Comparison of effects of nanofluid utilization (Al_2O_3 , SiO_2 , TiO_2) with reference water in automotive radiators on exergetic properties of diesel engines

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Abstract

In this study, nanofluids formed by using ethylene glycol and three kinds of nanoparticles such as Al_2O_3 , SiO_2 , and TiO_2 were added to the four-stroke internal combustion engine radiator and compared with the conventional coolant (pure water). This comparison is based on the exergy performances which are the main theme of the second law of thermodynamics. The tests were carried out at a fixed engine speed of 1800 rpm using diesel fuel, and the outputs were obtained from the test setup experimentally. A total of six nanofluid tests were performed on two different dispersions (0.2% and 0.4%). As a result of this study, the best exergy efficiency was obtained by using TiO_2 particles with a 35.67% value. Increasing the percentage of nanoparticles in the fluid from 0.2 to 0.4 positively affected efficiency. Pure water generally lagged behind nanofluid performance in experimental parameters. Compared to conventional coolant (pure water), the lowest exhaust temperature value was measured by using an Al_2O_3 /Ethylene Glycol mixture with a difference of 59 K. Also, by using Al_2O_3 nanoparticles as a coolant, 8.858 kW of exergy exhaust value was obtained. This is the best emission value measured in the experimental study. While calculating values close to each other in the use of other nanoparticles, the worst exergy exhaust results were obtained by using the conventional refrigerant. Consequently, in this paper, exergetic outputs such as exergetic efficiency, exergy destruction, exergy heat, exergy work, exergy total exhaust, and entropy production rate were calculated for pure water and each nanofluid.

Keywords Exergy analyses · Nanofluid · Automotive radiator · Al_2O_3 nanoparticle · SiO_2 nanoparticle · TiO_2 nanoparticle

1 Introduction

The cooling system has vital importance in regulating the engine temperature. The resulting temperature in the combustion chamber of the engine cylinder reaches 1500–2000 °C. These temperature values are above the melting point of the materials from which the cylinder block and head of the engine are produced. Most of the engine blocks are produced from cast iron and aluminum alloys that have lower melting points compared to burning temperature. Therefore, if the high temperatures

generated by combustion gases cannot be removed, serious deformations will occur on the cylinders.

The radiator is the main part of an engine cooling system. It consists of three basic parts; inlet tank, outlet tank, and core. Two types of working fluids are generally in the engine cooling system. They are air and coolant. The main purpose of the air is to remove the heat from the hot coolant and ensure circulation that it is cold in the engine block [1]. Trivedi and Vasava modeled the mass flow rate of the air passing through the automotive radiators on the CFD [2]. The current automotive radiators work with circulating

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fluid which is regulated by water and a mixture of water and coolant materials like ethylene glycol (EG). Under normal weather conditions, the mixing ratio of water and EG is generally applied as 50:50 in the radiators. However, in colder weather conditions, when the percentage of EG in the mixture is increased, the circulating fluid becomes more resistant to freezing. The conventional heat transfer fluids such as water and ethylene glycol are often limited due to their low thermal conductivities [3]. The enhancement of heat transfer in an automotive radiator may create a saving in energy, reduce process time, raise the thermal rating, and lengthen the working life of the equipment. The current system is no longer enough and so, a new heat transfer technology requirement rises day by day.

Yu et al. explained applications area of nanofluids such as transportation, electronics cooling, defense, space, nuclear systems cooling, and biomedicine, etc. in their study [4]. Nanoparticles have also the potential to be used in the engine cooling system since they increase the rate of heat transfer of the fluids. Hussein et al. examined the variation of Nusselt numbers at different Reynold numbers using TiO_2 -Water and SiO_2 -Water nanofluids as coolants in automotive radiators. They obtained maximum Nusselt number enhancements of up to 11% for TiO_2 and 22.5% for SiO_2 in water [5]. Vajjha et al. used Al_2O_3 /Ethylene glycol and CuO /Ethylene glycol nanofluids as a coolant to flat tube in the automotive radiator and studied laminar heat transfer numerically [6]. In this experimental study, the effects of nanoparticle utilization in diesel engine radiator will be investigated. Nanoparticles, water, and ethylene glycol mixture will be used as a coolant fluid to enhance heat transfer. Exergy analysis will be done on the system. The control volume of the system is composed of an engine and heat exchanger (engine radiator) together. In terms of understanding energy efficiency, the first law of thermodynamics, that is, the quality of energy is as important as the quantity. Considering this quality, not enough information has been given in the studies in the literature so far. Therefore, it is very important to make the second law analysis of thermodynamics in terms of understanding the nature of heat transfer in automotive radiators. This study was made to fill this gap in the literature. Exergy is briefly defined as the maximum useful work of a system as it comes to equilibrium with a reference environment [7]. The second law of thermodynamics forms the basis of the exergy analysis which has recently become popular [8]. Çalışkan et al. studied the effect of exergetic output of different dead state temperatures using HOME fuel on the John Deere 45 T diesel engine [9]. Tosun has made exergy analyses of diesel No.2, canola biodiesel, and peanut biodiesel on ICE [10]. Çalışkan used diesel No.2, SME, and HOME fuels on the John Deere 45 T diesel engine to calculate exergy analyses in his study [7]. Ma et al.

conducted energy and exergy studies using different inlet airflow rates on the natural convection energy recovery loop analysis [11]. Heydari et al. conducted exergy analyses to optimize the hydrothermal performance of a specific heat exchanger through Taguchi empirical method [12]. Yan et al. worked on the experimental studies for energy economy management on a new generation air conditioning system [13]. Ahmadi et al. examined thermodynamically the effects of regeneration of the combined heat and power (CHP) system existing in a petrochemical plant and calculated the exergy efficiency [14]. In a similar study, Ahmadi et al. conducted energy, exergy, and environment analysis on the CHP system, known as 3E [15]. Dabiri et al. calculated a parametric analysis of the thermal characteristics in a special receiver for a special 3-collector concentrator [16]. Jozaalizadeh et al. used MILD (moderate or intense low oxygen dilution) technology in their study to increase thermal efficiency [17]. Toghraie et al. examined the effect of the solar chimney on thermal properties and some other results by changing the geometric parameters [18].

Nanoparticle effects on heat transfer can easily be observed when the literature is reviewed. Yu et al. used various types of nanofluids in their research and they reported that heat transfer enhancement can be achieved about 15–40% [4]. Particle volume fraction, particle material, particle size, particle shape, base fluid (water + ethylene glycol), temperature, and preparation method could be the effect on the heat transfer [19]. The thermal conductivity of water, ethylene glycol, and nanofluid mixture increase almost linearly with temperature, and the heat transfer rate is increased with an increase in volume concentration of nanoparticles (0.1%, 0.5%, 1%) reported by Bhanu et al. [20]. According to Eastman et al. research, the thermal conductivity of ethylene glycol nanofluids containing 0.3% volume fraction of copper particles can be enhanced up to 40% compared to that of ethylene glycol base fluid [21]. Rostami et al. tried to obtain the best neuron number by using the SiO_2 /water-ethylene glycol mixture in different volume fractions and temperatures with artificial neural network (ANN) and fitting methods, and it was investigated which method would be a more accurate estimation of nanofluidic thermal conductivity [22]. Rostami et al. compared ANN, the experimental and fitting method to estimate the thermal conductivity of multi-walled carbon nanotubes (MWCNTs)- CuO / water mixture. As a result of the study, it was found that the margin of error is less about the estimated data of the ANN method. In addition, it has been stated that the increase in the volume fraction of the nanoparticle at constant temperature causes an increase in its thermal conductivity [23]. Another MWCNT experiment was conducted by Afshari et al. In this study, MWCNT-Alumina/water (80%)—ethylene glycol (20%) mixture was tested in different

solid volume fractions and temperatures, and the effects of hybrid nanofluid on viscosity were investigated [24]. Aghahadi et al. obtained hybrid nanofluid by mixing Tungsten oxide (WO_3)-MWCNTs with engine oil and observed that the increase in the volume fraction of this nanofluid increases viscosity. In addition, it has been observed that the increase in temperature has an increasing effect on the nanofluid viscosity [25]. In the experimental study, Ruhani et al. developed a new model to investigate the rheological behavior of Silica-ethylene glycol/water (30:70 vol %) hybrid Newtonian nanofluid. As a result of the study, a linear relationship was found between shear stress and shear rate. Also, while the temperature increased from minimum to maximum in the maximum volume fraction, the viscosity value lost 89% [26]. In a similar study, Ruhani et al. used ZnO-Ag (50% -50%) / water hybrid nanofluid and concluded that viscosity decreases when temperature increases and increases when volume fractions increase [27]. Arasteh et al. observed the effects of different volume fractions on PEC number, average Nusselt number, and friction coefficients using water-graphene nanoplate/platinum hybrid nanofluid. As a result of the observation, all values increased due to the increase in the volume fraction [28]. In another nanofluid study, researchers tried liquid paraffin containing oleic acid and Al_2O_3 nanofluid at different temperatures and concentrations. Studies have shown that nanofluid act like a shear-thinning fluid. Besides, boosting nanoparticle concentration caused an increase in thermal conductivity. Also, while boosting the temperature decreased the viscosity, thermal conductivity increased [29]. Samani et al. worked on the removal of hexavalent chromium from water using chemically synthesized Polyanilin/Sawdust/Poly Ethylene Glycol (PANI/SD/PEG) composite as absorbent. In this study, PANI/SD/PEG performed well in removing hexavalent chromium from aqueous media. Also, the presence of PEG in the mixture provided a homogeneous mixture and more absorption [30]. Esfe et al. aimed to reduce the cost and increase the heat transfer coefficient by optimizing the MgO-water mixture. Accordingly, the researchers used different volume fractions, diameters of nanoparticles, and Reynolds numbers. As a result of the study, it was stated that the cost was reduced by 38% [31]. Golestaneh et al. examined the natural gas flow in cyclotubes by injecting black powder particles of different diameters and velocities into cyclotubes. As a result, boosting velocity increased the pressure drop [32].

In this study, different nanoparticles (Al_2O_3 , SiO_2 , TiO_2) and ethylene glycol were mixed in two different dispersions (0.2 and 0.4%) to form nanofluids. These coolants have been experimentally tested on the diesel-fuelled internal combustion engine and various empirical results have been obtained. The results were evaluated with the mathematical

calculations given under the methodology title, their effects on the exergy parameters were examined and all coolants were compared with each other. As far as our research, although nanoparticles have been tested separately and examined different thermal properties in the literature, it has been observed that the number of sources from which the exergy properties of nanofluids are made is limited. This point is the most interesting part of the article. Also, experimental studies have been carried out with these fluids in automotive radiators and compared with conventional coolants. There are no similar examples in this direction in the literature.

This study consist of two main stages. In the first stage, a comprehensive literature review was made, then the nanoparticle properties were specified and the mixing method of nanofluids was explained. The second stage mainly includes the analysis method and the conclusion parts. From this stage, a mathematical method was defined and experimental tests were carried out to make the thermodynamic analysis. As a result of these tests, the thermodynamic effects of nanoparticles on the diesel engine radiator were observed and future studies were mentioned in the conclusion part.

2 Methodology

2.1 Exergy analysis

The basic exergy formula is shown below.

$$\dot{E}x_{fuel} + \dot{E}x_{air} = \dot{E}x_{exh} + \dot{E}x_{heat} + \dot{E}x_{work} + \dot{E}x_{dest} \quad (1)$$

$\dot{E}x_{heat}$ (kW) means that the exergy transfer rate is related to heat loss from control volume to the environment, $\dot{E}x_{work}$ is called exergy coming from engine work; $\dot{E}x_{dest}$ (kW) represents exergy destruction due to irreversibilities. Table 1 shows that some values used in the experimental test to make an exergy analysis.

$$\dot{E}x_{fuel} = \dot{m}_{fuel} \epsilon_{fuel} \quad (2)$$

In Eq. (2), $\dot{m}_{fuel}$ (kg/s) expresses the mass flow rate of fuel consumption (measured values are shown in Table 2) while

Table 1 Experimental data

Diesel formula [10]	$\text{C}_{14}\text{H}_{25}$
Diesel LHV, H_u (kJ/kg) [10]	42980
Engine speed, N (rpm)	1800
T_0 (K)	298
T_{air} (K)	298
P_0 (kPa)	101.5
$\bar{R}$ (J/mol.K)	8.314

$\mathcal{E}_{\text{fuel}}$ (kJ/kg) expresses specific fuel exergy. It is formulated in Eq. (3).

$$\mathcal{E}_{\text{fuel}} = H_u \varphi \quad (3)$$

where H_u (kJ/kg) means lower heating value (LHV) and φ means that chemical exergy factor. φ can be defined as follows (4) [33]:

$$\varphi = 1.04041 + 0.1728 \frac{h}{c} + 0.0432 \frac{o}{c} + 0.2169 \frac{\alpha}{c} \left(1 - 2.0628 \frac{h}{c} \right) \quad (4)$$

where h , c , o , α indicate the mass fraction of hydrogen, carbon, oxygen, and sulfur contents in the fuel.

$$\dot{E}x_{\text{air}} = \dot{m}_{\text{air}} \mathcal{E}_{\text{air}} \quad (5)$$

where $\dot{m}_{\text{air}}$ (kg/s) is the mass flow rate of air and $\mathcal{E}_{\text{air}}$ (kJ/kg) is the specific exergy of the air which can be explained as in Eq. 6.

$$\mathcal{E}_{\text{air}} = (h - h_0) - T_0(s - s_0) \quad (6)$$

h and h_0 are enthalpies of the working and reference temperatures, respectively. s and s_0 is the entropy of the working and reference temperatures, respectively in Eq. 6.

Exhaust measurements obtained from the experiments are shown in Table 3.

$$\dot{E}x_{\text{exh}} = \sum \dot{m}_i (\mathcal{E}_{tm} + \mathcal{E}_{chem})_i \quad (7)$$

where $\dot{m}_i$ (kg/s) is mass flow rates of the combustion gases, $\mathcal{E}_{tm}$ (kJ/kg) and $\mathcal{E}_{chem}$ (kJ/kg) are the thermomechanical and chemical exergies of these gases.

Thermomechanical and chemical exergies are described as follows: (Eqs. 8–9) [34]. Based on exhaust temperatures which are shown in Table 4, enthalpy and entropy values of the generated emission gases are found [35].

$$\mathcal{E}_{tm} = (h - h_0) - T_0(s - s_0) \quad (8)$$

$$\mathcal{E}_{chem} = \bar{R} T_0 \ln \frac{y_i}{y^e} \text{ or } \mathcal{E}_{chem} = \bar{R} T_0 \ln \frac{1}{y^e} \quad (9)$$

where $\bar{R}$ is the general gas constant (8,314 J/mol.K), y_i is the mole fraction of the component and y^e is the mole fraction of the component given under the definition of the environment in Table 5.

$\dot{E}x_{\text{heat}}$ is the exergy of the heat transfer rate from the automotive radiator. It has been formulated as follows: (Eq. 10) [10].

$$\dot{E}x_{\text{heat}} = \left(1 - \frac{T_0}{T_{CW_{ave}}} \right) \dot{Q} \quad (10)$$

where measured cooling water temperatures from the radiator are shown in Table 6. $\dot{Q}$ (kW) is the heat rate from the automotive radiator to the environment through the coolants. $\dot{Q}$ is explained in Eq. 11.

Table 2 Experimental fuel mass flow rates

	Pure water	0.2% Al ₂ O ₃ /EG	0.4% Al ₂ O ₃ /EG	0.2% SiO ₂ /EG	0.4% SiO ₂ /EG	0.2% TiO ₂ /EG	0.4% TiO ₂ /EG
$\dot{m}_{\text{fuel}}$ (kg/s)	0.001	0.00098	0.001	0.00103	0.00105	0.000997	0.00098

Table 3 Measured emission values for each test

Emission	Initial Measurement	0.2% Al ₂ O ₃ /EG	0.4% Al ₂ O ₃ /EG	0.2% SiO ₂ /EG	0.4% SiO ₂ /EG	0.2% TiO ₂ /EG	0.4% TiO ₂ /EG
O ₂ (%)	20.89	12.93	13.87	14.28	15.1	13.97	13.28
CO ₂ (%)	0.02	6.03	5.26	4.97	5.07	5.42	5.79
CO (%)	0	0.046	0.051	0.050	0.030	0.048	0.046
NO (ppm)	17	479	359	339	279	371	446
NO ₂ (ppm)	4	52	70	67	58	68	64

Table 4 Measured exhaust temperatures for each test

	Pure water	0.2% Al ₂ O ₃ /EG	0.4% Al ₂ O ₃ /EG	0.2% SiO ₂ /EG	0.4% SiO ₂ /EG	0.2% TiO ₂ /EG	0.4% TiO ₂ /EG
Exhaust temperature (K)	585	537	526	572	565	557	548

Table 5 Definition of the environment [36]

Reference component	Mole fraction (%)
N ₂	75.67
O ₂	20.35
CO ₂	0.0345
H ₂ O	3.03
CO	0.0007
SO ₂	0.0002
H ₂	0.00005
Others	0.91455

$$\dot{O} = \dot{E}_{fuel} - \left[\dot{E}x_{work} + \sum \left(\dot{m}_{exh} \Delta h_{exh} \right)_i \right] \quad (11)$$

where $\dot{E}_{fuel}$ (kJ/s) is the energy input rate to the control volume (Eq. 13). $\dot{E}x_{work}$ (kW) is the net exergy work rate and as formulated in Eq. 14.

In Eq. (12), the mass flow rate balance is described. In other words, it could be said that input mass flow rates are equal to output mass flow rates.

$$\dot{m}_{fuel} + \dot{m}_{air} = \dot{m}_{exh} \quad (12)$$

$$\dot{E}_{fuel} = \dot{m}_{fuel} H_u \quad (13)$$

$$\dot{E}x_{work} = \dot{W} = \frac{2\pi NT}{60} \quad (14)$$

where N and T (Nm) are obtained revolution per minute and torque of the engine (Table 7), respectively.

Exergetic efficiency can be found by the ratio of the net work exergy to input exergy. (Eq. 15)

Fig. 1 Experimental setup

$$\Psi = \frac{\dot{E}x_{work}}{\dot{E}x_{in}} \quad (15)$$

$\dot{S}$ (kW/K) is the entropy production rate. It can be found as follows: (Eq. 16)

$$\dot{S} = \frac{\dot{E}x_{dest}}{T_0} \quad (16)$$

2.2 System description

The experimental setup is shown in Fig. 1. Experimental setup composed of a radiator, radiator fan, test engine, dynamometer, emission analyzer, and computer-controlled engine tester. K-type thermocouples were used to measure radiator inlet and outlet temperatures. The experimental setup is also schematically in Fig. 2. Pressure,

Table 6 Measured cooling water temperatures from the radiator

	Pure water	0.2% Al ₂ O ₃ /EG	0.4% Al ₂ O ₃ /EG	0.2% SiO ₂ /EG	0.4% SiO ₂ /EG	0.2% TiO ₂ /EG	0.4% TiO ₂ /EG
Temperature cooling water in (K)	336	322.8	319.9	334.9	331.9	330.1	325
Temperature cooling water out (K)	341.1	339.3	339	340.8	340.6	340.2	339.5

Table 7 Measured torque values from engine

	Pure water	0.2% Al ₂ O ₃ /EG	0.4% Al ₂ O ₃ /EG	0.2% SiO ₂ /EG	0.4% SiO ₂ /EG	0.2% TiO ₂ /EG	0.4% TiO ₂ /EG
Torque (Nm)	53.5	56	64	67	74	77	85

Fig. 2 Schematic representation of the experimental setup

Table 8 The accuracy of the measurements

Parameter	Accuracy
Load	± 1%
Speed	± 10 rpm
BSFC	± 2% max
Brake Power	± 2% max

temperature, fuel consumption values were obtained by the use of the NETFREN Engine Test System.

Engine performance values (torque etc.) were obtained with the help of the computer program of TT Electric AMP 160-4B dynamometer control unit and exhaust emissions were measured by MRU Air Fair Delta 1600-V emission monitoring system. The accuracy of the measurements and uncertainties are shown in Tables 8 and 9.

All experiments in this study were carried out on a four-stroke, four-cylinder Mitsubishi Canter diesel engine. Test engine specifications are presented in Table 10.

2.3 Nanofluids properties and preparation

Al_2O_3 , SiO_2 , TiO_2 nanoparticles were used as an additive to water and ethylene glycol mixture. To provide a more homogeneous mixture of nanoparticles and the base fluid, SONICS vibra cell magnetic stirrer was used at 20 min., pulse 10 03 and Amp 1 60%. All nanoparticles were purchased from Sigma-Aldrich company are shown in Table 11. Nanofluids were tested shortly after they were prepared homogeneously with a magnetic stirrer and were continuously circulated in the cooling system

Table 9 The uncertainties in the calculated results [37]

OIML Class	Type of error	Maximum permissible error ^a			
		CO	CO ₂	O ₂	HC
I	Absolute	± 0.006% vol	± 0.4% vol	± 0.1% vol	± 12 ppm vol
	Relative	± 3%	± 4%	± 3 vol	± 5%

^a Absolute or relative, whichever is greater

Table 10 Specifications of the test engine

Brand	Mitsubishi/Canter
Model	4D31
Cylinder Configuration	In-Line 4 Cylinders
Engine Volume	3298 cc
Bore	100 mm
Stroke Length	105 mm
Engine Power	95.6 kW @ 3200 rpm
Torque	294.2 Nm @ 1800 rpm
Cooling System	Water Cooling

Table 11 Properties of the nanoparticles

	Al_2O_3	SiO_2	TiO_2
Purity	99.99%	99.99%	99.99%
Particle Size	30 nm	< 30 nm	10– 50 nm

throughout the experiment. For this reason, no precipitation has occurred in nanofluids and stability has been neglected.

For all nanoparticles, the first mixture consists of 20 gr nanoparticles, 1 kg EG, and 9 kg water (10% EG—%90 water). As a result, the mass percentage of nanoparticles in the first mixture was obtained as 0.2%. The second mixture consists of 40 gr nanoparticles, 1 kg EG and 9 kg water. The mass percentage of nanoparticles in the second mixture was obtained as 0.4%. Thus, the percentage of nanoparticles in the mixture was increased and its effects on the exergetic properties of the system were examined. The coolant with based nanoparticle in the cooling system is circulated with the help of the pump and mixed. Experiments were performed three times for each nanoparticle and their averaged results were evaluated.

3 Results and Discussion

In this paper, different types of nanofluids were added to the automotive radiator, and comparisons were made with the conventional coolant used in the present according to the exergy parameters. By mixing the nanofluids with

ethylene glycol already used in radiators, the accuracy of the experiments has been increased. These aspects of the work reveal their originality. Besides, the results of the study are more suitable for practice, since the tests are carried out completely experimentally in the laboratory environment. In this section, each exergy parameter has been examined separately, its graphics are drawn and interpreted.

3.1 Effect of different types of coolants on exergetic efficiency

The exergy method quantifies the locations, types, and sizes of wastes and losses and provides meaningful efficiency, which is always a measure of the approach to the ideal. For this reason, exergy analysis accurately represents the margin available to design more efficient energy systems by reducing inefficiencies [38]. As shown in Fig. 3, the best result with 35.67% was obtained when the TiO_2 nanoparticle was used with 0.4% dispersion. This result shows that TiO_2 is 62.14% more efficient than the pure water currently used. In addition, SiO_2 and Al_2O_3 nanoparticles obtained similar results at 0.4% dispersion (28.99% and 26.32%, respectively). Generally, the exergy efficiency tended to increase as the nanoparticle concentration ratio increased for all nanofluids. The thermal performance of the nanofluid consisting of titanium dioxide and water on the flat plate solar collector was investigated. The researchers observed that the TiO_2 /water mixture used at 0.02% volume concentration increased the efficiency by 34% [39].

Fig. 3 Exergetic efficiency change with different types of coolants

3.2 Effect of different types of coolants on exergy destruction

Exergy loss caused by irreversibility in the system is called exergy destruction. Therefore, systems with high exergy destruction values are expected to have a low exergetic efficiency. While the TiO_2 nanoparticle with the best exergy efficiency showed the lowest result with 18.516 kW for this parameter, the pure water coolant with the worst exergy efficiency showed the highest exergy destruction result with 23.584 kW as seen in Fig. 4. Briefly, exergy efficiency and exergy destruction values are inversely proportional parameters. When using SiO_2 nanoparticles 22.955 kW result is obtained, while this result is calculated as 23.346 kW for Al_2O_3 nanoparticle. The results show that the irreversibility factors affect Al_2O_3 the most among nanoparticle-based coolants. In addition, better results were obtained in the mixture prepared with 0.4% dispersion compared to 0.2% dispersion. The volume fraction of the hybrid nanoparticles increases exergy efficiency. This is because the increase in thermal efficiency gained with increasing concentration replaces friction losses in the tube [40].

3.3 Effect of different types of coolants on exergy heat

As indicated by Eqs. 10 and 11, the heat of exergy value varies depending on many factors. The heat rate ($\dot{Q}$) value will change depending on the work, exhaust exergy, and energy input rate ($\dot{E}_{\text{fuel}}$). When the exergy heat results are compared, the best result was obtained with the use of 0.4% dispersed TiO_2 based nanofluid with a value of

Fig. 4 Exergy destruction change with different types of coolants

Fig. 5 Exergy heat change with different types of coolants

1.027 kW in Fig. 5. This value is 0.688 kW more than pure water used as a conventional coolant. Ehsan et al. tried three different nanofluids, TiO₂ /water, Al₂O₃/water, and CuO/water, in heat exchanger and obtained the worst heat transfer coefficient from CuO/water [41]. In these results, unlike the other results, 0.4% Al₂O₃ nanofluid gave better results than 0.4% SiO₂ nanofluid. The effects of Al₂O₃-ZnO/water nanofluids on thermal performances were observed by using 1: 1 (50% Al₂O₃ and 50% ZnO), 1: 2 (33.34% Al₂O₃ and 66.66% ZnO), and 2: 1 (66.64% Al₂O₃ and 33.34% ZnO) mixture ratios on the flat plate collectors. The average exergy efficiency enhancements for the Al₂O₃-ZnO/water nanofluid at 1:1, 1:2, and 2:1 mixture ratios were 6%, 7.5%, and 9%, respectively. These results carried out that the increase in Al₂O₃ in the mixture positively affected the exergy efficiency [40]. When 0.4% Al₂O₃ was used, 1.547 kW value was obtained, and 1.586 kW was obtained when 0.4% SiO₂ was used. Boosting nanoparticle concentration decreases the exergy heat values. Heat transfer through heat exchanger was examined using Al₂O₃ nanofluid at different concentrations (0.3–2%). Researchers obtained the best heat transfer characteristic at the highest volume concentration [42].

3.4 Effect of different types of coolants on exergy work

As shown in Eq. (15), the increase in exergetic efficiency is due to the increase in exergy work. For the increase of the exergy work, the motor gets more torque, which makes the system more efficient according to exergy. As can be seen in Fig. 6, the $\dot{E}_{x,work}$ value increased when the nanoparticle was used, unlike the conventional coolants. The

Fig. 6 Exergy work change with different types of coolants

highest increase was obtained from the use of TiO₂ nanoparticles with 16.014 kW. Experimental results show that adding nanoparticles into the coolant increases the exergy work value. The highest increase was obtained when TiO₂ nanoparticle-based nanofluid was added to the radiator. The highest increase value was obtained when TiO₂ nanoparticle-based nanofluid was added (16.014 kW). This result is 58.88% more than pure water. The use of SiO₂ at 0.4% dispersion achieved a 15.62% better result than Al₂O₃ use at 13.942 kW. Increasing nanoparticle concentrations from 0.2 to 0.4 in the nanofluid caused an increase of approximately 1.5 kW. Among TiO₂/water, Al₂O₃/water, and CuO/water nanofluids, the worst pumping power value were obtained with the use of CuO / water. The pumping power value increased with the volume concentration value [41].

3.5 Effect of different types of coolants on exergy total exhaust

Total exergy produced by components such as O₂, CO₂, CO, NO, NO₂, N₂ and H₂O, which is caused by combustion reaction, is called total exhaust exergy. Looking at Fig. 7, using 0.2 and 0.4 dispersions of Al₂O₃ nanoparticles, values of 9.219 and 8.858 kW were obtained, respectively. These results show that the most desirable exergy exhaust value occurs in the Al₂O₃ nanoparticle compared to other nanofluid and conventional coolants. These results show that the most desirable exergy exhaust value occurs in the Al₂O₃ nanoparticle compared to other nanofluid and conventional coolants. After Al₂O₃ nanoparticle, 0.4% TiO₂ nanofluid showed better results than others with

Fig. 7 Exergy total exhaust change with different types of coolants

9.335 kW. In the use of 0.4% SiO₂ based nanofluid, and exergy exhaust value of 9.616 kW was obtained. In general, it has been observed that the increase in dispersions positively affects the exergy exhaust value. The worst result occurred with the use of conventional coolant (10.43 kW). Özgür studied the variation of emission values of various nanoparticles added to diesel and biodiesel fuels at different rates. At the end of this study, it was observed that CO (25 ppm dosage, 10.4% max. reduction, biodiesel) and NO_x emissions were generally reduced by SiO₂ nanoparticle addition [43].

3.6 Effect of different types of coolants on entropy production rate

Entropy production, which is caused by irreversibilities in a process, is proportional to the exergy consumption of that process. Exergy and entropy analyses are known as interrelated terms because they are based on the second law of fundamental thermodynamics [44]. As shown in Eq. (16), the entropy production rate ($\dot{S}$) varies depending on exergy destruction at constant T_0 (298 K). The low entropy production rate for a system means that the system has fewer irregularities, that is, the system is more efficient. Even when looking at the results of other parameters, the entropy production rate can be sorted. When pure water is used as a refrigerant, an entropy production rate of 0.0791 kW/K is obtained, as seen in Fig. 8. This value is the worst result compared to others. TiO₂ nanoparticles showed the best performance in this parameter (0.0621 kW/K). Better results were obtained in the use of SiO₂ with a slight difference compared to the use of Al₂O₃.

Fig. 8 Entropy production rate change with different types of coolants

In this part, it has been observed that the increase in dispersion has a positive effect on the system by decreasing the value of the entropy production rate. Kumar et al. examined the exergy and energy performances by using different shapes of Al₂O₃ nanoparticles on a wavy fin radiator. In the study, it was stated that based fluid water has a high irreversibility value and that nanoparticles added with different shapes increase entropy generation efficiency. However, it has been reported that hybrid nanofluids have less irreversibility compared to base fluids [45].

3.7 Distributions of exergy for each test

According to the equation of exergy balance, the exergy coming from the system should be equal to the exergy entering the system. Figures 9, 10, 11, 12, 13, 14, and 15 show the percent distribution of the exergy conservation from input fuel exergy for each experiment.

The highest exergy destruction percent was obtained when Al₂O₃/EG was used as a coolant (52.38%), while the lowest percentage was obtained with 41.25 to 0.4% TiO₂ based nanofluid. This means that the 0.4% TiO₂/EG mixture is more efficient according to exergetic properties. The exergy work values directly affect the efficiency of exergy and energy input rate ($\dot{E}_{fuel}$). In addition, torque and motor speed (1800 rpm) values are affected by exergy work. The best exergy work percentage with 35.67 was obtained when 0.4% TiO₂/EG nanofluid was used as a coolant in an automotive radiator. The most desirable emission percentage was obtained when a 0.4% Al₂O₃/EG mixture was used as a coolant (19.34%). It can be said that the Al₂O₃ nanoparticle has an emission improving feature when the

Fig. 9 Distribution of exergy for pure water

Fig. 12 Distribution of exergy for 0.2% SiO₂/EG Fig. 10 Distribution of exergy for 0.2% Al₂O₃/EG Fig. 13 Distribution of exergy for 0.4% SiO₂/EG Fig. 11 Distribution of exergy for 0.4% Al₂O₃/EG Fig. 14 Distribution of exergy for 0.2% TiO₂/EG

Fig. 15 Distribution of exergy for 0.4% TiO₂/EG

exergy exhaust percentage of 0.2% Al₂O₃/EG nanofluid was also examined. Exergy heat percentages close to each other in all tests. The highest percentage of exergy heat was 3.74, while the lowest percentage was 2.29.

4 Conclusion

After the experimental results were evaluated mathematically, the coolant with the best exergetic efficiency was TiO₂ based nanofluid. When using the 0.2% and 0.4% concentrations of TiO₂ nanoparticles, efficiency parameters of 31.76% and 35.67% were obtained, respectively. As can be seen from these results, boosting nanoparticle concentration in the nanofluid has a positive effect on the exergetic efficiency. The value of exergy destruction refers to the irregularities in the system. According to this definition, the nanofluid with the lowest exergy destruction value is expected to have a high exergetic efficiency value. While the highest exergy destruction value was obtained with pure water (23.584 kW), 0.4% TiO₂/EG nanofluid (18.516 kW) with the lowest exergy destruction value was also specified as the most efficient nanofluid. Exergy work value is generally higher inefficient systems where the motor produces more torque. Calculations were made according to the measured torque values in the experiments and the best exergy work value with 16.014 kW was obtained when 0.4% TiO₂/EG nanofluid was used. While SiO₂ (13.942 kW) and Al₂O₃ (12.058 kW) nanoparticles were carried out close values, the worst result was obtained using conventional coolant (10.079 kW). Generally, the most desirable emission values obtained with Al₂O₃/ Ethylene glycol nanofluids use as coolants according to other nanofluids. And exergy total exhaust (8.858 kW) values were obtained used 0.4% Al₂O₃ based nanofluids. The emission values can be further improved

by increasing the weight percentage of the nanoparticle in the coolants. Exergy heat value varies depending on many different parameters (such as $T_{cw,in,out}$, T_{exh} , $\dot{E}_{fuel}$, $\dot{E}_{work}$, $\dot{m}_{exh}$). From the results, the highest $\dot{E}_{heat}$ value was obtained from pure water with 1.715 kW, however, the results for other nanofluids are close to each other.

Generally desired results were achieved in the system, but the cost of nanoparticles is the biggest obstacle to increasing the concentration of nanoparticles in the nanofluid. In addition, a circulation pump can be installed in the cooling system of the engine to prevent the precipitation of these nanoparticles in the mixture and to obtain a more homogeneous mixture. As a result, better thermal results can be obtained. Different cogeneration systems can be tried to reduce the exergy destruction value of the system.

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Data availability All data and materials are available.

Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

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