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A study of TiO_2-enhanced nanofluids in internal combustion engines using neural networks

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In this study, the effects of nanoparticle addition to internal combustion engines were investigated. Firstly, engine coolant was prepared by mixing nanoparticles with water in different ratios (0%, 0.15%, 0.3%, 0.5% and 0.6%). Nanoparticles were investigated by SEM and XRD techniques. Then, the prepared coolants with different ratios of nanoparticles were tested on the engine at different loads (2.5 kW, 3.8 kW, 6 kW, 9 kW and 10 kW), and their heat transfer performances were investigated. Then, an ANN model was trained using the results, and the optimal TiO_2 nanoparticle doped mixing ratio (0.26%) was determined. At the last stage, the techno-economic analysis of the TiO_2 added coolant determined with the help of ANN was carried out, and the payback period and cumulative net present value were determined. Unlike other studies, ANN and economic analyses were performed and a contribution to the literature for the use of nanoparticle doped liquids was presented. The results show that the highest improvement in heat transfer performance is in the case of 0.6% nanoparticle addition with 40.8%. According to the ANN study, the highest performance increase is with the addition of 0.26% nanoparticles. The economic analysis made according to the result of the ANN study shows that the payback period will be less than 4 years.

Keywords Cooling system, Energy efficiency, Neural network, Techno-economic analysis, Nanofluids, Engineering economics, TiO_2 nanoparticles

Abbreviations

ANN	Artificial neural network
EV	Electric vehicles
IRR	Internal rate of return
NI	National instruments
NPV	Net present value
PLC	Programmable logic controller
SEM	Scanning electron microscope
XRD	X-ray diffraction

The engine cooling system is one of the crucial parts of an internal combustion engine that enables the tasks of preventing overheating of engine parts and engine oil, raising the engine to the most efficient heat as soon as possible and keeping the engine at operating temperature to give full power. Regardless of the operating conditions, the cooling system should run the engine at the most efficient temperature during engine operation, because parts such as cylinder walls, pistons and cylinder head absorb a large amount of heat[1]. Therefore, these parts of the engine may get overheated, the oil film may burn, and the oil layer may lose its lubricating property which may cause costly damages. Since the engine must work to reach optimum power, the cooling system is not activated until the relevant temperature is reached. In this process, fuel consumption, deposit formation and oil contamination are seen[2]. Thus, the cooling system should keep the engine at the normal operating temperature. Cooling fluid (a mixture of pure water and antifreeze—in countries with extreme weather conditions) is used as the coolant in liquid-cooled engines where the heat generated inside the engine is taken by the engine coolant

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and is cooled in the radiator. The cooling fluid circulates through the water pump. The hot engine coolant in the radiator is naturally cooled by the incoming air, as the radiator fan rotates or the vehicle moves forward[3]. Providing an efficient heat transfer and thermal conductivity means maximizing the engine performance. Therefore, development in the chemical structure and physical features of the coolant brings enhanced heat transfer and fuel economy to the automotive industry.

In recent years, studies to improve heat transfer have demonstrated the benefit of nanoparticles ranging in size from 10 to 100 nm in the fluid content of liquid-cooled engines. Nanofluids have very high thermal conductivity values compared to previously used fluids. Increasing the heat transfer will increase the efficiency of the cooling system, and the high thermal performance of the liquid used in the cooling system will also increase the efficiency of the vehicle engine[4]. In this direction, especially metal nanoparticles with high thermal conductivity are used. Examples of these are TiO_2, SiO_2, Al_2O_3, CuO, Fe_2O_3, graphene and carbon nanotubes.

In the literature, the efficiency of the vehicle cooling system in heat transfer with the addition of these particles has been shown. Guerrero et al.[5] applied TiO_2 nanofluid in a diesel passenger van under Quito ambient conditions in order to improve heat exchange transfer and thermal conductivity at extremely low concentrations, and indicated the rise of CO_2 emissions by 2%, the decrease of CO, HC and PM2.5 up to 16, 17 and 60%, respectively. Erkan et al.[6] used Al_2O_3, SiO_2, and TiO_2 in a four-stroke internal combustion engine radiator along with ethylene glycol and obtained the best exergy efficiency from TiO_2 nanoparticles of 35.67%. In this study, Al_2O_3/ethylene glycol coolant performed the lowest exhaust temperature value. In another study, Hilmin et al.[7] applied a thermoelectric generator that generates electrical energy from waste heat due to increase the efficiency of the engine and added a nanofluid containing TiO_2 to the cooling system to increase the efficiency of the generator. The results of the study proved that TiO_2 had improved thermal conversion and electrical power output compared with water only, at different engine speeds. Senejani and Mehdipour[8] simulated the cooling circuit of a real-scale internal combustion engine with GT-suite software by which the effect of Al_2O_3 and TiO_2 nanofluids as coolants were presented. The results of this simulation indicated the presence of TiO_2 and Al_2O_3 (2 vol%) decreases the engine wall temperature by 6.7% and 7%, respectively. Shah et al.[9] employed water-based Fe_2O_3 nanofluid in three concentrations (0.003, 0.005, and 0.007 vol%) of Fe_2O_3/water mixture with inlet temperatures of 45, 50, and 55, and five flowrates (10–14 LPM). Fe_2O_3/water nanofluid presented the best result in heat transfer rate (21.89% for 0.007 vol%) when compared to water. Alves et al.[10] applied Al_2O_3 and CuO nanoparticles and compared the results with ethylene glycol and water (50%–50%) in an internal combustion engine as a water jacket coolant. They declared that Al_2O_3 and CuO nanoparticle doping enhanced the cooling ability, Nusselt number value raised 12.25% and 16.64%, and the total heat transfer mounted to 2.22% and 2.79%, respectively. Naveen and Kishore[11] compared water-ethylene glycol coolant with water-ethylene glycol-based nano coolant containing graphene nanoparticles in an automotive car radiator. Their results were promising with a heat transfer rate of 68%, improvement of convective heat transfer coefficient of 66.22%, and Nusselt number enhancement of 53.4% with the addition of nano coolant. Muruganandam and Mukesh Kumar[12] studied the effect of multi-walled carbon nanotubes experimentally on a diesel engine radiator and found that mechanical efficiency and total fuel consumption of 0.3% nanofluids are 8 to 18% and 9 to 18% respectively higher than water as coolant in the load ranges under consideration. Duca et al.[13] investigated the impact of a catalytic stripper on the chemical composition of an internal combustion engine. Similarly, Kharabati et al.[14] evaluated the effect of SiO2 nanoparticles on internal combustion engines. In another experimentally based study, Jassim[15] investigated the energy interaction of environment-engine by using nanoparticle lubricants. The results of the experimental study highlight that nano-copper augmented the energy efficiency. Alves et al.[16] used a mixture of Al_2O_3 and CuO-based nanofluid in an internal combustion engine and performed a numerical simulation study. The results of the performance analysis proved that the heat removal increased by 2.79% and flow velocity decreased by 40% as a consequence of implementing Al_2O_3 and CuO-based nanofluid compared to ethylene glycol. Differently, Mustafa et al.[17] reviewed the pros and cons of nanolubricants on EVs (Electric vehicles). The experimental studies summarized above indicate that there are increases in heat transfer performance at different rates. However, even if the same nanoparticle and similar ratios are used, the heat transfer effect varies significantly. This is thought to be due to the experimental conditions and nanoparticle doped liquid preparation. However, the only unchanged situation is that nanoparticle doped heat transfer fluids increase performance.

With a different approach, studies have been carried out on the addition of nanoparticles to different liquids and their thermophysical effects[18–21]. Moghadam et al.[18] studied the effect of multiwall carbon nanotubes/water nanofluid on smooth and straight, square, and circular grooved surfaces in the meaning of pool boiling performance. Zolfalizadeh et al.[19] investigated the effect of graphene/water nanofluid on the thermal efficiency, thermal performance factor, pressure drop, overall heat transfer, convective heat transfer coefficient, and heat transfer characteristics of a shell-and-tube heat exchangers. Pourpasha et al.[20] studied on the effect of using TiO_2 doped on multi-walled carbon nanotubes on the heat transfer performance. Alizadeh et al.[21] investigated the impact of multi-walled carbon nanotubes on the thermal properties of transformer oil.

As the nanoparticle additive increases the surface/volume ratio, it increases the heat transfer[22]. These heat transfer agents reduce mechanical losses by increasing the viscosity of the coolant. It is aimed to increase the thermal efficiency of the engine with these additives, which cause the improvement of dynamic performance, and the resulting nanofluids. Also, by combining these additives with normal coolant, there is the possibility of a protective film on engine cylinder surfaces that will increase the workability and reliability of engine life[23]. In this study 20 nm diameter TiO_2 nanoparticles were mixed with water and used as a coolant in an internal combustion engine radiator in various concentrations and their stability were tested. The effect of the nanofluid on thermal efficiency was studied experimentally in different engine brake power values and TiO_2 concentrations.

In the literature, there are many attempts that experimentally studied the effect of nanoparticles on heat transfer (Table 1). TiO_2 has been used in some studies for heat transfer performance enhancement. However, no comprehensive study has been found in the literature in which engine coolants with different ratios of nanoparticle

Author(s) and year	Type of nanoparticle	Type of engine	Research focus	Solution approach
Muruganandam and Mukesh Kumar (2020)[12]	MWCNT/water	Diesel	Mechanical efficiency evaluation	Experimental
Senejani and Mehdipour (2020)[8]	Al_2O_3, TiO_2	Internal combustion	Heat transfer of the engine cooling coil	Experimental, simulation
Hilmin et al. (2020)[7]	TiO_2	Thermoelectric generator (TEG)	TEG power output and efficiency	Experimental
Erkan et al. (2021)[6]	Al_2O_3, SiO_2, TiO_2	Diesel	Exergetic properties	Experimental, exergy analysis
Duca et al. (2021)[13]	$C_{40}H_{82}$	Internal combustion	Size-selective chemical characterization	Experimental, Principal component analysis, Hierarchical clustering
Kharabati et al. (2021)[14]	SiO_2	Internal combustion	Thermal and rheological behaviour evaluation	Experimental
Jassim (2021)[15]	Nano-Cu	Petrol	Energy interaction evaluation	Experimental
Alves et al. (2022)[16]	Al_2O_3, CuO	Internal combustion	Performance evaluation	Experimental, simulation
Mustafa et al. (2022)[17]	Nanolubricants	Internal combustion	Nano lubricant evaluation on EVs	Literature review
Guerrero et al. (2022)[5]	TiO_2	Diesel	Pollutant emissions	Experimental
Shah et al. (2022)[9]	Fe_2O_3-water	Internal combustion	Heat transfer potential evaluation	Experimental, mathematical modeling
Alves et al. (2022)[10]	Al_2O_3, CuO	Internal combustion	Comparative performance analysis	Experimental, simulation
Naveen and Kishore (2022)[11]	Water-EG	Automotive car radiator	Heat transfer potential evaluation	Experimental
This study	TiO_2 enhanced nanofluids	Internal combustion	Techno-economic analysis	Experimental, simulation, ANN

Table 1. Brief summary of the literature review.

additives are investigated experimentally, the optimum operating point is determined using the ANN method, and then the payback and cumulative present values are calculated by performing a techno-economic analysis. For this reason, in this study, the effect of TiO_2 nanoparticles in terms of heat transfer to the engine cooling system was analyzed experimentally with the help of ANN, and its techno-economic effect was investigated.

Materials and methods

In the study, firstly, SEM and XRD analyzes of TiO_2 nanoparticles were performed. Then, the cooling liquid with TiO_2 nanoparticles was prepared. Then, the effect of nanoparticle-added coolants on the heat transfer performance was experimentally investigated. Then, the optimum TiO_2 mixing ratio was determined by examining the experimental results in a wide range with the help of the ANN model. At the last stage, techno-economic analyzes were carried out for the determined rate, and the payback period and cumulative net present values were determined.

Experimental setup

In this experimental study, an Erin Motor brand, 4-stroke, single-cylinder, 1.16 L volume, naturally aspirated engine working with natural gas fuel was used[24]. The experimental system includes engine, heat exchanger, dynamometer, cooling system, control system and measurement equipment. The motor is loaded using an AC generator. With the help of an adjustable resistance load bank, which can be controlled by PLC, the test system is loaded precisely. In this way, the motor load could be precisely controlled. Again, a data collection system was established with NI's Labview software and an interface was developed. While the motor speed was measured with the data acquisition card with the help of an incremental encoder, the current and voltage values drawn from the generator were also precisely measured and the load values were calculated. The schematic view of the test system is given in Fig. 1 in detail.

The engine cooling system is presented in Fig. 2. The experimental setup includes ambient temperature/pressure/moisture meter, thermal camera, water flow meter, anemometer and temperature meter. The natural gas-fueled and electronically controlled internal combustion engine is water-cooled and the engine is cooled with the help of a radiator and fan. PT100 type temperature meters are mounted at the radiator inlets and outlets. Again, the water flow was measured by attaching a turbine-type miniature flow meter to the radiator inlet. Again, radiator temperatures were continuously monitored with the Fluke TiS60 thermal camera, making sure that the engine coolant inlet and outlet temperatures and radiator temperatures were in balance before data collection. Thus, measurements were made in steady-state conditions at stable points. The inlet and outlet flow rates and temperatures of the forced airflow passing through the radiator were measured with the help of a turbine-type anemometer.

Preparation, characterization and stability of TiO2 nanofluids

Titanium dioxide was purchased from Nanografi in the form of nanopowder (P25) with purity of 99.9% and in size of 20 nm. TiO_2 nanoparticles (TiO_2NPs) were analyzed by SEM in order to evaluate their morphological properties. The crystallographic structure of the TiO_2NPs was analyzed by XRD. TiO_2NP-doped nanofluids were prepared by the direct dispersion of dry nanoparticles into the water as coolant and stirred for 1 h by a magnetic stirrer. After stirring the fluid was kept in an ultrasonic homogenizator for 3 h of sonication under 40 W capacity operating conditions at 30 ± 2 kHz frequency. At the end of the homogenization process, the TiO_2NPs were studied at 3 different concentrations where the total coolant volume was kept constant at 4 L. Nanofluids doped

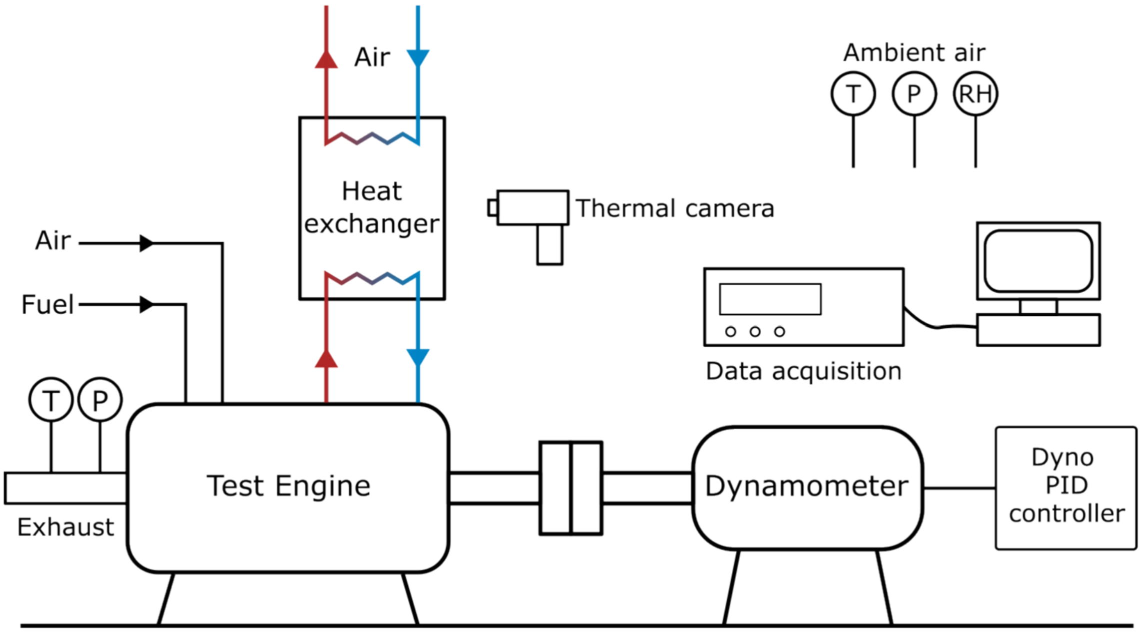

Figure 1. Experimental schematic of the engine test system.

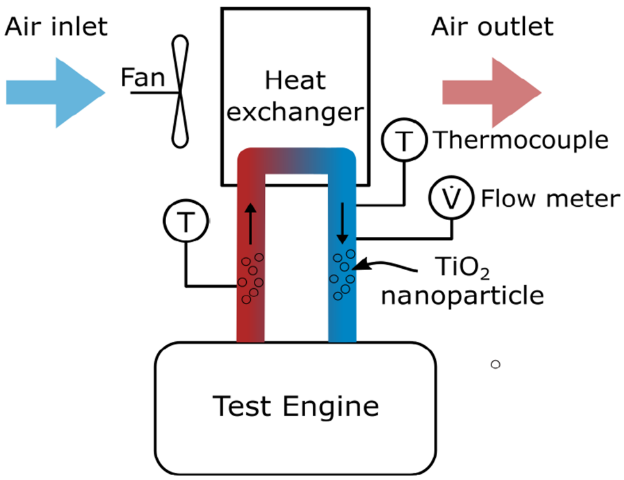

Figure 2. Experimental schematic of the cooling system.

with TiO_2NPs at 0.15, 0.3, 0.5 and 0.6 wt.% concentrations were studied at pH: 7.0. All experiments were made in triplicate. The stability of the TiO_2NP doped nanofluids was monitored for five hours.

Determination of UxA value

The product of the total heat transfer coefficient and the heat transfer surface area is widely used to evaluate the heat transfer performance of the cooling system. In this study, heat transfer performance will be analyzed with UxA value. The following formulae were used to calculate the UxA value[25,26]:

$$Q_c = \dot{m}_c C_{p,c}\left(T_{c,i} - T_{c,o}\right) \tag{1}$$

$$Q_a = \dot{m}_a C_{p,a}\left(T_{a,o} - T_{a,i}\right) \tag{2}$$

$$Q_m = UAF\Delta T_{lm} \tag{3}$$

$$\Delta T_{lm} = \frac{\Delta T_1 - \Delta T_2}{ln\left(\Delta T_1 / \Delta T_2\right)} \tag{4}$$

$$F = \frac{\ln\left[{(1-RS)}/{(1-S)}\right]}{\left(1-{1}/{R}\right)\ln\left[1+R\ln(1-S)\right]} \tag{5}$$

$$R = \frac{\left(T_{a,o}-T_{a,i}\right)}{\left(T_{c,i}-T_{c,o}\right)} \tag{6}$$

$$S = \frac{\left(T_{c,o}-T_{c,i}\right)}{\left(T_{a,i}-T_{a,o}\right)} \tag{7}$$

where m is the flow rate, C_p is the specific heat Q_a and Q_c are the heat transfer rates for air and coolant sides, respectively, Q_m is the arithmetic mean heat transfer rate, U is the overall heat transfer coefficient, A is the heat transfer surface area, F is the correction factor, ΔT_{lm} is the logarithmic mean temperature difference, T is the temperature, and R and S are the correction factor variables. The subscripts c, a, i and o refer to the coolant, air, input and output, respectively.

The ANN module of Matlab software was utilized in the modeling part of the study. A typical ANN schematic is visualized in Fig. 3. The ANN model consists of a hidden layer (consisting of five neurons) and an output layer (consisting of one neuron). Engine power and mixing ratio were used as inputs. The UxA value of the heat exchanger was estimated with the help of the method trained with the Levenberg–Marquardt approach, which is a frequently used method. 70% of the experimental data was used for training the model, 15% for testing and 15% for validation.

For the economic analysis of nanoparticle doped coolant addition, basic methods frequently used in the literature such as internal rate of return (IRR), net present value (NPV) and payback period were used. According to the results obtained from these methods, the economic evaluation of nanoparticle doped coolants was carried out. Related formulae are presented below[27]:

$$\$0 = NPV\sum_{t=1}^{t}\frac{C_t}{(1+IRR)^t} - C_0 \tag{8}$$

where C_t is the net cash flow during period t, C_0 is the total initial investment cost, and t is the number of time periods.

$$NPV = \frac{Cash\ Flow}{(1+r)^t} - Initial\ Investment \tag{9}$$

where r is the discount rate.

$$Payback\ Period = \frac{C_0}{Yearly\ Cash\ Flow} \tag{10}$$

Results and discussion

The TiO_2NPs were evaluated by SEM and XRD analyses. SEM results indicated that the nanoparticles were spherical and distributed with sizes between 20–32 nm. The nanoparticles with a primary particle size of 25 ± 1.8 nm and a specific surface area of 39–71 m^2/g were monitored in the SEM image (Fig. 4). The SEM results reveal that the nanofluids prepared with these TiO_2NPs are in nanofluid structure due to the nanometric volume of the TiO_2NPs distributed in the coolant (≤ 100 nm). Also, the possibility of TiO_2NP aggregation is low due to their relatively small nano-size. These results are in accordance with a previous study in which the surface properties of TiO_2NPs were analyzed[5]. TiO_2NP-doped nanofluids were prepared at 0.15, 0.3, 0.5 and 0.6 wt.% concentrations. The resulted nanofluids were mixed homogeneously by sonication at pH: 7.0 in order to avoid the aggregation and the stability of the prepared nanofluid was monitored for 5 h. The amount of aggregation monitored in the stability tests was ignorable and stabile nanofluids were obtained at all concentrations for half an hour. As

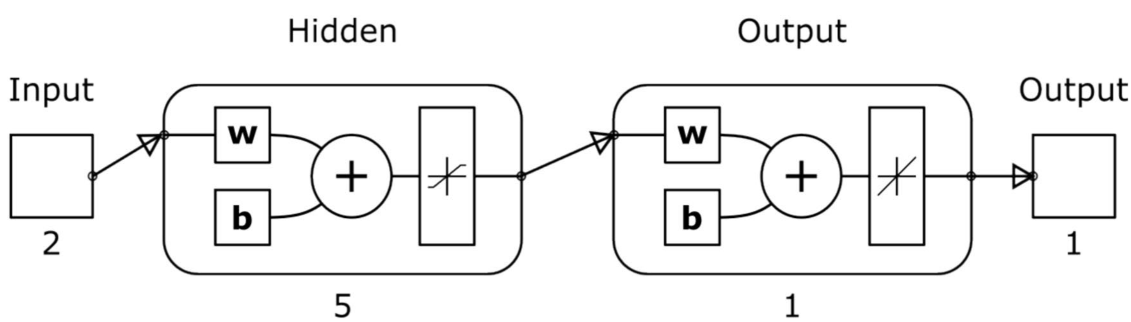

Figure 3. Simple model of ANN.

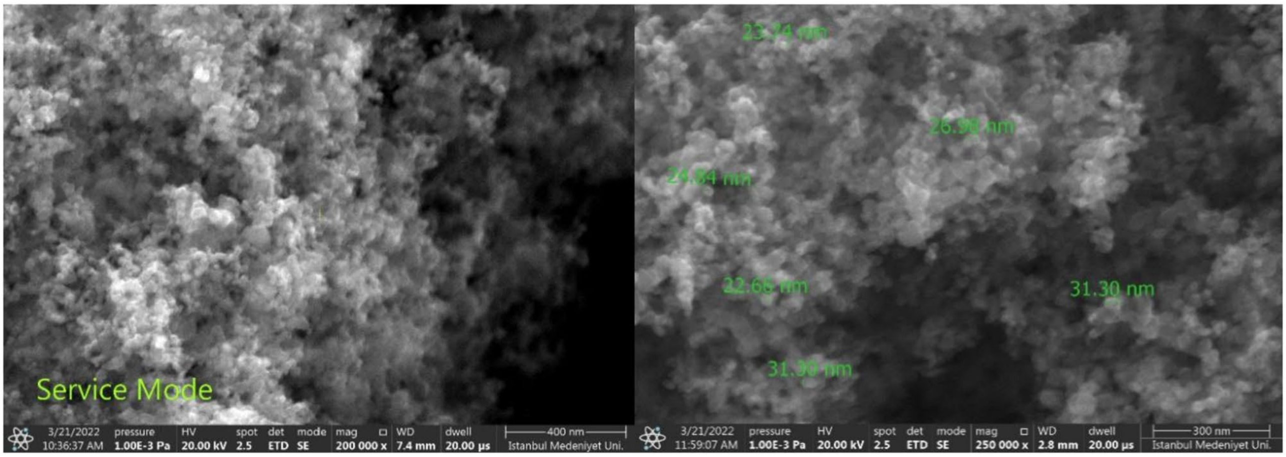

Figure 4. SEM images of the TiO_2NPs at different magnitudes.

presented in Fig. 4, TiO_2 nano powder used in this study was uniformly distributed and it resulted in low particle size and reduced agglomeration via the homogenization process accordingly.

The TiO_2NPs were analyzed by XRD in order to confirm the crystallinity and purity of the nano powder (Fig. 5). The XRD diffraction patterns of the TiO_2NPs obviously provided that the nanoparticles were in Anatase form with characteristics 2θ peaks at 25.8° (101), 37.6° (004), 48.7° (200), 54.1° (105), 55.2° (211), 63.3° (204), 69.2° (116), 70.9° (220), 75.8° (107). XRD-diffraction peaks showed the nanocrystalline nature of the nanoparticles with negligible impurities are parallel with literature[25]. The XRD results with 2θ peaks at 25.8° affirming TiO_2NP anatase form without impurity can be confirmed by SEM topological analysis.

In this study, tests were carried out on a TiO_2-doped nanofluids SI engine with natural gas. Tests were carried out at 5 different engine loads (2.5 kW, 3.8 kW, 6 kW, 9 kW and 10 kW). TiO_2-doped nanofluids in mass ratios of 0%, 0.15%, 0.3%, 0.5% and 0.6% were used and tested as engine coolant. UxA value was calculated by the logarithmic temperature difference method. UxA value can be qualified a as conductance value for a heat exchanger. Since a comparative study was carried out and the total heat transfer surface area is not known, the area and the heat transfer coefficient are given as a product.

The effect of different nanoparticle ratios on heat transfer at different engine loads is given in Fig. 6. According to these results, the highest improvement in heat transfer (UxA) at a 2.5 kW engine load was obtained with the addition of 0.6% nanoparticles at a rate of 31.4% compared to the condition without nanoparticles. At 3.8 kW engine load, the best improvement in heat transfer was obtained with the addition of 0.6% nanoparticles at a rate of 40.8%. At 6, 9 and 10 kW engine loads, the best improvement in heat transfer was 40.3%, 30.7% and 39.1, respectively, under the condition of adding 0.6% nanoparticles.

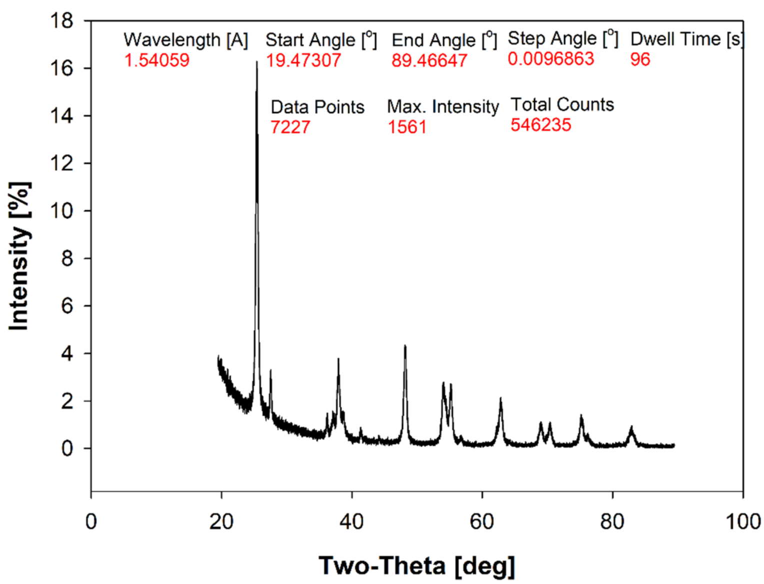

Figure 5. XRD graph of the TiO_2NPs.

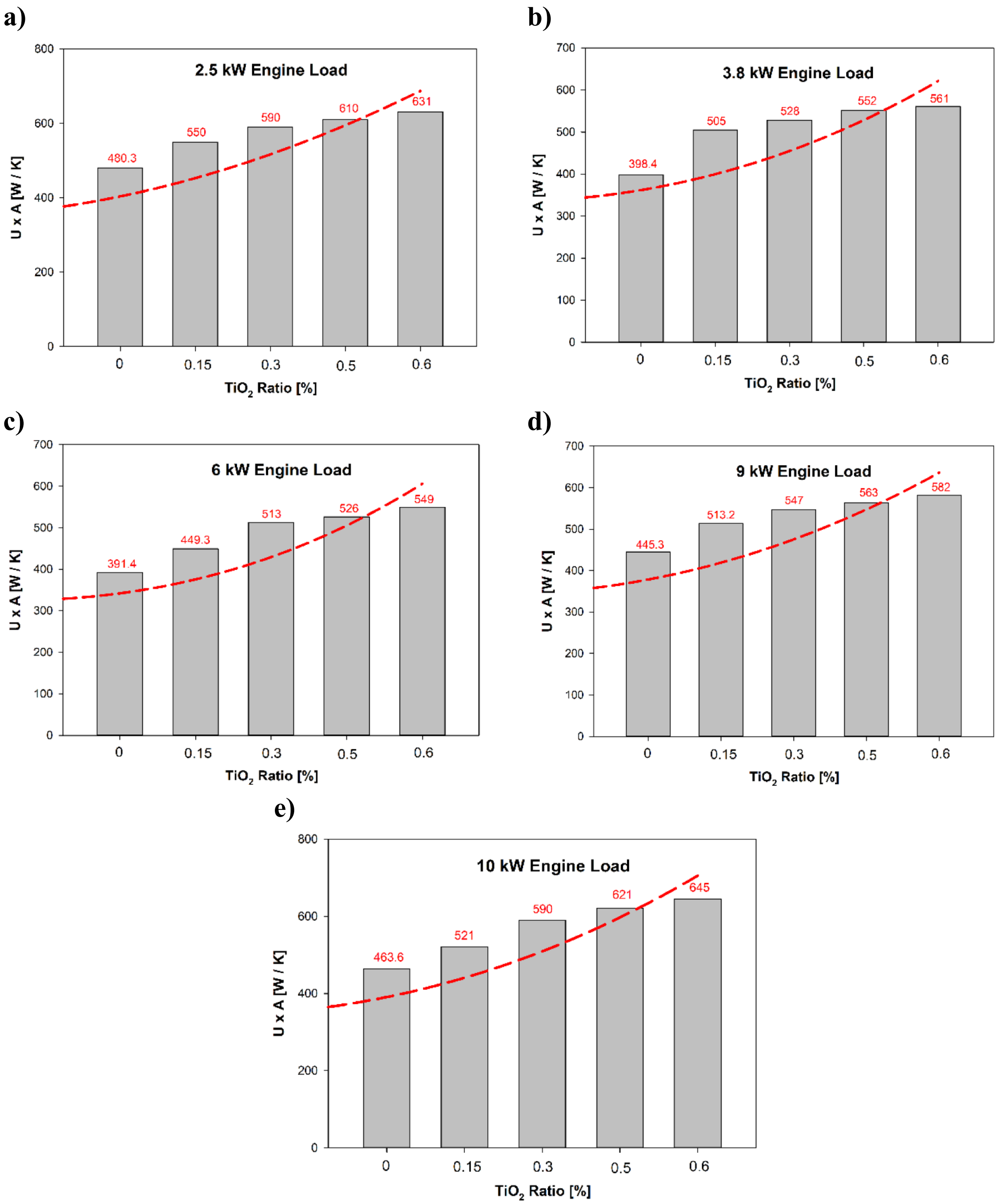

Figure 6. Investigation of the effect of different ratios of TiO_2 added coolant on heat transfer under (**a**) 2.5 kW engine load, (**b**) 3.8 kW engine load, (**c**) 6 kW engine load, (**d**) 9 kW engine load and (**e**) 10 kW engine load.

The lowest improvement in heat transfer was obtained with the addition of 0.15% TiO_2 nanoparticles. Again, with the use of 0.6% TiO_2 in the base fluid, the thermal conductance value of heat exchanger (UxA) increased from 480 W/K to 631 W/K at a 2.5 kW motor load. With the use of 0.6% TiO_2 in the base fluid, the UxA value increased from 398 W/K to 561 W/K at a 3.8 kW motor load. With the use of 0.6% TiO_2 in the base fluid, the UxA value increased from 391 W/K to 549 W/K at a 6 kW motor load. With the use of 0.6% TiO_2 in the base fluid, the UxA value increased from 445 W/K to 582 W/K at a 9 kW motor load. With the use of 0.6% TiO_2 in the base fluid, the UxA value increased from 463 W/K to 645 W/K at a 10-kW motor load.

From the obtained results, it was concluded that the UxA value increased significantly with the addition of nanoparticles. The results of this experimental study were compared with the reviewed studies in the literature. It was observed that the results obtained are in parallel with the studies in the literature.

An ANN model was created with Matlab software using the experimental results obtained. As input, engine loads and different TiO_2 ratios were entered as two different inputs, and the product of the overall heat transfer coefficient and the heat transfer surface area (UxA) was obtained as output. As a result, the correlation coefficient (R) for the train part was obtained as 0.98006. The overall—R-value was obtained as 0.96512. The heat transfer results obtained with the help of the ANN model are given in Fig. 7. The results obtained prove that there is a significant increase in heat transfer up to 0.26% TiO_2 addition, especially at high engine loads (7.5 kW, 8.75 kW and 10 kW), and there is no significant improvement at higher concentrations.

According to the results obtained, 0.26% TiO_2 nanoparticle addition was chosen as the optimum operating point. Because, at 7.5 kW engine load, 0.04%, 0.086%, 0.13%, 0.17%, 0.21%, 0.26%, 0.3%, 0.34%, 0.38%, 0.43%, 0.47%, 0.51%, 0.55% and 0.6% TiO_2 addition Heat transfer with 1.7%, 5.7%, 12.2%, 19.4%, 24.7%, 27.6%, 28.7%, 29%, 28.9%, 28.8%, 28.8%, 29.2%, 30% and 31.6%, respectively. As can be seen, the improvements in heat transfer remained almost constant after the 0.26% TiO_2 addition. Again, similar results were obtained at other engine loads (8.75 kW and 10 kW). In the economic analyses, calculations were made using this operating point (0.26% TiO_2).

The heat transfer performance of the analyzed internal combustion engine was investigated by adding TiO_2 nanoparticles at different rates into the cooling water. Thanks to the experimental studies carried out in this study and the analyzes performed with Artificial Neural Networks, economic analyzes were carried out considering that a 0.26% TiO_2 ratio provides the highest benefit for heat transfer.

Since the heat transfer properties of the cooling system are improved with the nanoparticle added to the engine cooling water, some possible changes can be made. In this case, there are 2 different options.

1. Making minor revisions in the engine cooling system: In this option, the same cooling can be achieved with a lower air or water flow rate by changing the speed of the circulation pump or the radiator fan. For this purpose, the desired change can be made at a very affordable cost (< 1% of the total price of the engine) by adjusting the belt-pulley assembly to which the pump or fan is connected.
2. Making changes to the engine cooling system: This option includes replacing the existing circulation pump or radiator fan with a smaller one. In this way, it will be ensured to obtain the same cooling rate with a lower air or water flow rate. This change can be made at a higher cost (> 5% of the total price of the engine) than the first option.

In this study, the improvements that can be achieved by making minor revisions in the existing engine cooling system are analyzed. The changes in UxA values for different power and nanoparticle additive ratios are explained in detail above. Since the pump consumes more power in the cooling system compared to the fan, cost analysis has been performed on the pump. By changing the speed (n), the pumps can operate at different flow rates (Q) and head (H) without decreasing their efficiency. With this revision, it is aimed to consume less power by enabling the pump to operate at a lower speed, that is, at a lower head and flow rate, with high efficiency.

The economic analysis is based on the average UxA increase. Some assumptions have been made for the economic analysis. Relevant assumptions are presented in Table 2 below.

By adding nanoparticles to the engine cooling water and reducing the pump speed, the power consumed by the engine for the pump will decrease and therefore less fuel consumption will occur. As a result, less fuel consumption can be achieved with a very low investment cost. Considering this analysis for a single-engine for a large number of vehicles, there is a significant fuel saving and a significant emission reduction opportunity. In

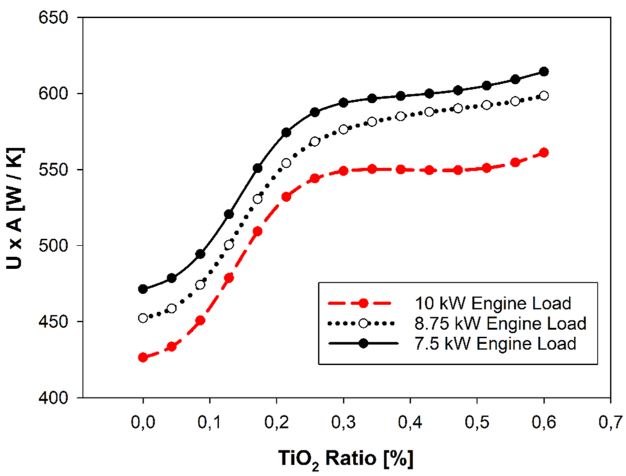

Figure 7. Calculated UxA values by using ANN model.

Parameter	Unit	Value
Pump power	kW	0.35
Pump efficiency	%	80
Heat transfer mean rate change	%	15
Cooling water change period	year	1
Engine revision cost	$	100
Nanoparticle unit cost	$/g	4
Nanoparticle cost change	%	− 5
Natural gas unit cost	$/m^3	0.779
Natural gas cost change	%	15
Annual working hours	h	1000
Engine mean power	kW	6.3
Engine efficiency	%	15
Discount rate	%	20
Economical life	years	20

Table 2. Assumptions for economic analysis.

this way, it was concluded that the reduction of greenhouse gas emissions to be realized will contribute to both the United Nations Sustainability targets and the European Green Deal.

The results of the economic analyzes made under the assumptions stated above are presented in Table 3. The present value of the net profit is calculated as $955, while the payback period of the investment is calculated as 3 years and 7 months. The payback period of less than 4 years is considered to be a reasonable period for such investments. All economic indicators show that the revision process is economically feasible. While the IRR and NPV values are quite high, the investment's payback period is calculated to be less than 4 years.

The variation of the cumulative cash flow over the years for the case study is given below. As presented in Fig. 8, net cash flow quickly turns positive. As a result, the addition of nanoparticles to the internal combustion engine water cooling system seems economically feasible.

IRR (%)	Net present value ($)	Payback period
56	955	3 years 7 months

Table 3. Economic analysis results.

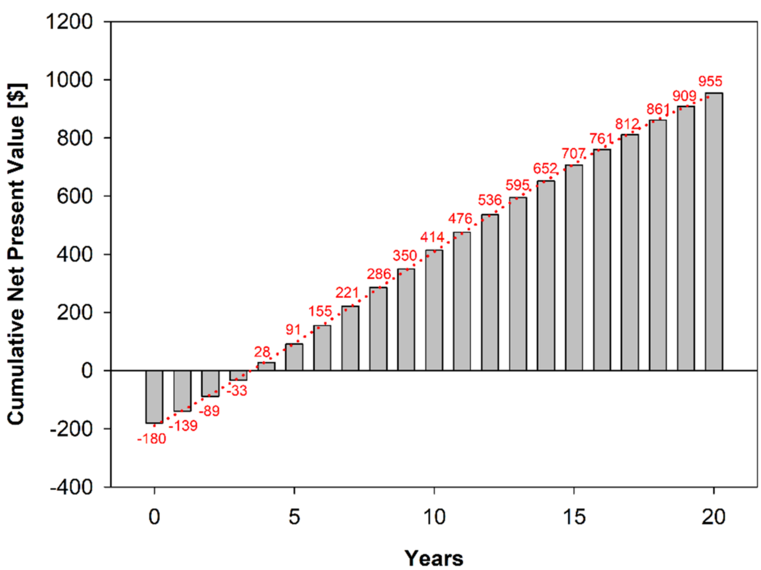

Figure 8. Variation of the cumulative cash flow over the years.

Conclusion

In the study, firstly, SEM and XRD analyzes were performed for TiO_2 nanoparticles. Then, different ratios of TiO_2 nanoparticle solutions (0%, 0.15%, 0.3%, 0.5% and 0.6%) were prepared. Then, the effect of using nanofluids as a coolant on heat transfer at different engine loads (2.5, 3.8, 6, 9 and 10 kW) was investigated. Then, the optimum nanoparticle ratio in terms of heat transfer was determined with an ANN model developed with the help of Matlab. In the last stage, techno-economic analysis was carried out. The findings are summarized as below.

- The best improvement in UxA value was obtained with the addition of 0.6% TiO_2. The highest improvement in UxA value at all engine loads was determined as 40.8% at 3.8 kW engine load. TiO2 nanoparticle-doped nanofluid demonstrated a satisfactory enhancement in heat transfer properties when compared with conventional coolant; therefore, its application and commercial distribution in the automobile industry is promising in near future.
- Using the ANN model, the best result in terms of heat transfer was obtained with 0.26% nanoparticle addition. The ANN was found to be successful in predicting the heat transfer performance of nanoparticle doped liquids. This indicates that the ANN can be used more in the future.
- As a result of the economic analysis, with the addition of 0.26% nanoparticles, the payback time was calculated as 3 years and 7 months, while a cumulative net present value of $ 955 was obtained. Economic analyses show that the use of nanoparticle doped liquids has a significant potential for current prices and performance impact.

It would be appropriate to plan future studies depending on the results obtained from the related study. Depending on the issues addressed in this study, future predictions are listed below.

- Performing settling and performance tests for different mixing ratios of nanoparticles for long periods of time (6 months and 1 year).
- Conducting tests on a larger capacity engine with nanoparticle-added coolant.
- Economic analyses based on actual dimensions.
- Investigation of the usability of ANN in nanoparticle doped cooling systems.

Data availability

The datasets used and/or analysed during the current study available from the corresponding author on reasonable request.

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Author contributions

S.P. made the experimental works. Y.K. made the experimental works. A.A. wrote the main manuscript. S.K. made the analyses.

Competing interests

The authors declare no competing interests.

Additional information

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