Case Studies in Thermal Engineering 31 (2022) 101847

Contents lists available at ScienceDirect

Case Studies in Thermal Engineering

journal homepage: www.elsevier.com/locate/csite

Effect of Al_2O_3 addition to an internal combustion engine coolant on heat transfer performance

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ARTICLE INFO

Keywords:
Heat transfer improvement
Nanoparticle
Nanofluid
Al_2O_3
Vehicle radiator

ABSTRACT

In vehicle cooling radiators, in general, water is used as a cooling fluid. Adding of nanoparticles to the cooling water has a significant effect on heat transfer performance of the radiator. One of the most popular nanoparticle for this kind of applications is Al_2O_3. There are some critical issues for the application of nanofluids as homogeneity of nanoparticle distribution and concentration of nanoparticles. In the present study, the Al_2O_3 particles used in an internal combustion engine cooling radiator to enhance heat transfer performance. The experimental works were done for different concentrations as 0.25, 0.50 and 1.0 wt% and engine brake power values. The enhancement of the heat transfer performance is achieved up to 37.2% (9.4 kW brake power and 1% concentration). The lowest overall heat transfer improvement was obtained as 2% (11.5 kW brake power and 0.25% concentration). The obtained results showed that adding of nanoparticles to the cooling water improves the heat transfer performance.

Nomenclature

A	Heat transfer surface area
Al_2O_3	Aluminum oxide
Cp	Specific heat
Dyno	Dynamometer
LMTD	Logarithmic mean temperature difference
SDS	Sodium Dodecyl Sulfonate
U	Overall heat transfer coefficient
Ø	Volumetric concentration of the nanoparticles

1. Introduction

Problems related to energy, the environment and the economy are being experienced intensively all over the world. The most

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https://doi.org/10.1016/j.csite.2022.101847
Received 20 September 2021; Received in revised form 11 January 2022; Accepted 1 February 2022
Available online 3 February 2022

important of the problems in question are those related to the environment. It is becoming increasingly difficult to return the negativity created on the environment. The majority of the problems related to the environment increase the problems of both energy and economics. In order to achieve the COP21 goals, it is necessary to make radical improvements [1]. The addition of nanoparticles in different fluids is a very current study topic. There are many studies on the investigation of the thermochemical properties of the mixture resulting from the addition of different nanoparticles to different liquids [2–10]. In this context, in this study, the addition of nanoparticles to cooling water was investigated in order to improve the performance of internal combustion engines.

Improvements in internal combustion engines is a continuous research topic that attracts attention of the researchers. There are numerous attempts to increase efficiency of the automotive processes. Cooling process is one of the most interesting one among others. Researchers have been trying to improve the heat transfer performance of the cooling radiator to increase the performance of the internal combustion engine and decrease the fuel consumption [11]. One of the most promising technology to increase the cooling radiator heat transfer performance is adding nanoparticles to the cooling fluid. There are no lifetime problems for nanofluids. There is only a case of precipitation of the nanoparticle used. There are numerous studies for testing the performance of different nanoparticles at different conditions [12–24]. Some researchers were investigated the performance of different nanoparticles while some examined the shape and size of the nanoparticles for different aspects. However, many researchers are studying the effects of nanoparticles on heat transfer performance.

The thermal properties of the liquid-solid mixture formed when a nanoparticle is added to the liquid differ depending on the liquid. When evaluated in terms of heat transfer, improvements are seen in the heat transfer properties of the nanofluid. The improvement in question varies depending on the properties of the nanoparticle and the mixing ratio. The studies in the literature also aim to find the optimum point of the said recovery.

The most promising nanoparticle studied by many researchers is Al_2O_3. Pak and Cho experimentally investigated the effect of Al_2O_3 and TiO_2 addition with 1–3 vol% to the cooling water in terms of heat transfer performance [25]. They examined the effect of nanoparticles on thermophysical properties. They defined that the Nusselt number increased with the increase of nanoparticle rate. Lai et al. investigated the affect of Al_2O_3-water mixture on heat transfer performance during convective heat transfer process [26]. The nanofluid was used for cooling by flowing through a pipe. Pipe surface temperatures and fluid temperatures were measured. In the case where the nanoparticle concentration was 1% by volume, the number of Nusselts increased by 8%, and when it was 0.5%, it increased by only 3%. Jung et al. carried out experimental studies to evaluate the effect of Al_2O_3 addition to the cooling water on convective heat transfer performance and fluid flow by a rectangular microchannel [27]. They obtained an increase in convective heat transfer coefficient more than 15% with 1.8 vol% concentration. Additionally, friction losses obtained was insignificant, and they proposed a new type of convective heat transfer coefficient for nanofluids at micro channel. Ho et al. implemented an experimental study to analyze the

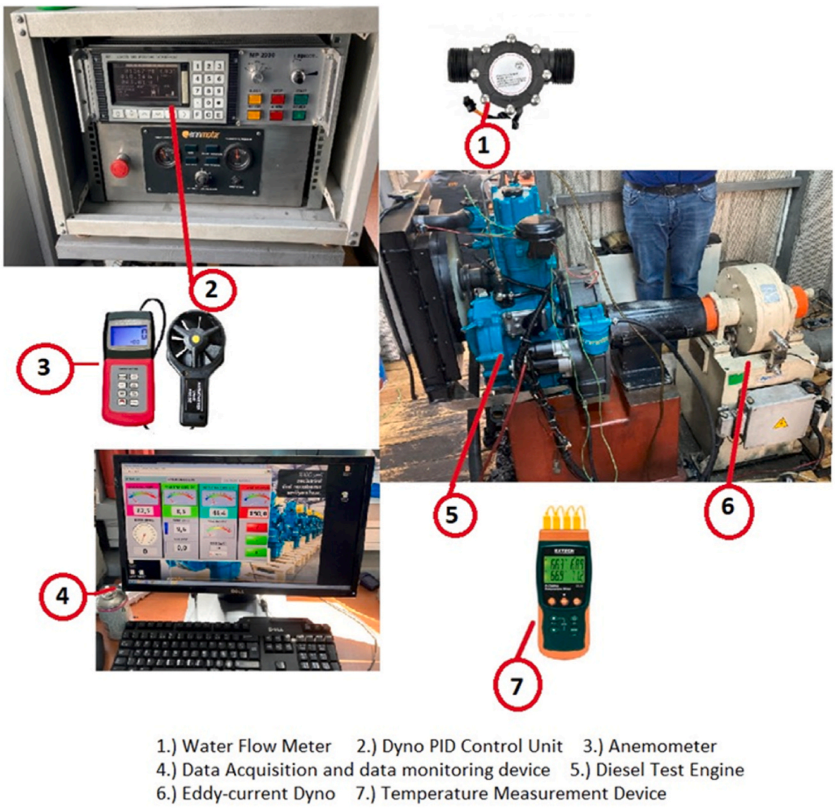

Fig. 1. Experimental rig.

effect of Al_2O_3 on cooling water on heat transfer performance using rectangular micro channels [28]. They examined the parameters such as pumping load, friction coefficient, heat transfer coefficient, thermal resistance and wall temperature. They achieved an increase in heat transfer rate for nanoparticle cooled micro channel about 51%.

Neguen et al. investigated the Al_2O_3-water mixture on cooling performance for electronic component experimentally [29]. The effects of adding nanoparticles to distilled water on convective heat transfer performance have been studied with experimental studies. They achieved an increase in heat transfer coefficient more than 40%. Peyghambarzade et al. carried out experimental studies to evaluate the effects of adding Al_2O_3 particles to the car radiator cooling water [30]. They obtained that heat transfer efficiency increases even for low concentrations. It has been determined by the studies that the fluid flow rate is a very effective parameter on the heat transfer performance, while the fluid inlet temperature is insignificant. It has been stated that the heat transfer efficiency increases up to 45% even at low nanoparticle concentrations.

The aim of this study was to examine the effect of nanoparticle addition on engine heat transfer performance without any

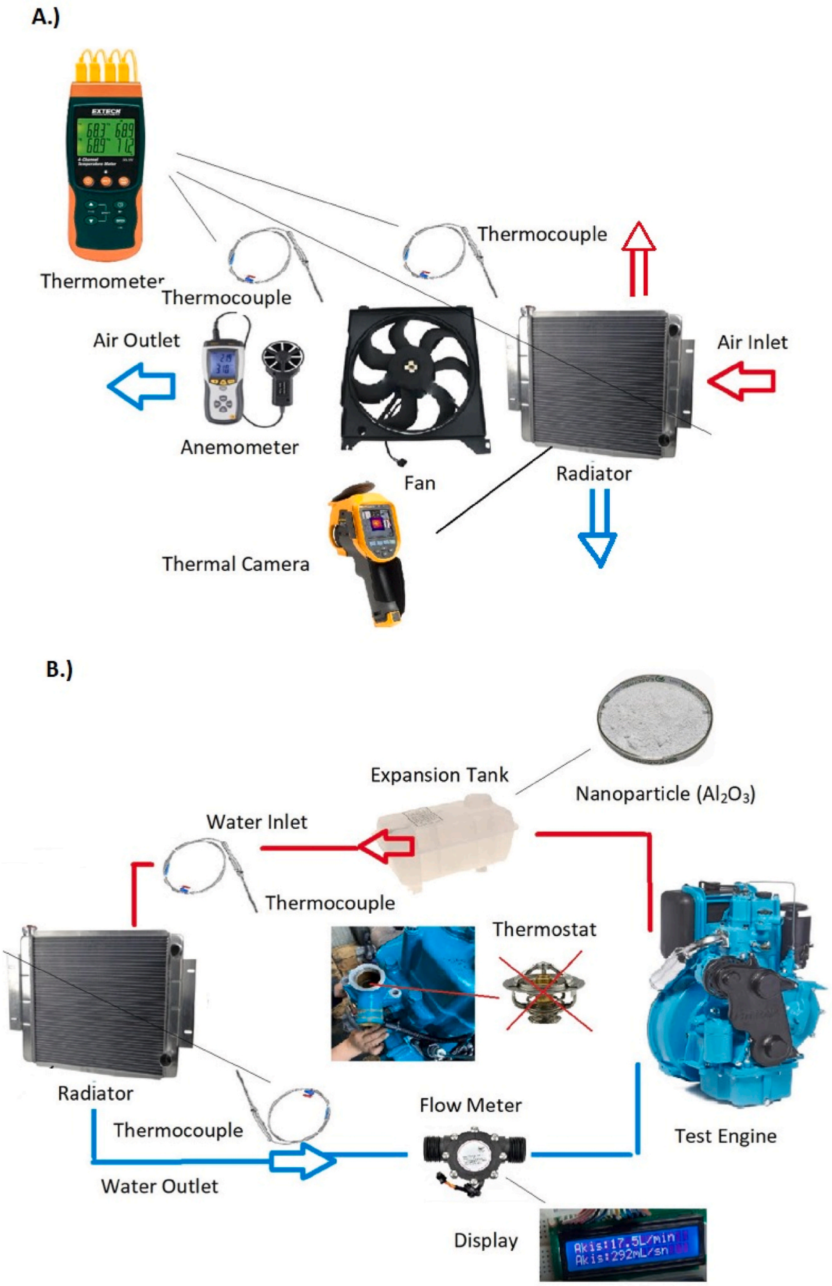

Fig. 2. Cooling loop and equipment.

settlement. In this context, preliminary studies were carried out as stated in the manuscript to ensure that there was no precipitation during the experiments. In the present study, effects of nanoparticles on the performance of a typical automobile radiator were investigated experimentally. As nanoparticle, the Al_2O_3 was utilized at different concentrations. The dispersion of nanoparticles in the water was investigated with the pH analyses at different concentrations. The effects of nanofluids on heat transfer performance were analyzed for different concentrations and engine brake power values. The most important contribution of this study in the literature is that the test studies were carried out on a real engine and cooling system. This makes the results more realistic.

2. Experimental setup and procedure

An experimental test rig was developed to test the effects of nanofluids on vehicle radiator. As shown in Fig. 1 and Fig. 2, the experimental system used in this study includes internal combustion engine, dynamometer, vehicle radiator, centrifugal pump, flow lines, control unit and expansion tank. It also includes measurement equipment as water flow meter, ambient moisture meter, thermal camera, anemometer, multi channel temperature meter, data acquisition and monitoring system and thermocouples. During the tests, the pump gives a constant coolant fluid flow rate. The cooling fluid fills the radiator tank, and the total fluid volume is 4 L which is constant during all the experiments.

The cooling fluid and air temperatures are measured at the inlet and outlet of the radiator. Additionally, the radiator heat distribution is analyzed by measuring the surface temperatures with a thermal camera. The engine output power can be adjusted by the control system. The heat rejected to the cooling fluid from the engine vary with respect to the engine power output. Therefore, the cooling fluid inlet temperature changes by engine power. In this study, total heat transfer characteristics were analyzed to evaluate the effects of nanoparticle addition.

The test liquids are water based for this study. Firstly, the experiments were done with pure water. Then, small amount of nanoparticles were added to the cooling water with different rates. Therefore, effects of nanoparticle addition to the cooling water were evaluated in the meaning of heat transfer performance.

First, nanoparticle added cooling waters were prepared. By adjusting the required pH ratios, cooling liquids with nanoparticle additions at different concentrations were prepared. Subsequently, engine tests were started. The thermostat was removed from the engine cooling unit prior to the tests. The engine has been operated at the specified load until it reaches the regime temperature. Subsequently, tests were carried out on coolants with different nanoparticles. Again, the engine was operated for a long time until it reached the regime conditions. Design of experiment table is given in Table 1 below.

3. Nanofluid preparation

Nanofluid preparation has been still a technical challenge due to very strong van der Waals interactions that cause aggregates of nanoparticles. There are different methods to achieve stable nanofluids such as addition of surfactant, surface modifications, etc. The stabilization of nanofluids affects the heat transfer characteristics of the nanofluids. Aggregation of nanoparticles creates larger particles (micron scale) that take away the advantages of nanoparticles on heat transfer.

The Al_2O_3 nanoparticles used in this study are approximately spherical with the diameter of about 20 nm. The stabilization of nanoparticles were done by using SDS (Sodium Dodecyl Sulfonate) surfactant. Different pH of nanofluids were tested to achieve stabilization of nanofluids (Fig. 3). By the stabilization tests, the optimum levels of solutions were determined. The nanofluid samples were prepared for different nanoparticle concentrations and pH levels.

For this study, three Al_2O_3 concentration levels (0.25, 0.50 and 1.0 wt%) were tested by investigating the earlier studies. The samples were evaluated for stabilization after 15 min, 1 h, 3 h and 5 h. For the pH levels between 6 and 8, very stable nanofluids were achieved for different concentrations. In this way, it has been proven that no precipitation took place during the engine tests.

4. Mathematical model

In this study, heat transfer performance of an internal combustion engine radiator evaluated by adding nanoparticles to coolant water. In the mathematical calculations, thermophysical properties of nanofluids are used. Nanofluid thermophysical properties may be determined by different analyzers or estimated by mathematical correlations presented in the literature. In this study, the following mathematical correlations are utilized in the determination of density and specific heat of nanofluid at different temperatures and concentrations [31–34].

Table 1
Design of experiment.

Preparation Of The Nanofluid Mixture (–)	Al_2O_3 Ratio (%)	Engine Loading Condition (kW)	Engine Tests (–)
Preparation of nanofluid in accordance with preliminary tests	W/O	9.4	Running the engine in stable conditions
Preparation of nanofluid in accordance with preliminary tests	0.25	9.4	Running the engine in stable conditions
Preparation of nanofluid in accordance with preliminary tests	0.5	9.4	Running the engine in stable conditions
Preparation of nanofluid in accordance with preliminary tests	1	9.4	Running the engine in stable conditions
Preparation of nanofluid in accordance with preliminary tests	W/O	11.5	Running the engine in stable conditions
Preparation of nanofluid in accordance with preliminary tests	0.25	11.5	Running the engine in stable conditions
Preparation of nanofluid in accordance with preliminary tests	0.5	11.5	Running the engine in stable conditions
Preparation of nanofluid in accordance with preliminary tests	1	11.5	Running the engine in stable conditions

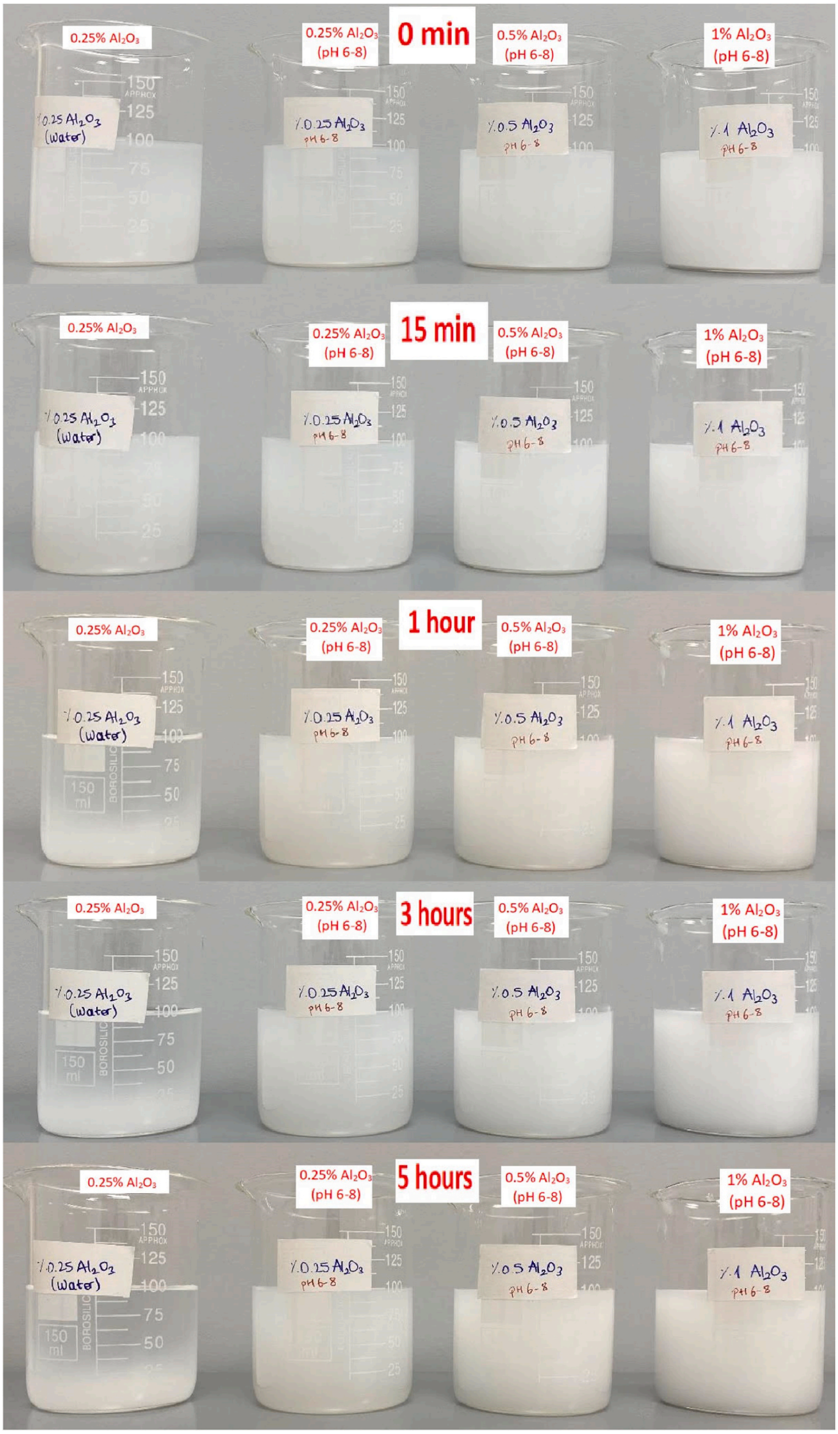

Fig. 3. Photographs taken for the stability analysis at different pH and concentration levels.

$$\rho_{nf} = \varnothing\, \rho_p + (1 - \varnothing)\rho_{bf}$$

$$C_{p,nf} = \frac{(1-\varnothing)\rho_{bf} C_{p,bf} + \varnothing\, \rho_p C_{p,p}}{\rho_{nf}}$$

where Ø is the volumetric concentration of the nanoparticles, C_p is the specific heat, and ρ is the density. The subscripts nf, bf and p refer to the nanofluid, base fluid, and nanoparticles, respectively. The thermophysical properties of Al_2O_3 are presented in Table 2. As can be seen, Al has higher density and lower specific heat values.

In the experiments, the hot coolant fluid flowing inside the radiator transfers heat to the air flowing over the radiator. The rejected and obtained heat transfer rates are calculated as below [36]:

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

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

where Q_a and Q_c are the heat transfer rates for air and coolant sides, respectively. The subscripts c, a, i and o refer to the coolant, air, input and output, respectively. In an ideal case, the rejected heat by the coolant must be equal to the heat obtained by the air. Due to the experimental errors and leakages, the equality never achieved. The arithmetic mean of the heat transfer rate is calculated as below [36]:

$$Q_m = \frac{Q_c + Q_a}{2}$$

The performance of the radiator for different coolants may be evaluated by using the logarithmic mean temperature difference method (LMTD). The LMTD is calculated as below [36]:

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

where $\Delta T_1 = T_{c,i} - T_{a,o}$ and $\Delta T_2 = T_{c,o} - T_{a,i}$. The radiator performance is defined by the following equation [36]:

$$Q_m = U\, A\, F\, \Delta T_{lm}$$

where U is the overall heat transfer coefficient, A is the heat transfer surface area, and F is the correction factor. The correction factor is calculated as below [37]:

$$F = \frac{\ln\left[(1 - R\,S) / (1 - S)\right]}{\left(1 - {}^{1}/_{R}\right)\, ln[1 + R\ln(1 - S)]}$$

where R and S are calculated as below:

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

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

In the analyses of experimental results in the meaning of cooling performance, UA values are utilized and calculated as below [36]:

$$U\, A = \frac{Q_m}{F\, \Delta T_{lm}}$$

5. Results and discussion

Experimental works in the current study were conducted on a real internal combustion engine. Therefore, the results of the conducted experimental studies provide important information about the application, as they will give close-to-reality results. Tests

Table 2
Some thermophysical properties of Al_2O_3 nanoparticles [35].

Particle size	Density	Specific heat	Specific surface area	Purity
Nm	*kg/m^3^*	*J/kg K*	*m^2^/g*	*%*
20	3970	890	140	+99

were carried out for 2 different engine brake power values and 3 different nanoparticle concentration ratios and tests were carried out under real conditions with a standard engine cooling system. The effects of nanoparticle admixture on total heat transfer performance were investigated in the conducted tests.

For better understanding of the nanoparticle addition to cooling fluid, initial experiments were carried out with pure water. The UA values were calculated for pure water and nanofluids with different concentrations. The experiments were done for 2 different engine power values as 9.4 and 11.5 kW.

The cooling fluid inlet and outlet temperatures varied between 50.1 and 70.2 °C and 46.3 and 58.7 °C during the experiments, respectively. The cooling air inlet temperature was about 30 °C while the outlet temperature values varied between 38 and 42 °C.

Fig. 4 shows the results of overall heat transfer performance for 9.4 kW engine brake power. It is clear that the overall heat transfer performance increases as the nanoparticle concentration increases for a fixed engine brake power. For pure water, the UA was calculated as 407.9 W/K. For the nanoparticle concentrations of 0.25, 0.50 and 1.00%, the UA values were calculated as 445.5, 449.9 and 559.6 W/K, respectively. In comparison with pure water, the highest increase of the UA value was achieved for 1.0% concentration as 37.2% and the lowest increase of the UA value was achieved for the 0.25% concentration as 9.2%.

Fig. 5 shows the results of overall heat transfer performance for 11.5 kW engine brake power. It can be seen that the overall heat transfer performance increases as the nanoparticle concentration increases. For pure water, the UA was calculated as 348.2 W/K. For the nanoparticle concentrations of 0.25, 0.50 and 1.00%, the UA values were calculated as 355.0, 362.7 and 374.1 W/K, respectively. In comparison with pure water, the highest increase of the UA value was achieved for 1.0% concentration as 7.4% and the lowest increase of the UA value was achieved for the 0.25% concentration as 2.0%. The improvement in cooling system heat transfer with a small contribution of nanoparticles shows that the subject has a serious potential in terms of energy efficiency in internal combustion engines.

As can be seen from Figs. 4 and 5, for both engine brake power levels, the nanoparticle addition to the cooling fluid creates an increase in heat transfer performance. Therefore, it may be deduced that the nanoparticle addition to the cooling water enhances the heat transfer performance of the cooling radiator. For low power application, the nanofluid has higher heat transfer rates. Hence, it is observed that the cooling radiator heat transfer performance is improved in higher rates for partial loads of the internal combustion engine. Partial load performance improvement is a very important case for most of the thermal processes and turbo machines. For thermal processes and turbo machines, design were done for full load conditions, mainly. Therefore, performance enhancement for these kind of machines at partial loads is a very significant research area. Results of this study show that the cooling performance increases for low load conditions of an internal combustion engines with nanoparticle addition to the cooling water.

It is also clear that the heat transfer performance increases with the increase of nanofluid concentration. If there is no problem with the nanoparticle precipitation to the bottom over time or causing damage to the water line, the addition of nanoparticles to the cooling water of internal combustion engines will be able to be applied.

Additional analyses were done for the heat distribution of the radiator. Thermal images of the radiator were captured during the experiments. The temperature of the radiator was in the range of about 25–60 °C during the image capturing. The thermal images of the radiator were presented in Figs. 6 and 7 for the different engine brake power values. It can be observed from the figures that the increase of nanoparticle addition rates in cooling fluid improves the heat dissipation over the radiator. Better the heat dissipation means better the heat transfer performance. It has been concluded that the results obtained from both the examinations carried out with the thermal camera and the heat transfer graphs are parallel, and the heat transfer in the engine cooling system increases significantly with the increasing amount of nanoparticles.

Within the scope of the study, only the effect of nanoparticle addition on the performance of the engine's heat transfer was investigated. From the results obtained, it is predicted that thanks to the improvement in heat transfer, the power of the water pump and fan will be reduced in the future, the radiator sizes will be reduced, and power losses and pressure losses will be minimized. In this way, it is predicted that the fuel consumption and emission values of the engine will decrease with the reduced pumping loss.

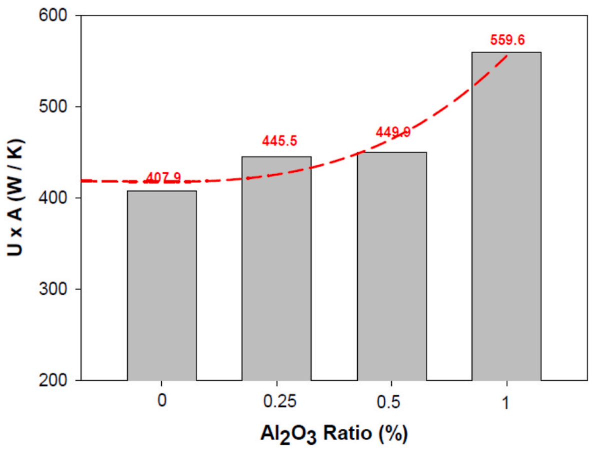

Fig. 4. Effect of nanoparticle addition on heat transfer performance (9.4 kW).

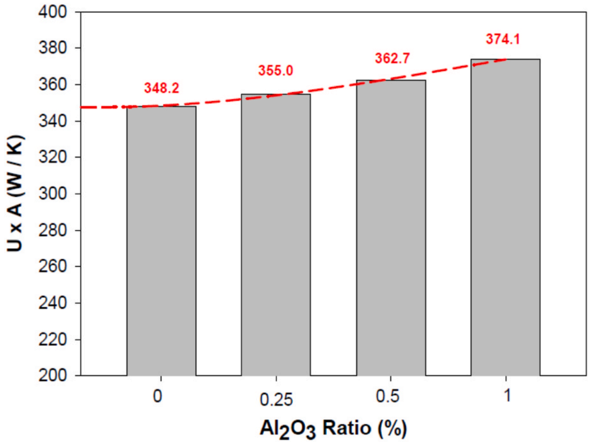

Fig. 5. Effect of nanoparticle addition on heat transfer performance (11.5 kW).

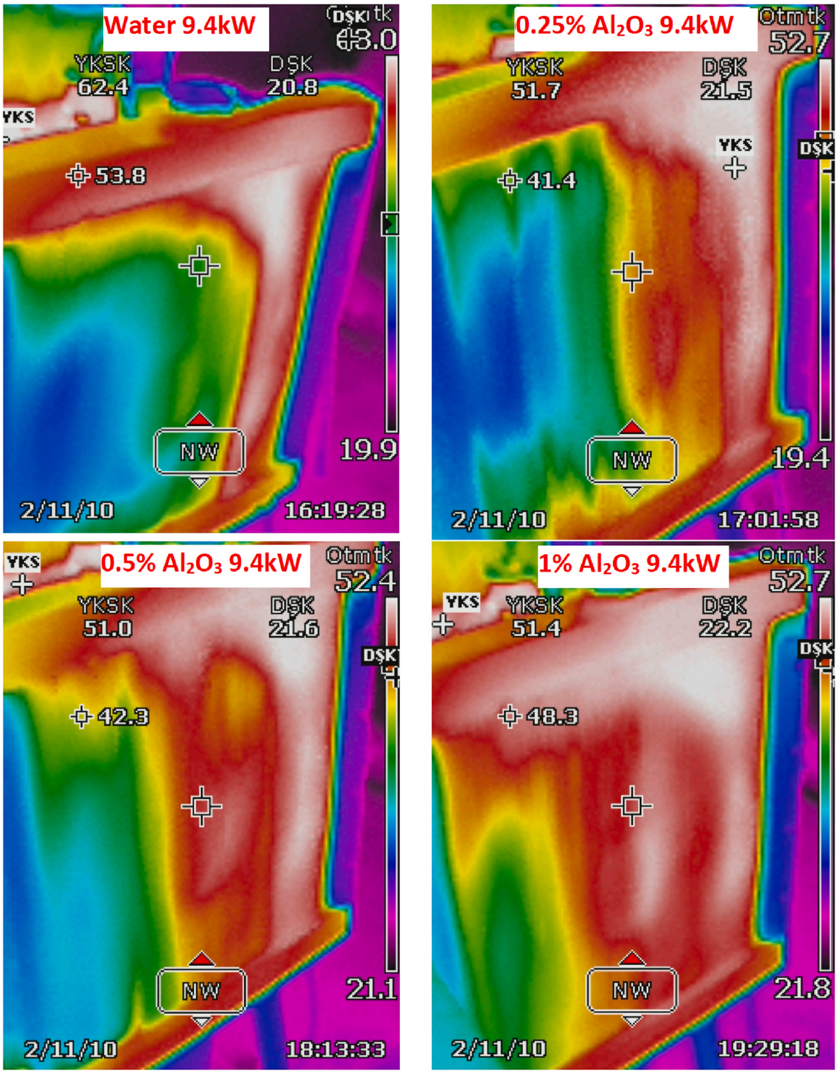

Fig. 6. Radiator thermal images for 9.4 kW engine power.

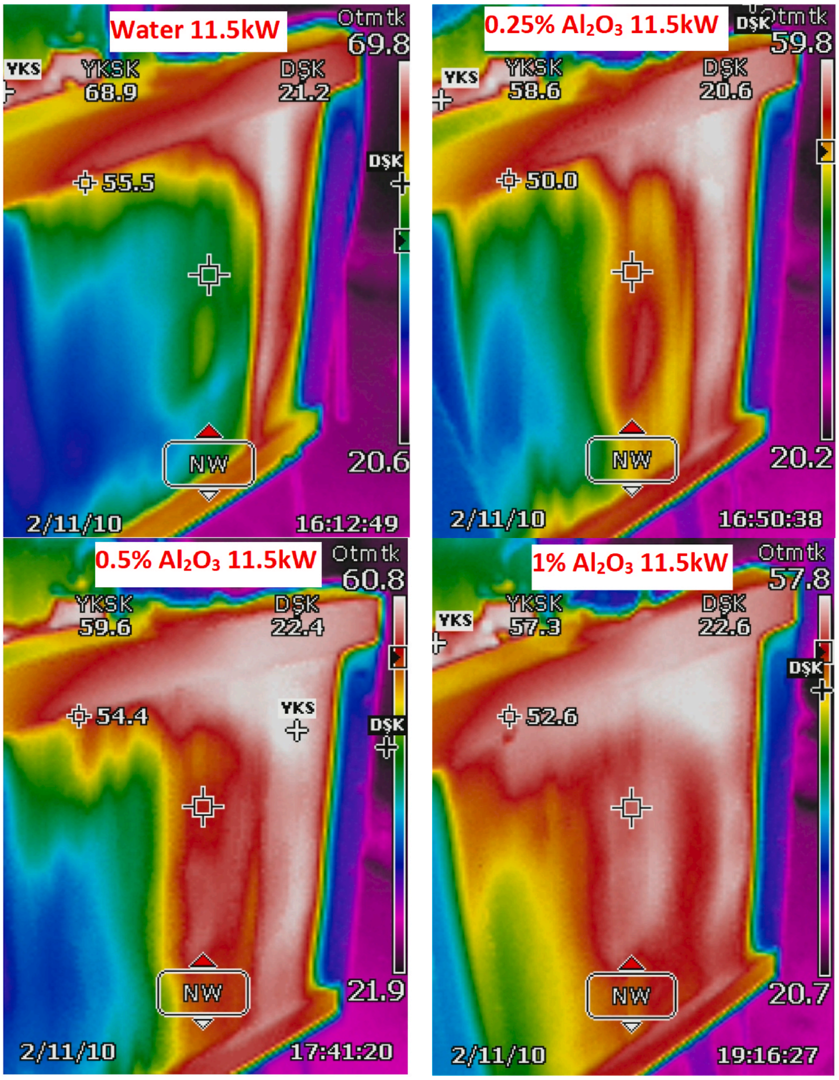

Fig. 7. Radiator thermal images for 11.5 kW engine power.

6. Conclusion

In this article, the effects of using nanoparticles in cooling fluid of an internal combustion engine radiator were investigated. As nanoparticle, Al_2O_3 was used in the experimental works. An important improvement was achieved in heat transfer performance of the radiator by adding nanoparticles to the pure cooling water. The heat transfer performance increased with the increase of nanofluid concentration, and the heat transfer performance improvement was achieved higher for the low power tests. The results shows that using of nanofluids in cooling radiator enhances the heat transfer performance significantly.

Author statement

The authors declare that there is no conflict of interest and all authors have seen and approved the manuscript being submitted.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgement

Authors would like to thank the Erin Motor Incorporated Company for supporting us financially and morally. Authors would like to thank Esra Begüm AYTAN and GeneOn Biotechnology Company for their support in preparing the mixture.

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