases, the thermal conductivity decreases [15]. Furthermore, studies have concluded that the heat transfer performance of the radiator in the heat transfer fluid is significantly increased with the increase in nanoparticle concentration [16, 17].

Table 1. Heat transfer studies in automobile radiators where nanofluids are used.

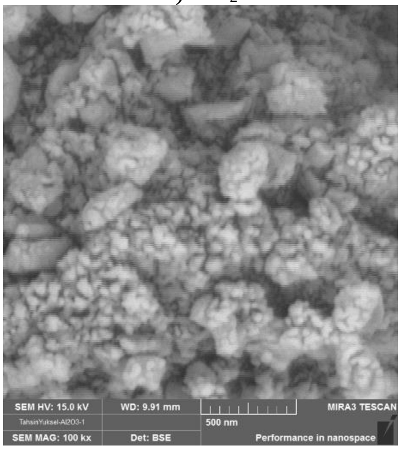
Researchers (Year)	**Nanofluid**	**(% vol.)**	**Findings**
Said et al. [4] 2019	Al_2O_3 – (EG-W) (50:50) TiO_2 - (EG-W) (50:50)	0.05 - 0.3	It has been found that the thermal conductivity of 0.3% Al_2O_3 NF was higher than TiO_2 NF.
Tijani and Sudirman [5] 2018	Al_2O_3 – (EG-W) (50:50) CuO – (EG-W) (50:50)	0.05 - 0.3	The heat transfer performance of CuO NF is the highest.
Jadar et al. [12] 2017a	MWCNT – (DI-W)	0.1	An increase in heat transfer performance of 45% has been obtained with the use of NF.
Peyghambarzadeh et al. [13] 2011	Al_2O_3 – W Al_2O_3 – EG (0, 10, 20 EG)	0 - 1 0 - 1	The heat transfer increase obtained with NFs has been approximately 40%.
Hussein et al. [14] 2014	SiO_2 – W	1 - 2.5	It has been determined that using NF increases heat transfer performance by up to 50%.
Tadepalli et al. [15] 2018	Al_2O_3, SiO_2, SiC, TiO_2, CuO - Liquid Oxygen	1 - 5	It has been found that the increase in temperature decreases the thermal conductivity, while the increase in volumetric concentration increases the thermal conductivity.
Subhedar et al. [16] 2018	Al_2O_3 – (EG-W) (50:50)	0.2 - 0.8	It has been found that using NF improves heat transfer performance even in the lowest amount (0.2%).
Ahmed et al. [17] 2018	TiO_2– W	0.1 - 0.3	It has been found that the increase in the volumetric concentration of NF positively affected the average heat transfer coefficient.
Peyghambarzadeh et al. [18] 2011	Al_2O_3 – W	0.1 - 1	45% heat transfer increase has been obtained with Al_2O_3 NF.
Elias et al. [19] 2014	Al_2O_3 – (EG-W) (50:50)	0 - 1	The volumetric increase of NF has increased the density, viscosity, and thermal conductivity values.
Nieh et al. [20] 2014	Al_2O_3 – (EG-W) (50:50) TiO_2 - (EG-W) (50:50)	0.2	It has been determined that TiO_2 NF has higher thermal conductivity than Al_2O_3.
M’hamed et al. [21] 2016	MWCNT – (EG-W) (50:50)	0.1 - 0.5	The increase in volumetric concentration has affected the average heat transfer increase in direct proportion.
Li et al. [22] 2016	SiC - (EG-W) (40:60)	0 - 0.5	The thermal conductivity of SiC NF is higher compared to the base fluid.
Elsebay et al. [23] 2016	Al_2O_3 – W CuO – W	0 - 7	It has been found that the heat transfer rate in the radiator can be increased by increasing the NF addition rate.
Elsaid [24] 2019	Al_2O_3 - (EG-W) (0:100, 10:90, 20:80)	0 - 0.2	It has been found that Co_3O_4 NF has higher thermal performance than Al_2O_3 NF.
Muruganandam and Mukesh Kumar [25] 2020	MWCNT - W	0.1 - 0.5	The mechanical efficiencies of NFs are higher than water.
Mukherjee et al. [26] 2020	Al_2O_3 – W TiO_2 - W	0.125 - 1.5	Al_2O_3 NFs have provided better thermal conductivity and transient heat conduction performance.

Table 2. Properties of nanoparticles.

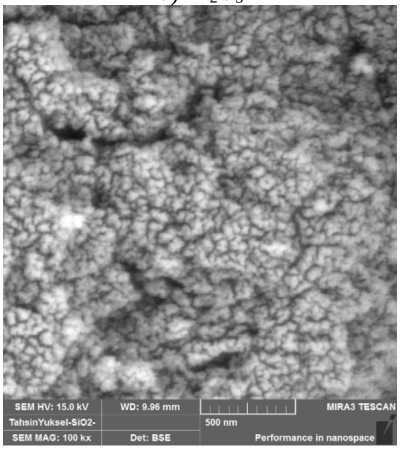
Properties	**TiO_2**	**Al_2O_3**	**SiO_2**
Colour	White	White	White
Particle size (nm)	25-45	28	5-20
Purity	99.9%	99.99%	99.99%
Particle morphology	Almost spherical	Almost spherical	Almost spherical
Dissolution in water	Indissoluble	Indissoluble	Indissoluble
Density (gr/cm^3)	4.23	3.5 – 3.9	2.3 [4, 27 - 30]
Thermal conductivity (W/mK)	8.95	40	1.34 – 1.4 [4, 27 - 30]
Specific heat (J/kgK)	686	765	745 [4, 27 - 30]



a) TiO_2



b) Al_2O_3



c) SiO_2

Fig. 1. SEM images of TiO_2, Al_2O_3, and SiO_2

However, it should be noted that the studies mentioned above were carried out in a laboratory environment. At this stage, it should not be ignored that there will be differences between the heat transfer values obtained from studies using only vehicle radiators in laboratory environments and the actual operating conditions obtained using a vehicle engine.

In order to evaluate the overall performance of a system, the geometry considered in the experiment and the system's geometry must be well-matched. When comparing the experimental and simulation results, even open or closed thermostats can cause large deviations in many parameters [31]. Although considering only a specific part, such as the radiator, gives us valuable results, it may be insufficient to reveal the performance values of the entire system. Examining only the radiator side causes the flow in areas such as water jackets, ducts, or connecting pipes inside the engine to be ignored. Using an internal combustion engine and existing cooling system, heat transfer values will show different values compared to laboratory conditions using conventional heat transfer fluids and NFs. The results calculated and found in the literature should be verified by applying all these results to real engines. In addition, it is aimed to form a basis for the numerical studies to be carried out thanks to this study. This study investigated the performance of nanofluid-assisted coolant in a vehicle cooling system. The examined system has all the cooling system components that a vehicle should have. Three different NFs (TiO_2, Al_2O_3, and SiO_2) prepared in different volumetric fractions (0.1% and 0.2%) were used in the study.

2. Materials and Methods

2.1. Nanofluids

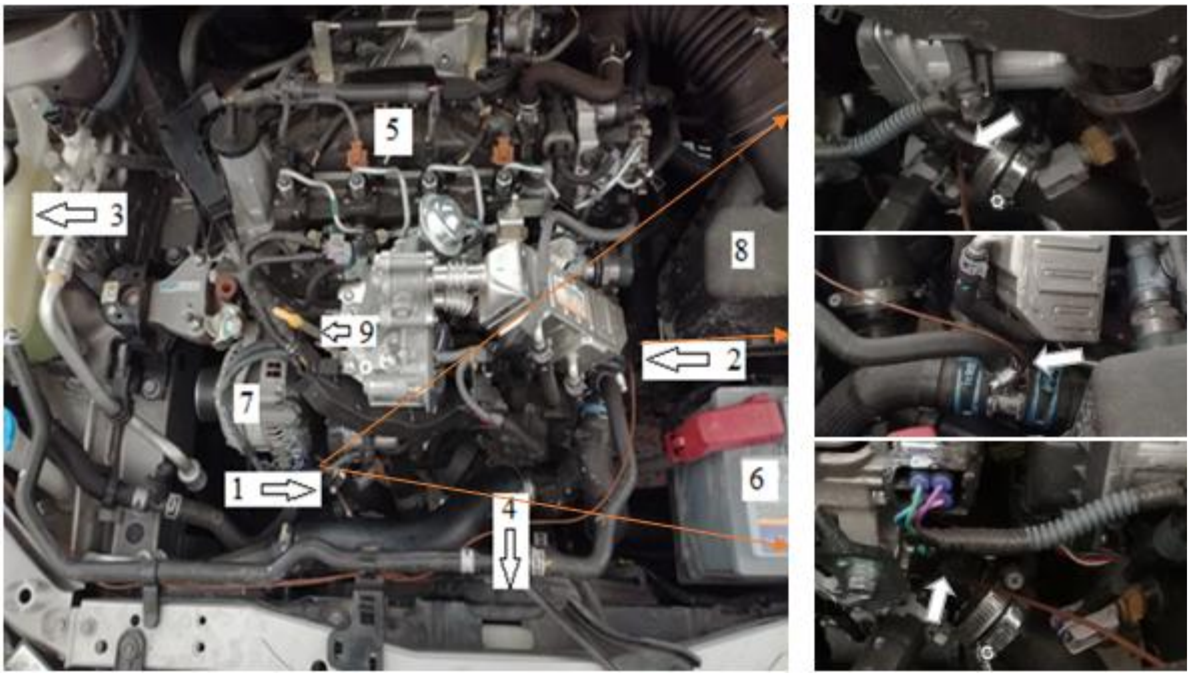
When comparing the cooling system's heat transfer performance, the preferred 1:1 mixture of EG-W as the base fluid to prevent freezing in cold climate conditions (approximately freezing point -34 °C, approximately boiling point 107 °C [32]) was used. NFs were prepared by mixing nanoparticles in volumes of 0.1% and 0.2% into the mixture. The nanodispersions used in the study (TiO_2, Al_2O_3, and SiO_2) were purchased in 100 ml ready-made packages prepared by the Nanography company. Sodium Dodecyl Sulphate (SDS) has been used as a surfactant for TiO_2 and Al_2O_3 NFs used in the study.

No surfactant has been used for SiO_2. Later, NFs were prepared by using an ultrasonic mixer to prevent sedimentation and agglomeration. The technical properties of the specified NFs are given in Table 2. The SEM images obtained as a result of their examination in Sivas Cumhuriyet University Advanced Technology Research and Application Center Laboratories are given in Fig. 1.

Eq. (1) was used to calculate the volume percentage of NFs and the volume of the base fluid. The lower concentration was obtained by adding the base fluid pre-calculated using Eq. (2). [22,24,27]:

$$\varphi = \frac{m_n / \rho_n}{m_n / \rho_n + m_f / \rho_f} x100 \tag{1}$$

$$\Delta V = V_2 - V_1 = V_1(\varphi_1 / \varphi_2 + 1) \tag{2}$$



1-Fluid outlet (Radiator inlet thermocouple connection)
1-Thermostat slot
2-Fluid inlet (Radiator outlet thermocouple connection)
3- Expansion tank
4- Radiator
5- Engine
6- Accumulator
7- Alternator
8- Air filter
9- Dipstick

Fig. 2. Temperature measurement points on the engine

2.2. Experimental Setup

The vehicle in the Sivas Cumhuriyet University Automotive Laboratory was used in the experiments. Some technical features of the vehicle and the cooling system on which the tests were carried out are given in Table 3. Fig. 2 shows all temperature measurement points. T-type thermocouples were used in these measurements Thermocouples placed in the motor body are insulated, so they are not affected by the outside temperature. In the experiments, fluid temperatures were measured from the radiator inlet (1) and outlet (2), and all measurements were recorded every 5 seconds with a data logger. The engine rpm of the vehicle was monitored from both the tachometer of the vehicle and the Bosch BEA 350 device, which was connected to the vehicle through the OBD (On-board Diagnostics), and the measurements were made by keeping it at 2000 rpm. In the experiments, the thermostat was removed from the engine to examine the fluid temperature change continuity and to facilitate fluid circulation.

Table 3. Engine and radiator specifications.

Experiment vehicle	Descriptions
Model of the vehicle	2014
Number of cylinders	4
Engine volüme	1400 cm^3
Fuel type	Diesel
Cooling system	
Heat transfer fluid capacity	~4.5 L
Thermostat opening temperature	~82 °C
Fan operating temperature	~90 °C
Radiator dimensions (mm)	625x390x25

The experimental setup was first filled into the vehicle's cooling system, whose features are specified in Table 3, with the fluid formed by the mixture of EG-W at a ratio of 1:1 as the base fluid, and experiments were carried out. To avoid any problems in fluid circulation, the air of the system was deaerated every time the heat transfer fluid was filled into the engine. In the following stages, the experiments continued by mixing NFs in the same amount of EG-W mixing with the ratio of 0.1% and 0.2% volumetric concentration. Temperatures above 50 °C were included in the experimental measurements. The vehicle was operated in a closed laboratory environment with ventilation to eliminate the differences in experimental operating conditions. The laboratory temperature was kept at 20 °C, and the exhaust gas discharge of the vehicle was given to the outside environment. After the experiments, the engine cooling system was cleaned by washing it with water. The experiments with each fluid (EG-W, EG-W- TiO_2 (0.1%), EG-W- TiO_2 (0.2%), EG-W- Al_2O_3 (0.1%), EG-W- Al_2O_3 (0.2%), EG-W- SiO_2 (0.1%), EG-W- SiO_2 (0.2%)) were repeated four times. In the experimental environment, which was kept at 20 °C, experimental measurements were started when the inlet temperature of the heat transfer fluid to the radiator was 50 °C, and the measurements were terminated when the radiator inlet temperature was 90 °C. At this temperature value, the fan on the radiator was activated, reducing the heat transfer fluid temperature in circulation. In this process, the engine operating cycle was fixed at an average of 2000 rpm. The study measured the time of the heat transfer fluid from the radiator inlet of the cooling system from 50 °C to 90 °C.

2.3. Uncertainty Analysis

The accuracy of the measurement values obtained from the experimental study is critical. There may be errors in temperature measurements due to measurement tools and the experimental system. The error analysis method for determining the uncertainty in experiments was presented by Kline and McClintock [24,33]. Considering the errors occurring during temperature measurement, the total error calculation can be obtained from equation (4). The WR uncertainty arising from different independent variables is obtained from equation (3). In the expressions in the equation, R dependent variable is a function of arguments x1, x2, x3,…, xn. From here: R = R (x1, x2, x3,…, xn). WR is the uncertainty in the result and the uncertainties in the arguments w1, w2, w3,…., wn. The resulting uncertainty expression is as follows:

$$W_R = \left[\left(\frac{\partial R}{\partial x_1} w_1 \right)^2 + \left(\frac{\partial R}{\partial x_2} w_2 \right)^2 + ... + \left(\frac{\partial R}{\partial x_n} w_n \right)^2 \right]^{1/2} \quad (3)$$

Total uncertainty (WR) can be determined as in equation (4);

$$W_R = \left[(a_1)^2 + (a_2)^2 + ... + (a_n)^2 \right]^{1/2} \quad (4)$$

a_1 - Error caused by the measurement device ± 0.5 °C,

a_2 – Error caused by thermocouple ± 0.5 °C,

a_3 – Error caused by connection points of measuring elements ±0.1 °C,

a_4 – Average error that can be made in measuring the temperature at the radiator inlet ±0.25 °C,

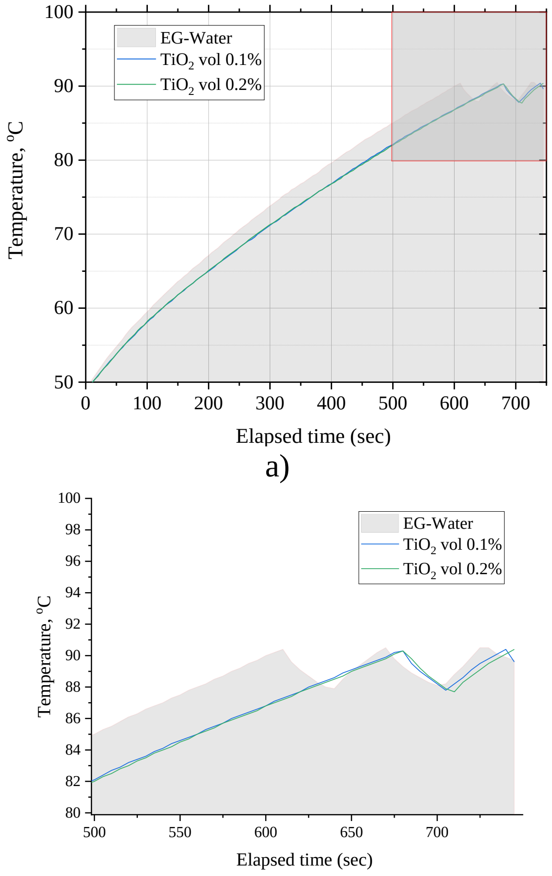
a_5 – Average error that can be made in measuring the ambient or experimental environment temperature ±0.25°C,

a_6 – Average error that can be made in measuring the temperature at the radiator outlet ±0.25 °C,

The uncertainties in the fluid temperature measurement at the engine radiator inlet, the engine radiator outlet, and the test environment or ambient temperature measurements were determined as ± 0.76 °C for the whole system.

3. Results and Discussion

In Fig. 3, the experiment's results with TiO_2 nanofluid are given. The experiments observed that the base fluid temperature increased to 90 °C in the 609th second. This value was found to be 680 seconds and 681 seconds for 0.1% and 0.2% TiO_2 NF, respectively. Although reaching the desired temperature early is the desired situation in engines, it should not be forgotten that the thermostat that controls the flow in the engine is removed here. The thermostat makes it easier for the engine to reach the desired temperature by bypassing the flow to the engine until a specific temperature value. It then allows the flow, preventing the engine's temperature from rising further. However, when the thermostat is removed, the fluid that passes freely into the engine increases the time for the engine to reach the desired set value.



a)

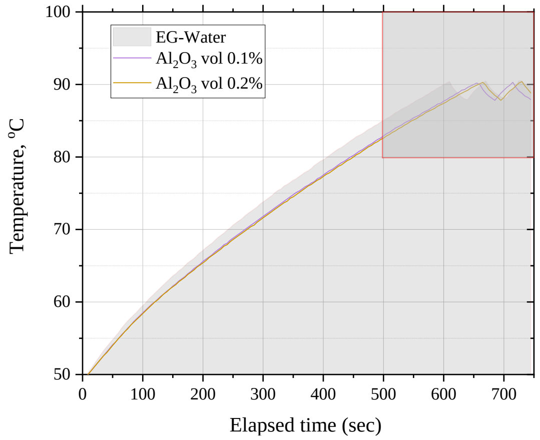
b)

Fig. 3. Comparison of EG-W mixture and TiO_2 (0.1% and 0.2%) NF mixture (50-90 °C)

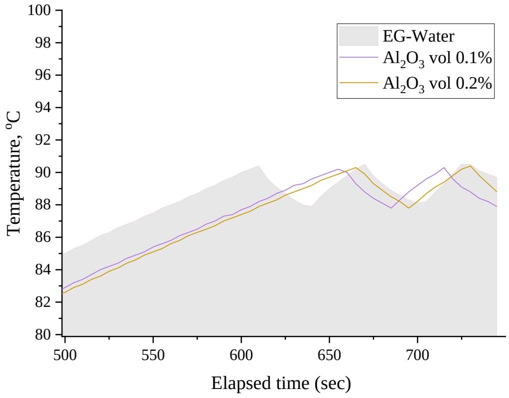
On the other hand, liquids with higher thermal conductivity transfer more heat to the external environment, extending this period even more. In the case that occurs here, reaching the desired temperature value later can be interpreted as an increase in the thermal performance of the fluid and is attributed to the increase in heat transfer. In Fig. 3, it takes longer depending on the heat discharged from the radiator with 0.1% and 0.2% TiO_2 NF.

However, interestingly, no significant difference was observed between 0.1% and 0.2% TiO_2 NFs. Said et al. [34] found that the rate of increase in TiO_2 NFs between 0.05% and 0.3% was approximately 65% less than the other NF (Al_2O_3) examined. The results obtained from this study and Said et al.'s results show parallelism. As a result, although TiO_2 increases the heat transfer rate, the heat transfer is quite limited with the increase in concentration.

Fig. 4 the results of the experiment with Al_2O_3 NF results. Similar to TiO_2 NF, an increase in heat transfer was observed in 0.1% and 0.2% Al_2O_3 NF. It can be said that the increase obtained here is at a lower rate compared to TiO_2. While the time to reach optimum operating conditions in TiO_2 took 680 seconds, this time was around 655 seconds in Al_2O_3.



a) General view (50-90 °C)

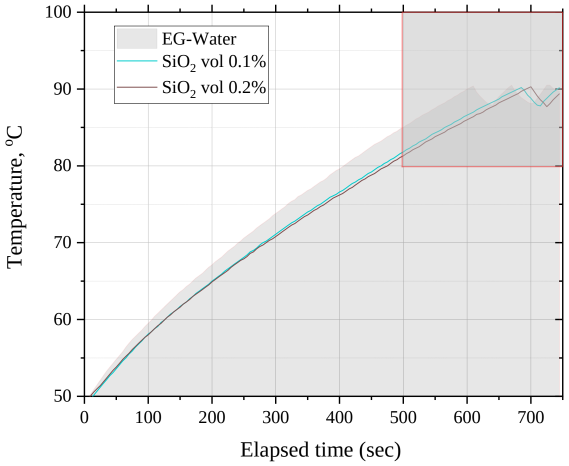


b) Detail view

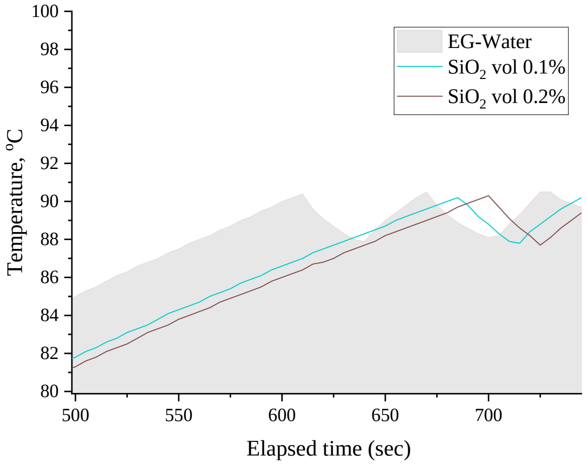
Fig. 4. Comparison of EG-W mixture and Al_2O_3 (0.1% and 0.2%) NF mixture (50-90 °C)

However, unlike TiO_2, there is a distinct difference between 0.1% and 0.2%. The difference increases in parallel with the increase in temperature. Experiment results with SiO_2 NF are given in Fig. 5. The time to reach the optimum operating temperature in

SiO_2 NF compared to other NFs increased significantly under optimum operating conditions. SiO_2 increased the time to reach 90 °C by approximately 14.8%. In addition, SiO_2 NF was also affected at the highest level by the temperature increase. While the 300 sec temperature difference was 0.3 °C, this difference increased to 0.6 °C in 600 sec.



a) General view (50-90 °C)



b) Detail view

Fig. 5. Comparison of EG-W mixture and SiO_2 (0.1% and 0.2%) NF mixture (50-90 °C)

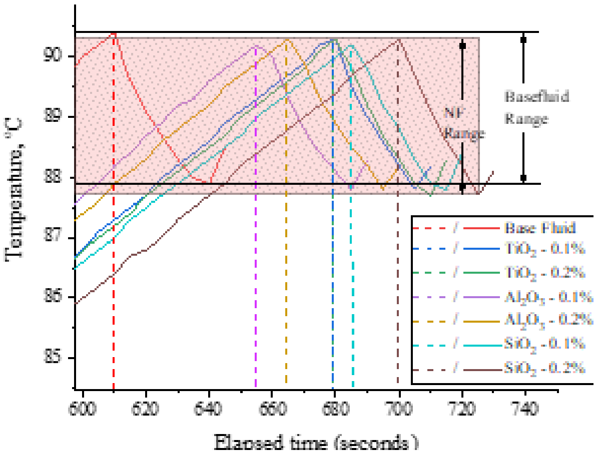


Fig. 6. Comparison of EG-W mixture and 0.1% and 0.2% NF

Comparisons of all examined NFs by concentration value are given in Fig. 6. It was determined that the heat transfer performance of the heat transfer fluid increased by approximately 9% with Al_2O_3 NF, approximately 12% with TiO_2 NF, and approximately 15% with SiO_2 NF. In addition, when the volumetric fractions of NFs mixed into the base fluid were examined, the highest heat transfer values were obtained with 0.2% volumetric fractions. This showed that the increase in NF volumetric fraction in the heat transfer fluid positively affected the heat transfer [15].

Among the NFs used, the highest heat transfer was achieved with the SiO_2 mixture. As it is known, the presence of nanoparticles and their random motion in the base fluid cause the thickness of the thermal boundary layer to decrease and contribute to the improvement of heat transfer. Although the heat transfer enhancement is generally attributed to the nanoparticle dispersion in the literature, the Brownian motions of the particles should not be ignored [35]. It can be said that the smaller size of SiO_2 in our study than the other nanoparticles examined and the Brownian motions (random movement of nanoparticles in the base fluid) due to the relatively increasing number of particles in the nanofluid contribute to the improvement of heat transfer. Compared to the base fluid, TiO_2 Al_2O_3 and SiO_2 NFs with 0.1% concentration extended the time to reach the optimum operating temperature value by 11.5%, 7.4%, and 12.3%, respectively. These values were 11.5%, 9.0% and 14.8% for TiO_2 Al_2O_3 and SiO_2 NFs with 0.2% concentration, respectively. On the other hand, as expected, NFs moved the operating range down. Working fluids were filled into glass containers (jars) after the experiments to monitor the behavior of solid nanoparticles in the base fluid. No sedimentation was observed in EG mixed into water, while there were sedimentations in all NFs, which were kept in the same condition for approximately two weeks. Therefore, sedimentation was identified as a problem for NFs, which had higher heat transfer performance than the base fluid. Therefore, in the cooling systems of vehicles that are kept unused for a long time, the heat transfer fluid will collapse on the canal surfaces and form a mold layer. However, for frequently used internal combustion engines are not considered a significant problem.

4. Conclusions

This study investigates the usability of 3 different NFs (TiO_2, Al_2O_3, and SiO_2) at different concentration ratios (0.1% and 0.2%) in an existing vehicle cooling system. The results obtained within the scope of the study are thought to contain valuable results in preparing numerical studies and verifying laboratory tests. The essential findings obtained as a result of the study can be listed as follows:

Thanks to nanofluids, the heat produced in the engine is transferred to the environment at higher rates through the radiator, reaching optimum operating conditions later. This situation can be interpreted as an increase in the heat transfer rate and is directly related to the amount of heat transfer. NFs used in the cooling system extended the time to reach optimum operating conditions by 11.5%, 9.0% and 14.8% for Al_2O_3, TiO_2, and SiO_2, respectively.

In the study, it was determined that the performance increase due to the increase in TiO_2 concentration was quite limited. The most remarkable heat transfer change due to the concentration increase was observed in SiO_2. Particle size is thought to be effective here.

The operating temperature range associated with the on-off of the radiator fan has changed in the use of NF. The main reason for this change is that NFs respond faster to thermal changes in the system than the base fluid. Within the scope of the study, the stability states of nanofluids were also investigated. It has been observed that precipitation occurs in nanofluids that are kept for a certain period. It has been observed that nanoparticles adhere to the walls of radiator pipes similarly.

Conflict of Interest Statement

The authors must declare that there is no conflict of interest in the study.

CRediT Author Statement

Tahsin Yüksel: Conceptualization, Supervision, Writing-original draft,**Abdullah Kapıcıoğlu:** Conceptualization, Validation, Data curation, Formal analysis

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Nomenclature

EG	: ethylene Glycol
W	: water
DI	: de-ionized
NF	: nanofluid
MWCNT	: multi-wall carbon nanotubes
OBD	: On-board Diagnostics
V	: volume, m^3
m	: mass (kg)
ρ	: density ($kg.m^{-3}$)
n	: nanofluid
f	: base fluid
1	: initial
2	: final

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