Case Studies in Thermal Engineering 43 (2023) 102763

Contents lists available at ScienceDirect

Case Studies in Thermal Engineering

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

Experimental investigation of bimetallic nanoparticles heat transfer characteristics in automotive radiators

Altay Arbak [a], Azade Attar [b], Melda Altikatoglu Yapaoz [c], Mustafa Armağan [a], Yasar Bulbul [d], Emir Kasım Demir [e], Yasin Karagöz [a,*]

[a] *Istanbul Medeniyet University, Department of Mechanical Engineering, Istanbul, Turkey*
[b] *Yildiz Technical University, Department of Bioengineering, Istanbul, Turkey*
[c] *Faculty of Science and Letters, Department of Chemistry, Yildiz Technical University, Istanbul, Turkey*
[d] *Istanbul Medeniyet University, Department of Economics, Istanbul, Turkey*
[e] *Bioengineering Program, Istanbul Medeniyet University, Istanbul, Turkey*

ARTICLE INFO

Handling Editor: Huihe Qiu

Keywords:
Bimetallic nanoparticle
Heat transfer enhancement
Convective heat transfer

ABSTRACT

Improvement of the thermal properties of coolants used in automobile radiators increases the cooling performance of the engine. Metallic nanoparticle additives generally improve the thermal properties of the coolant. In this study, the heat transfer characteristics of a nanofluid prepared with bimetallic additives (CuO–ZnO) for automotive radiators were experimentally investigated. Experiments were made for four different fluids under constant heating power. These are water-bimetal mixture fluids with 0.1%, 0.2% and 0.3% particulate additives. UA values of the heat exchanger were calculated using the logarithmic temperature difference method and compared for different concentrations. As a result, it was observed that the 0.3% additive ratio had the highest UA value. In addition, with the increase of the bimetallic nanoparticle additive rate, the heat transfer also increases. Finally, an economic analysis was carried out for the use of nanoparticles in the water cooling system for a single cylinder natural gas engine.

1. Introduction

The purpose of radiator utilization, which has an important place in the automotive industry, is to ensure long-term and efficient operation of the engine. Combustion in the engine produces massive heat that can cause deformation of the cylinder, piston or lubricants [1]. Radiators have been developed to prevent this and act as the engine's cooling system. The radiator takes energy from the engine via the coolant. Therefore, the amount of energy transferred is directly related to the performance of the coolant. In a standard radiator, the coolant temperature rises to 70–90° Celsius; hence it takes time to get efficient performance [2]. Water and ethylene glycol are the most commonly used radiator coolants; however, their capability of transferring energy is quite limited due to their chemical structure and thermophysical characteristics [3]. In the last decades, the researchers concentrated on reducing vehicle weight, which decreases operating costs and results in a more fuel-efficient engine, including the engine cooling system. As a result, an efficient radiator with a novel technological coolant is a requirement. Nanotechnology provides coolants containing particles in nanometric sizes is called nanofluids. This technology brings higher and faster thermal transfer of the deposited heat by high surface area of the nanoparticles involved in cooling fluid [4]. The aim of minimizing the radiator size could be achieved by the integration of

* Corresponding author.
E-mail address: yasin.karagoz@medeniyet.edu.tr (Y. Karagöz).

https://doi.org/10.1016/j.csite.2023.102763
Received 17 November 2022; Received in revised form 16 January 2023; Accepted 18 January 2023
Available online 24 January 2023

nanofluids.

There are numerous reports evaluating the use of nanoparticles in the coolant provides advanced heat transfer. Asadi and Pourfattah [5] compared the thermal effects of two different (ZnO and MgO) nanoparticles added to a motor oil-based fluid. Nanofluids were prepared at different concentrations and tested at different temperatures. Thus, thermal conductivity improved with increasing temperature and solid concentration. The maximum enhancement of the thermal conductivities of ZnO and MgO nanofluid was also found to be slightly above 28% and 32%, respectively. ZnO nanofluid caused more increase in dynamic viscosity than MgO nanofluid. Yadav et al. [6] prepared different nanofluids by adding copper nanoparticles separately into vegetable oil, paraffin heavy liquid and motor oil base fluids. As the volume fraction (%) increased, the relative viscosity and relative thermal conductivity of all three nanofluids increased. The viscosity of all nanofluids decreased with the increase in temperature. The thermal conductivity of the vegetable oil-based nanofluid was found to be the highest. Mukherjee et al. [7] investigated the thermal properties of nanofluids formed by the addition of SiO2 nanoparticles to engine cooling-based commercial fluid. The thermal conductivity increased with increasing nanoparticle concentration and temperature. In the study, the thermal conductivity value showed a maximum increase of 21% with a determined percentage concentration and temperature parameter. Ahmad et al. [8] investigated the heat and mass transfer properties of Al_2O_3–Cu/water hybrid nanofluid and Cu/water nanofluid. For both fluids, the porous medium increased the shear stresses and also decreased the heat transport rates. In addition, it was stated that the mass transfer rate increased with the chemical reaction and the heat transfer rate decreased with the effect of viscous dissipation. Abbas et al. [9] determined the thermal properties of the Fe_2O_3–TiO_2 (50:50)/distilled water hybrid nanofluid at different volume concentrations. The maximum heat transfer rate and Nusselt improvements were found to be 26.7% and approximately 21%, respectively, with the volume concentration moving from the minimum to the maximum value. Convective heat transfer improved with increasing flow rate and inlet temperature. Sepehrnia et al. [10] prepared 5W30 motor oil based ZnO-MWCNT (30:70) hybrid nanofluid at different concentrations. Viscosity decreased with increasing shear rate and temperature, and increased with increasing volume fraction. Chandrasekaran et al. [11] prepared nanofluids by adding different concentrations of cerium oxide nanoparticles to water and ethylene glycol (3:2) base fluid. As the flow rate and volume concentration of the nanofluid increased, the heat transfer rate increased. In addition, according to certain parameters, the Nusselt number and heat transfer rate were found to be maximum 13.39% and 6.2%, respectively. Contreras and Filho [12] prepared nanofluids of multi-walled carbon nanotube nanoparticles with ethylene-glycol (50:50) base fluid, and investigated the thermal effects of nanofluids at different concentrations. While the dynamic viscosity decreased with increasing temperature, it increased with increasing percent concentration. Thermal conductivity improved with increasing temperature and percent concentration. The heat transfer rate and the overall heat transfer coefficient were determined, so that the maximum increases were found to be 4.6% and 4.4%, respectively. Alves et al. [13] simulated the thermal effects of nanofluids formed by adding Al_2O_3 and CuO nanoparticles to ethylene glycol and water (50:50) base fluid. The Nusselt number enhancement of Al_2O_3 and CuO nanofluids was found to be 12.25% and 16.64%, respectively, and the heat transfer coefficient of the nanofluids was also improved by 170% and 188%, respectively. The total heat transfer increase with the use of Al_2O_3 and CuO nanofluids in the water jacket of the internal combustion engine was found to be 2.22% and 2.79%, respectively.

Bimetallic structures can generally be explained by the addition of a metal to another metal and the added metal increasing the activity [14]. Metals added to the surfaces of nanoparticles provide high oxidation and reduction therefore, bimetallic nanoparticles are often used to improve the properties of the monometallic particle. The efficiencies of bimetallic nanoparticles are thought to result from the electrical interaction between metals. The noble metal added to the transition metal increases the electrical density of the transition metal, making the particle a more effective catalyst. With the change of electronic properties, the distances of atoms between metal atoms will change. Thus, bimetallic nanoparticles have more effective properties than monometallic nanoparticles [15]. In this study, CuO–ZnO bimetallic nanoparticles were synthesized and added to the cooling liquid of the automobile radiator at different rates and the heat transfer efficiency was determined. This is the first report dealing with the utilization of CuO–ZnO bimetallic nanoparticles as nanofluids.

Elias et al. [16] determined the thermo-physical effects of the nanofluid formed by adding Al2O3 nanoparticles into a water and ethylene glycol (50:50)-based coolant. With increasing nanoparticle volume concentration, the thermal conductivity, viscosity and density of the nanofluid increased while the specific heat decreased. Suganthi et al. [17] created different nanofluids by adding ZnO nanoparticles at different concentrations into ethylene glycol and ethylene glycol-water (50:50) based cooling fluids. The thermal conductivity of ZnO-ethylene glycol nanofluid improved with increasing ultrasonication time. Qadri et al. [18] investigated the thermal effects of nanofluids formed by adding (1:3) graphene/cuprous oxide (GO/Cu2O) composite based nanoparticles in ethylene glycol and water base fluid. As the weight concentration of the nanocomposite in the nanofluid increased, the thermal conductivity and boiling point increased. Moghaieb et al. [19] investigated the properties of steady-state turbulent convective heat transfer of nanofluids formed by adding ϒ-Al2O3 nanoparticles in distilled water at different volume concentrations. Thus, the convective heat transfer coefficient increased with the flow velocity and a maximum improvement of 43.54% was achieved.

Niknejadi et al. [20] investigated the laminar forced convection of water-based nanofluid containing Fe3O4 nanoparticles inside a twisted tube and found that the hydrothermal performance of nanofluid in the twisted tube is superior to that of the water in the plain tube. In another study, Dehkordi et al. [21] studied nanofluid boiling phenomenon using molecular dynamics simulation affected by the external electric field in order to estimate the effects of the electric field on H2O/Fe3O4 nanofluid dynamical behavior in an atomic microchannel. Miandoab et al. [22] studied the effects of twisted-tape inserts on the heat transfer and pressure drop across a horizontal tube carrying water-based Graphene-Oxide nanofluid. The results of the study showed that *Nu* rises by increasing Re and the volume fraction, while the friction factor rises by reducing the Re and the twist pitch. Karimi et al. [23] tested the heat transfer enhancement of Silicon Carbide nanofluid flowing through the tube side in a shell and tube heat exchanger.they reported that heat transfer and pressure drop increase with increasing volume fraction of nanoparticles and mass flow rate. Sidik et al. [24] stated that there is no

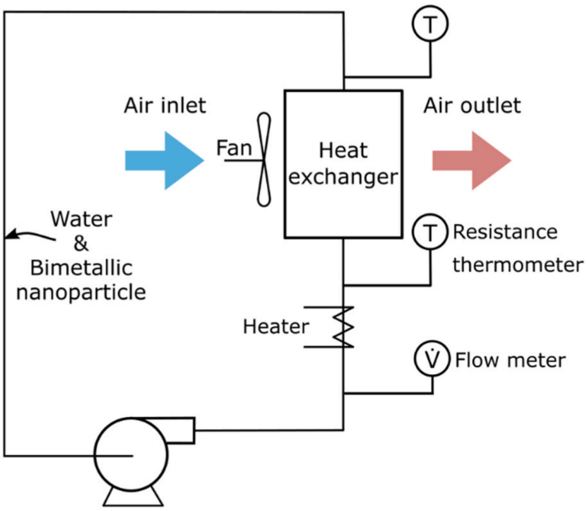

Fig. 1. Experimental setup.

Table 1
Measurement parameters and accuracy values.

Parameter	Equipment	Range	Accuracy
Coolant inlet, outlet temperature	Pt100 sensor	−200 to +850 °C	±0.5 °C
Coolant volumetric flow rate	Turbine meter	1–15 L/min	±3%
Air inlet, outlet temperature	NTC sensor	−10 to +50 °C	±0.5 °C
Air velocity	Anemometer	0–30 m/s	±(5% rdg+0.5)

comprehensive literature study on the engine cooling of nanofluids, so they carried out a review study. In the review study, the tables covering the preparation methods of nanofluids and the improvement of thermal conductivity were quite interesting. Subhedar et al. [25] prepared nanofluids with water-mono ethylene glycol (50:50) base fluid in different volumetric fractions of Al2O3 nanoparticles. The heat transfer of the nanofluid with the least concentration (0,2%) was improved by 30%.

In this study, the effect of the addition of CuO - ZnO bimetallic nanoparticle doped nanocoolant liquid, which are covalently bonded to each other, on heat transfer was investigated experimentally. This is the first report dealing with the utilization of CuO–ZnO bimetallic nanoparticles as nanofluids. The effect of bimetal nanoparticle added coolant in different ratios (0.1%, 0.2% and 0.3%) on the improvement in heat transfer was investigated, although it was added at a very low rate.

2. Materials and method

2.1. Synthesis of the bimetallic nanoparticles

The microwave-assisted polyol reaction was applied in the synthesis of CuO–ZnO nanoparticles [26]. The preparation of the core-shell bimetallic mixture was achieved by introducing equal molar amounts of copper(II) chloride and zinc(II) acetate in ethylene glycol. A homogenous mixture was achieved after 1 h at room temperature. The reaction was carried out in the microwave oven after obtaining the homogenous mixture. At the end of the reaction, the product was washed twice distilled water and left to dry overnight at 70 °C. The simultaneous reduction of the Cu(II) and Zn(II) ions via microwave assistance causes the formation of CuO–ZnO bimetallic nanoparticles.

2.2. Heat transfer experiments

A schematic drawing of the experimental installation is given in Fig. 1. Heat transfer experiments were carried out for four different fluids using this setup. Air velocity was kept constant in all experiments. The flow rate of the pump was changed gradually. The nanofluid is heated by two cartridge heaters mounted in a ½” cross pipe fitting with a total power of 160W and sent to the heat exchanger. The heat exchanger active area has a width of 120 mm and a height of 120 mm. The radiator consists of finned micro channels. A 120 mm wide CPU fan is fixed above the radiator. Air flow is provided by using this fan. PT100 type resistance thermometer was used to measure the inlet and outlet temperature of the fluid precisely.

The measured parameters and measurement accuracies are given in Table 1.

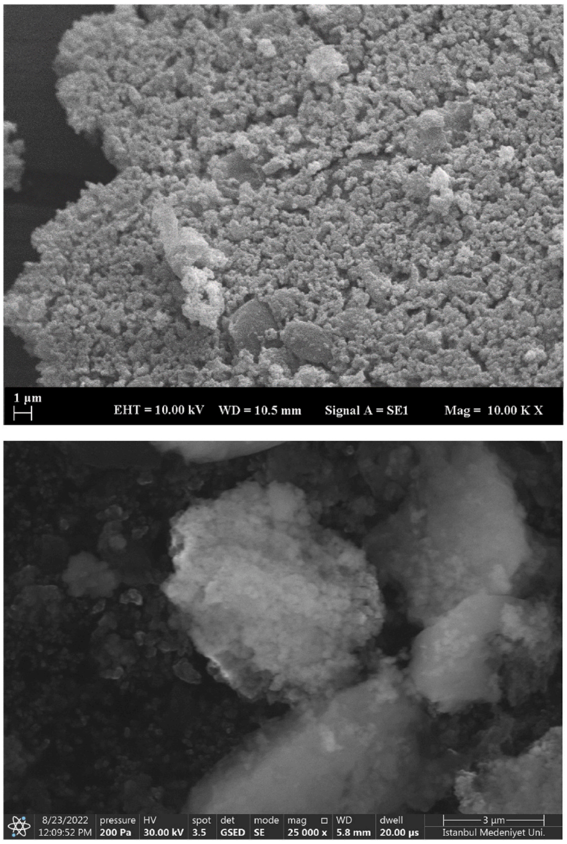

Fig. 2. SEM images of CuO–ZnO nanoparticles a) 1 µm b) 3 µm magnitude.

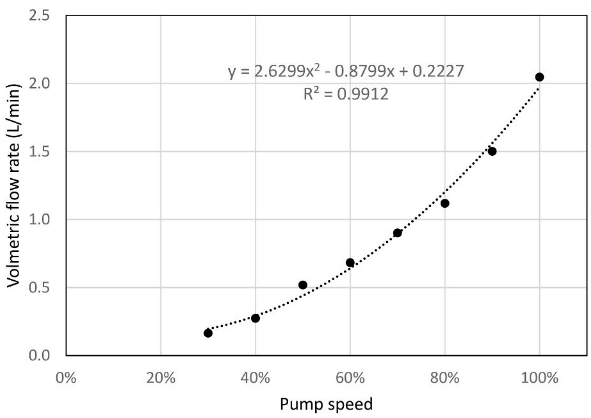

Fig. 3. Flow rate vs. pump speed.

3. Results and discussion

3.1. Characterization of the bimetallic nanoparticles

SEM images of the synthesized CuO–ZnO nanoparticles showed that the nanoparticles were spherical and found in clusters. The bimetallic nature of the particles cause an increase in the volume therefore the sizes of the CuO–ZnO nanoparticles were found to be between 90 and 160 nm individually. There are also SEM images with greater magnitude allowing the identification of clusters of bimetallic nanoparticle clusters. In Fig. 2a, it can be seen that the size of about 42% of the fabricated bimetallic nanoparticles are less than 100 nm and their average size is around 96.1 nm. The bimetallic nanoparticles were fabricated via microwave irradiance. It is known that power of microwave and period of irradiation are main factors affecting the product morphology in the microwave-assisted polyol reaction. Due to the reaction between ethylene glycol and acetates that left an excessive quantity of unreacted component, an

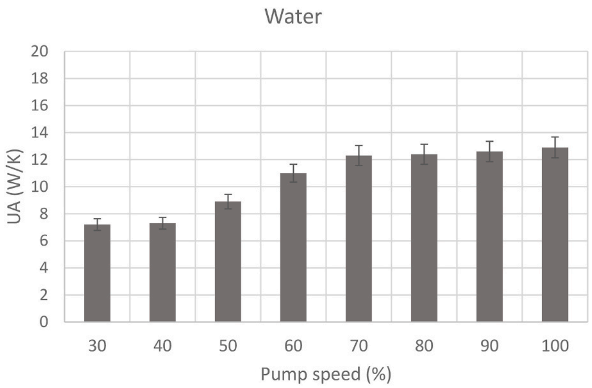

Fig. 4. UA values of base fluid (Water).

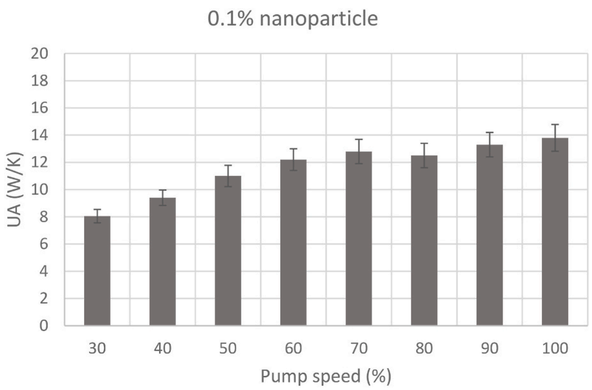

Fig. 5. UA values of 0.1% concentration.

integrated structure is created by increasing the ethylene glycol/acetates ratio. This excessive component acts to bind particles together like mortar paste [27]. Therefore, it appears in Fig. 2b that the CuO–ZnO nanoparticles stick together and agglomerated in a dense shape. Such differences in morphology can be attributed to the efficient synergistic effect and better fusion of the components at the molecular level of the two different components [28].

3.2. Heat transfer results

The flow rate of the pump has been changed in order to obtain different fluid velocities. In Fig. 3, the relationship between pump speed and volumetric flow is given graphically. In the measurements made at eight points, the fluid flow rate was studied in the range of 0.16–2 L/min.

The logarithmic mean temperature difference method was used to model the heat transfer. In Eq. (1), the equation expressing the cooling capacity of the radiator is given.

$$Q = UAF\Delta T_{lm} \tag{1}$$

Here ΔT_{lm} represents the logarithmic temperature difference, F represents the correction factor. In Eq. (2), it is shown how the logarithmic temperature difference is calculated using the fluid inlet and outlet temperatures.

$$\Delta T_{lm} = \frac{\Delta T_1 - \Delta T_2}{ln\left(\frac{\Delta T_1}{\Delta T_2}\right)} \tag{2}$$

The logarithmic temperature difference given in the above equation is defined for a counter flow heat exchanger. As in this study, the temperature difference in cross-flow heat exchangers must be corrected by the F factor (Eq. (3)).

$$F = \frac{ln\left(\frac{1-RS}{1-S}\right)}{\left(1-\frac{1}{R}\right)ln[1 + Rln(1-S)]} \tag{3}$$

The R and S parameters in Eq. (3) are given in Eq. (4) and Eq. (5), respectively, as functions of fluid temperatures.

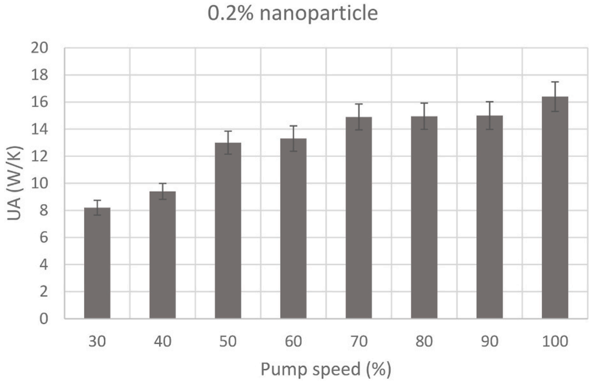

Fig. 6. UA values of 0.2% concentration.

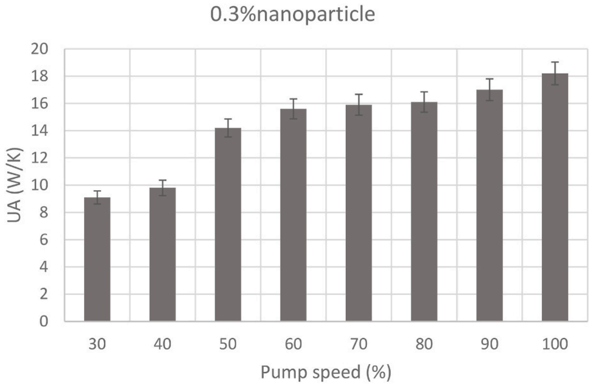

Fig. 7. UA values of 0.3% concentration.

$$R = \frac{T_{a,o} - T_{a,i}}{T_{c,i} - T_{c,o}} \tag{4}$$

$$S = \frac{T_{c,o} - T_{c,i}}{T_{a,i} - T_{a,o}} \tag{5}$$

$$UA = \frac{\dot{m}_c c_{p,c}\left(T_{c,i} - T_{c,o}\right)}{F \Delta T_{lm}} \tag{6}$$

As a result, UA values are calculated from the measured capacitance values with the help of equation (6). Since the heat exchanger surface area is not known exactly, the total heat transfer coefficient (U) is considered as the product of the heat transfer surface area (A) to characterize the heat transfer. Thus, the heat transfer performances in different experiments can be compared. Figs. 4–7 shows the calculated UA values for different nanofluids.

The uncertainty value of the UA value calculated from the measured parameters was calculated using the Kline and McClintock method [29]. In Eq. (7), the uncertainty calculation formula of the UA value is given. Here, the uncertainties of the specific heat of the fluid ($c_{p,c}$) and the temperature difference correction factor (F) are neglected. The uncertainty of the UA value was calculated for each experiment using the values in Table 1. On average, this value is equal to 6%.

$$\frac{w_{UA}}{UA} = \left\{ \left(\frac{w_{\dot{m}_c}}{\dot{m}_c}\right)^2 + \left(\frac{\Delta T_c}{\Delta T_c}\right)^2 + \left(\frac{\Delta T_{lm}}{\Delta T_{lm}}\right)^2 \right\}^{1/2} \tag{7}$$

In the first experiment, no nanoparticle additives were used, the base fluid experiments were carried out with water. In Fig. 4, the UA values obtained for the experiments using water are given as a bar graph for the values of the pump speed varying between 30 and 100%. These results form the basis for experiments with nanoparticle additives. That is, it is the smallest UA value for the given pump speed or fluid velocity. As can be seen from the graph, increasing pump speed increases the UA value. While UA is 7.2 W/K for 30% pump speed, this value goes up to 12.9 W/K at 100% pump speed.

In Fig. 5, UA values are given for experiments using 0.1% nanoparticle additives. There was an increase in UA for each pump speed compared to the base fluid. Although the upward trend seems to decrease for 80% pump speed, it remains within the measurement

Table 2
Economic analysis results.

IRR [%]	Net Present Value [$]	Payback Period
56	987	3.5 years

uncertainty. The UA increase rates were investigated at three different pump speeds representing low, medium and high pump speeds, 30%, 70% and 100%. From the results obtained, with the addition of 0.1% nanoparticles, 11.8% improvement in heat transfer, at low pump speed (30%), 4.1% improvement at medium pump speed (70%) and 6.9% improvement at high pump speed (100%). The results obtained are similar to many studies in the literature in terms of improvement in heat transfer with the addition of metallic nanoparticles [7–9].

Experiment results for 0.2% contribution are given in Fig. 6. UA values increased compared to the 0.1% additive ratio. It was observed that the UA value increased more at low pump speeds as a percentage. From the results obtained, with the addition of 0.2% nanoparticles, 12.2% improvement in heat transfer at low pump speed (30%), 4.1% improvement at medium pump speed (70%) and 21.3% improvement at high pump speed (100%). The results obtained, the improvement rates of the product of surface area and heat transfer with the addition of bimetallic nanoparticles are in line with many publications in the literature [7–9].

The highest UA values were obtained at 0.3% nanoparticle contribution rate. Fig. 7 shows the results. As in other nanofluid experiments, the UA value increases very rapidly at low speeds. From the results obtained, with the addition of 0.2% nanoparticles, 26.4% improvement in heat transfer at low pump speed (30%), 29.3% improvement at medium pump speed (70%) and 41.1% improvement at high pump speed (100%). Similar results were obtained in the literature in terms of increased conductance [7–9].

In this study, the effect of adding nanoparticles to the cooling water at different pump speeds at different rates on the heat transfer performance was experimentally investigated. In the results obtained, an improvement of up to 28.7% (40% pump speed) in UA value was observed in the nanocoolant with 0.1% bimetal nanoparticle addition, according to the condition of working with water alone. Again, an improvement of up to 31.5% (50% pump speed) in UA value was observed in the nanocoolant with 0.2% bimetal nanoparticle addition, according to the condition of working with water alone. Finally, at the highest pump speed, an improvement in UA value up to 41.1% (100% pump speed) was observed in the nanocoolant with 0.3% bimetal nanoparticle addition. From the results obtained, up to 40% improvement was observed in the heat transfer performance with the increasing bimetallic nanoparticle ratio compared to the working condition with water alone.

Using the results obtained in the study, improvements in heat transfer and fuel consumption were calculated with the addition of bimetallic noanoparticle in a single-cylinder, natural gas, naturally aspirated internal combustion generator engine (Erin Motor 1.16 L natural gas SI engine). Cost analysis has been made as a result of working with a lower powered pump in the engine water cooling system. Based on the known pump power of 0.35 kW and the engine overhaul value of $100 and the cost of $5/g bimetallic nanoparticles, the analysis was conducted for 20 years of economic life at an average engine power of 6.3 kW for an annual workin hour of 1000 h. From the results obtained, IRR and NPV values were investigated for the acceptance of 20% average heat transfer improvement, and the payback period of the investment was found as 3.5 years, while the net present value value was 987$ and the IRR value was 56%. The results of the economic analysis are given in Table 2.

4. Conclusion

In this study, heat transfer performance in a small automobile radiator using only water was compared with the experiments using fluids prepared with nanoparticle additives. In particular, an application has been made in which two different metal particles are bonded by covalent bond. It has been observed that bimetallic additives, which are used in very small amounts by mass, significantly increase the heat transfer performance. As expected, the increase in fluid flow caused an increase in the UA value. For the 0.3% nanoparticle contribution for the highest fluid velocity, the improvement in heat transfer is around 40%. These results show that smaller radiators can be made using bimetallic nanoparticles. As a result, by using the obtained outputs, the fuel consumption will be improved thanks to the reduction of the cooling system pump power by the addition of bimetallic nanoparticles in the internal combustion generator engine, the system will pay for itself in a payback period of 3.5 years and the net present value value for 20 years of economic life. It was concluded that it was calculated as 987$.

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.

Data availability

The authors are unable or have chosen not to specify which data has been used.

Acknowledgement

Istanbul Medeniyet University, Science & Advanced Technologies Research Center (BILTAM - Istanbul, Turkey) supported to the study with SEM analysis. Lastly, authors are grateful to Erin Motor Company (Istanbul, Turkey) for their technical equipment donation.

References

[1] S.O. Oyedepo, et al., Numerical modeling of heat transfer performance and optimization of car radiator using (H2O/Al2O3) nanofluids as coolant, Numer. Heat Tran. B Fund. (2022), https://doi.org/10.1080/10407790.2022.2083854.

[2] V. Kumar, R. Sahoo, Preheating effects on compression ignition engine through waste heat recovery using THNF-based radiator coolant: an experimental study, J. Therm. Sci. Eng. Appl. 14 (12) (Dec. 2022), https://doi.org/10.1115/1.4055005.

[3] I.N. Ibrahim, N. Sazali, A.S. Jamaludin, D. Ramasamy, S.M. Soffie, M.H.D. Othman, A review on vehicle radiator using various coolants, J. Adv.Res.Fluid.Mech. Therm.Sci. 59 (2) (2019) 330–337.

[4] X. Li, H. Wang, B. Luo, The thermophysical properties and enhanced heat transfer performance of SiC-MWCNTs hybrid nanofluids for car radiator system, Colloids Surf. A Physicochem. Eng. Asp. 612 (Mar. 2021), 125968, https://doi.org/10.1016/J.COLSURFA.2020.125968.

[5] A. Asadi, F. Pourfattah, Heat transfer performance of two oil-based nanofluids containing ZnO and MgO nanoparticles; a comparative experimental investigation, Powder Technol. 343 (Feb. 2019) 296–308, https://doi.org/10.1016/J.POWTEC.2018.11.023.

[6] S.K. Yadav, V. Vasu, U.K. Paliwal, Experimental study on thermo-physical properties of nano-fluids based on copper nanoparticles, Mater. Today Proc. 18 (Jan. 2019) 525–532, https://doi.org/10.1016/J.MATPR.2019.06.389.

[7] S. Mukherjee, T. Halder, S. Ranjan, K. Bose, P.C. Mishra, S. Chakrabarty, Effects of SiO2 nanoparticles addition on performance of commercial engine coolant: experimental investigation and empirical correlation, Energy 231 (Sep. 2021), 120913, https://doi.org/10.1016/J.ENERGY.2021.120913.

[8] S. Ahmad, K. Ali, M. Rizwan, M. Ashraf, Heat and mass transfer attributes of copper–aluminum oxide hybrid nanoparticles flow through a porous medium, Case Stud. Therm. Eng. 25 (Jun. 2021), 100932, https://doi.org/10.1016/J.CSITE.2021.100932.

[9] F. Abbas, et al., Towards convective heat transfer optimization in aluminum tube automotive radiators: potential assessment of novel Fe2O3-TiO2/water hybrid nanofluid, J. Taiwan Inst. Chem. Eng. 124 (Jul. 2021) 424–436, https://doi.org/10.1016/J.JTICE.2021.02.002.

[10] M. Sepehrnia, K. Mohammadzadeh, M.M. Veyseh, E. Agah, M. Amani, Rheological behavior of engine oil based hybrid nanofluid containing MWCNTs and ZnO nanopowders: experimental analysis, developing a novel correlation, and neural network modeling, Powder Technol. 404 (May 2022), 117492, https://doi.org/10.1016/J.POWTEC.2022.117492.

[11] M. Chandrasekaran, K.B. Prakash, C. Subramaniyan, N. Santhosh, V.D. Tamilarasan, Experimental investigation on heavy duty engine radiator using cerium oxide nano fluid, Mater. Today Proc. 66 (Jan. 2022) 1497–1500, https://doi.org/10.1016/J.MATPR.2022.06.284.

[12] E.M. Cardenas Contreras, E.P. Bandarra Filho, Heat transfer performance of an automotive radiator with MWCNT nanofluid cooling in a high operating temperature range, Appl. Therm. Eng. 207 (May 2022), 118149, https://doi.org/10.1016/J.APPLTHERMALENG.2022.118149.

[13] L.O. Ferrão Teixeira Alves, J.R. Henríquez, J.Â.P. da Costa, V. Abramchuk, Comparative performance analysis of internal combustion engine water jacket coolant using a mix of Al2O3 and CuO-based nanofluid and ethylene glycol, Energy 250 (Jul. 2022), 123832, https://doi.org/10.1016/J.ENERGY.2022.123832.

[14] N. Toshima, Metal nanoparticles for catalysis, Nanoscale Mater. (Jan. 2006) 79–96, https://doi.org/10.1007/0-306-48108-1_3/COVER.

[15] A. Maclennan, A. Banerjee, Y. Hu, J.T. Miller, R.W.J. Scott, In situ X-ray absorption spectroscopic analysis of gold-palladium bimetallic nanoparticle catalysts, ACS Catal. 3 (6) (2013) 1411–1419, Jun, https://doi.org/10.1021/CS400230T/ASSET/IMAGES/LARGE/CS-2013-00230T_0006.JPEG.

[16] M.M. Elias, et al., Experimental investigation on the thermo-physical properties of Al2O3 nanoparticles suspended in car radiator coolant, Int. Commun. Heat Mass Tran. 54 (2014) 48–53, https://doi.org/10.1016/j.icheatmasstransfer.2014.03.005.

[17] K.S. Suganthi, V. Leela Vinodhan, K.S. Rajan, Heat transfer performance and transport properties of ZnO-ethylene glycol and ZnO-ethylene glycol-water nanofluid coolants, Appl. Energy 135 (2014) 548–559, https://doi.org/10.1016/j.apenergy.2014.09.023.

[18] M.Z. Qadri, R.R. Chandran, S. Ravindra, V. Velmurugan, Synthesis and testing of graphene/cuprous oxide composite based nano fluids for engine-coolants, Mater. Today Proc. 2 (9) (2015) 4640–4645, https://doi.org/10.1016/j.matpr.2015.10.084.

[19] H.S. Moghaieb, H.M. Abdel-Hamid, M.H. Shedid, A.B. Helali, Engine cooling using Al2O3/water nanofluids, Appl. Therm. Eng. 115 (2017) 152–159, https://doi.org/10.1016/j.applthermaleng.2016.12.099.

[20] M. Niknejadi, M. Afrand, A. Karimipour, A. Shahsavar, A.H. Meghdadi Isfahani, Experimental investigation of the hydrothermal aspects of water–Fe3O4 nanofluid inside a twisted tube, J. Therm. Anal. Calorim. 143 (1) (Jan. 2021) 801–810, https://doi.org/10.1007/s10973-020-09271-0.

[21] K.G. Dehkordi, A. Karimipour, M. Afrand, D. Toghraie, A.H.M. Isfahani, Molecular dynamics simulation concerning nanofluid boiling phenomenon affected by the external electric field: effects of number of nanoparticles through Pt, Fe, and Au microchannels, J. Mol. Liq. 324 (Feb. 2021), 114775, https://doi.org/10.1016/j.molliq.2020.114775.

[22] A. Rezaei Miandoab, S.A. Bagherzadeh, A.H. Meghdadi Isfahani, Numerical study of the effects of twisted-tape inserts on heat transfer parameters and pressure drop across a tube carrying Graphene Oxide nanofluid: an optimization by implementation of Artificial Neural Network and Genetic Algorithm, Eng. Anal. Bound. Elem. 140 (Jul. 2022) 1–11, https://doi.org/10.1016/j.enganabound.2022.04.006.

[23] S. Karimi, M.M. Heyhat, A.H.M. Isfahani, A. Hosseinian, Experimental investigation of convective heat transfer and pressure drop of SiC/water nanofluid in a shell and tube heat exchanger, Heat Mass Tran. 56 (8) (2020) 2325–2331, Aug, https://doi.org/10.1007/s00231-020-02844-7.

[24] N.A. Che Sidik, M.N.A. Witri Mohd Yazid, R. Mamat, Recent advancement of nanofluids in engine cooling system, Renew. Sustain. Energy Rev. 75 (Aug. 2017) 137–144, https://doi.org/10.1016/j.rser.2016.10.057.

[25] D.G. Subhedar, B.M. Ramani, A. Gupta, Experimental investigation of heat transfer potential of Al 2 O 3/Water-Mono Ethylene Glycol nanofluids as a car radiator coolant, Case Stud. Therm. Eng. 11 (Mar. 2018) 26–34, https://doi.org/10.1016/j.csite.2017.11.009.

[26] S.A. Mousavi, M. Hassanpour, M. Salavati-Niasari, H. Safardoust-Hojaghan, M. Hamadanian, Dy2O3/CuO nanocomposites: microwave assisted synthesis and investigated photocatalytic properties, J. Mater. Sci. Mater. Electron. 29 (2) (2018) 1238–1245, Jan, https://doi.org/10.1007/S10854-017-8026-8/TABLES/2.

[27] H. Ajamein, M. Haghighi, S. Alaei, Influence of propylene glycol/nitrates ratio on microwave-assisted combustion synthesis of CuO-ZnO-Al2O3 nanocatalyst: structural and catalytic properties toward hydrogen production from methanol, Mater. Res. Bull. 102 (Jun. 2018) 142–152, https://doi.org/10.1016/J.MATERRESBULL.2018.02.026.

[28] H. Hou, J. Lan, Y. Yao, J. Xu, M. Feng, Li-storage performances of flower-like CuO/ZnO nanoparticles derived from bimetallic CuZn-L-phenylalanine precursor, Ionics 27 (4) (2021) 1589–1595, Apr, https://doi.org/10.1007/S11581-020-03877-Y/FIGURES/6.

[29] S. Kline, Describing uncertainty in single sample experiments, Mech. Eng. 75 (1953) 3–8.