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ORIGINAL ARTICLE

Experimental investigation of Silver / Water nanofluid heat transfer in car radiator

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ABSTRACT – Currently available fluids for heat transfer including refrigerants, water, ethylene glycol mixture, etc., have been widely exploited in various fields, especially in automobile cooling systems, for many years. However, these fluids possess poor heat transfer capability which means that to achieve acceptable heat transfer activity, high compactness and effectiveness of heat transfer systems are essential. This research work concentrates on preparation and use of water based Silver containing nanofluids in automobile cooling system. Nanoparticles volume fraction, fluid inlet temperature, coolant and air Reynolds numbers were optimized so that the heat transfer performance of the car radiator system was totally improved. It was found that increasing these parameters leads to enhancement of the heat transfer performance. In the best condition, the Ag/water nanofluids with low concentrations could amend heat transfer efficiency up to 30.2% in comparison to pure water.

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INTRODUCTION

Nanofluids which have wide range of applications in industry, are defined as suspensions of solid nanoparticles in form of organic or inorganic materials in basic fluids which are mainly utilized for heat transfer applications. These nanoparticles improve the heat transfer performance by raising conduction and convection coefficients which enables them to be more effective in various applications [1]. The currently available heat transfer fluids which are used for these purposes including refrigerants, water, ethylene glycol mixture, engine oil, etc., possess poor heat transfer capability. This implies that high compactness and effectiveness are key factors which can determine the overall performance of a good heat transfer fluid.

Recently, in different research works it has been reported that nanofluids have better performance as heat transfer agent compared to conventional fluids [2-12]. Among them, Choi [2] coined the term nanofluids to introduce the fluids containing suspended nanoparticles for the first time. Moreover, it was reported by Choi et al. [3] that addition of even less than 1 vol.% of nanoparticles to base heat transfer liquids increases thermal conductivity up to about two times. In addition, in a research Yu et al. [4] showed that by adopting different types of nanofluids, heat transfer performance can be improved by almost 15-40%. In another research, Xuan and Li [5] performed a research to assess the convective heat transfer coefficient of water/Cu nanofluids, where, considerable enhancement of heat transfer performance was observed. They have reported that for a given Reynolds number, the nanofluid containing 2 vol.% Cu nanoparticles had greater (by 60%) convective heat transfer coefficient in comparison to pure water. Additionally, in several investigations it has been shown that the nanofluids possessing low amount of nanoparticles can have 10% higher thermal conductivity [13-20]. In another research, Naphon [21] thermal conductivity of the fluid containing only 0.3 vol.% Cu nanoparticles was increased by about 40% which is significant.

Automobile radiator which is a key component of vehicle engines plays an important role and belongs to cross flow heat exchangers. They are also useful in huge vehicles including construction equipment, trains, compressor coolers, etc., which cause them to be of great importance. Vehicle weight can be reduced by deploying optimized design and size of radiator which is essential for achieving a cleaner environment. In many researches, it was tried to vary the geometry of heat exchanger apparatus through different fin types, various tube inserts, or rough surface [22-28]. Using electric or magnetic field or vibration techniques have been focused in some researches [29-32]. In this respective, Kulkarni et al. [31] reported that energy efficiency can be enhanced by optimizing topological and configuration features, however, much more attention must be paid to heat transfer fluid. However, deploying traditional approaches for increasing cooling rate through optimizing fins and micro channel is limited. Thus, innovative heat transfer fluids should be improved to enhance heat transfer capability of automotive car radiator. In other words, it is thought that nanofluids can be used instead of conventional coolants in engine cooling system. Considering the above mentioned features, it is possible to reduce weight and size of car radiator while increasing heat transfer performance [33].

So far, some experimental researches have been performed in order to find methods and nanomaterials that can amend performance of an automotive car radiator by exploiting nanofluids as coolants [34-40]. In this regard, application of EG

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based copper nanofluids in an automotive cooling system was investigated by Leong et al. [32]. In order to investigate the performance of nano-fluid based coolants in automotive car radiator, results obtained for various researches have been collected. In literature, it has been shown that adding 2% volume fraction Cu nanoparticles to base fluid to prepare the nanofluid, increases the heat transfer performance by almost 3.8% in which Reynolds numbers of air and coolant were 6000 and 5000, respectively. Moreover, Peyghambarzadeh et al. [38, 39], have used 1 vol.% Al_2O_3 in pure water and water/ethylene glycol mixture to conduct the experiments in an automobile radiator which resulted 45% and 40% increase in convective heat transfer coefficient, respectively.

In the present research, to prepare a nanofluid with enhanced heat transfer capability, silver nanoparticles are considered and added to water as the base fluid. Silver nanoparticles were chosen in this study as they possess higher thermal conductivity compared to other nanoparticles such as Cu and Al2O3. Thus herein, forced convection heat transfer coefficients of the prepared nanofluids are calculated in an automotive car radiator by using Ag/water nanofluids as coolants under fully laminar conditions. Car radiator is included in setup test in which effects of various factors including Reynolds numbers of air and coolant, nanoparticles concentration and temperature of circulating fluid on its heat transfer performance are studied.

METHODS AND MATERIALS

Experimental Test Rig and Procedures

Figure 1 shows the schematic diagram of the experimental apparatus used in this work. It includes flow lines, a reservoir tank, a centrifugal pump, heating elements, a fan with a frequency inverter, a hot wire anemometer, a flowmeter, a thermometer, and a cross flow finned tube heat exchanger (a car radiator). Reservoir tank is 60 liter in volume (60 cm in height and 35 cm in diameter) and the working liquid would fill 20% of the total volume. For providing same conditions for the used fluids, the total volume of the circulating liquid was kept constant in all experiments. The reservoir tank and pipe lines are thermally insulated which can be useful in inhibiting the heat loss to the surrounding. The centrifugal pump provides a constant flow rate of 90 l/min; the flow rates are controlled by using two adjusting valves, one at the main flow loop and the other one at the by-pass line (Figure 1). For heating the working fluid, three heating elements (each one 2 kW) and a controller were used to maintain the temperature between 80 and 90°C. Note that the velocity of the air was controlled by a frequency inverter which controls the fan speed. Air velocity was measured by a hot wire anemometer (Lutron YK-2004AH Type). For controlling and manipulating the flow rate, a flow meter (Technical Group LZM-15Z Type) with precision of 0.1 l/min was used. The temperatures of the fluids at inlet and outlet sections of the automobile radiator were measured by employing a thermometer (Lutron TM-946 Type) with two K-type thermocouples, having ±0.1°C accuracy. Two other J-type thermocouples were also utilized to monitor the temperature of the radiator wall. In the experimental setup, the thermocouples were located at the center of the radiator surfaces (both sides). As the flat tubes are very small and also their thermal conductivities are high, it seems to be rational to consider the temperature of inside and outside of the tube, as equal. The measured temperatures were monitored on two digital monitors with the accuracy of 0.1°C. Before performing the experiments, all thermocouples were thoroughly calibrated by employing a constant temperature water bath, and their accuracies were estimated to be ±0.2°C. The type of the radiator core is shown in Figure 2. It consists of 178 vertical tubes with four tube rows. The tube cross section is rectangular with circular ends. The fins and tubes are made by copper and there are 181 continuous fins. For cooling the liquid, an axial forced fan (PEM C90S-2 Type) was placed near to axis line of the radiator and thus air and water have indirect cross flow contact.

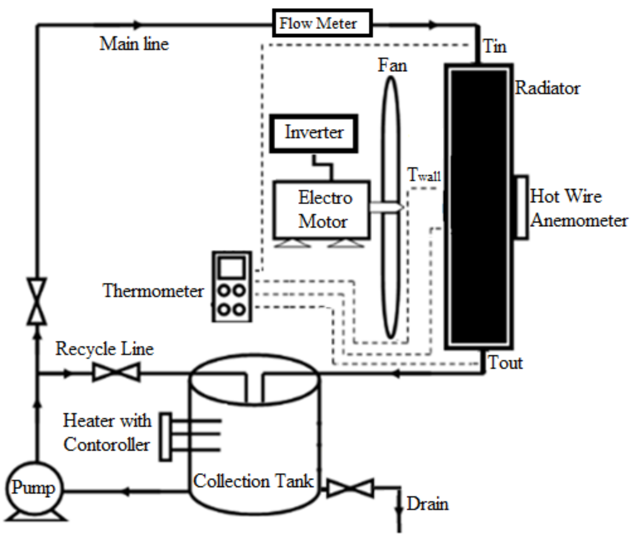

Figure 1. Schematic illustration of the experimental setup

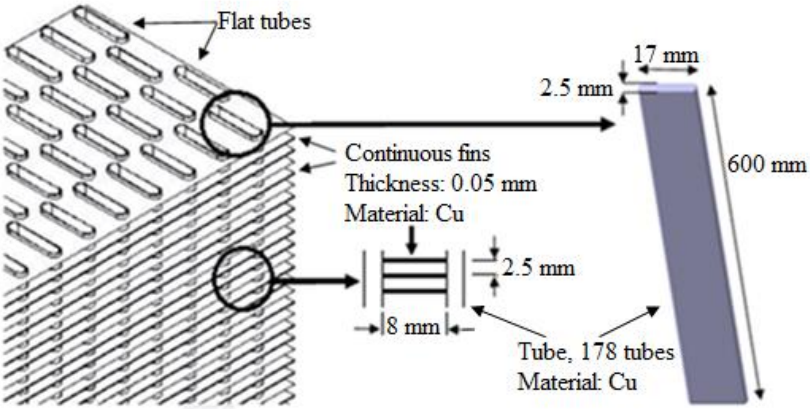

Figure 2. Schematic sketch and dimensions of the car radiator

To conduct the experiments, the nanofluids which were prepared by using small amount (0-0.5 vol.%) of silver nanoparticles in water were adopted. The Ag nanoparticles were purchased from a commercial company and as shown in Figure 3 they have mean diameter of 10 nm. In order to study only effect of the added nanoparticles, dispersants or stabilizers were not added to nanofluids because addition of any other materials can lead to changes in fluid properties [40] and the authors were intended to simulate the actual conditions of automobile radiator.

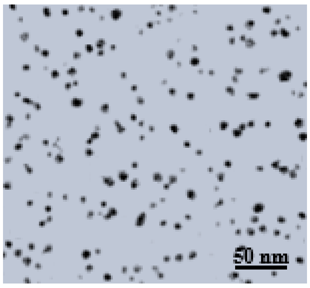

Figure 3. Transmission electron microscopy (TEM) image of the used Ag nanoparticles

Experimental Uncertainties

By calculating the errors of the measurements, uncertainty analysis was performed, in which, errors in measuring the hydraulic diameter and flow rate of nanofluid and air causes error and uncertainty range in assessing the coolant and air Reynolds numbers. Moreover, the uncertainty of the parameters such as heat transfer efficiency and Nusselt number of nanofluid is dependent on the errors which are found in measuring the temperatures, hydraulic diameter, and volume flow rate of the nanofluid. Based on uncertainty analysis which has been defined by Moffat [41], the measurement errors of the important factors are given in Table 1. Subscripts “nf”, “D_h”, “h”, “Re” and “Nu” refer to the nanofluid, hydraulic diameter (m), convection heat transfer coefficient (W/m^{2}K), Reynolds number and Nusselt number, respectively.

Table 1. The uncertainty of the measured parameters

Parameter	Value	Uncertainty
$D_{h,nf}$	4.36 (mm)	1.3%
$D_{h,air}$	3.81 (mm)	1.1%
Re_{nf}	500 to 1700	4.6%
Re_{air}	4000 to 5000	5.4%
h_{nf}	300 to 1100 (W/m^{2}k)	8.3%
Nu_{nf}	2 to 5	11.6%

Data Processing

Estimation of nanofluids physical properties

Concentration of the nanoparticles in the nanofluid can be regarded as equal throughout the prepared nanofluid, by considering the well distribution of them inside the base fluid. Some classical equations which are common for two phase fluids can be employed for studying the effective physical properties of the mixtures [37]. These equations have been adopted to estimate the physical properties of the nanofluid which include density (ρ), specific heat (C_p), viscosity (μ) and thermal conductivity (k) at different temperatures and concentrations [42-44].

The effective density of nanofluid (kg/m^3) is defined as follows:

$$\rho_{nf} = (1-\varphi_v)\rho_w + \varphi_v \rho_p \tag{1}$$

Subscripts "*nf*", "*w*" and "*p*" refer to the nanofluid, water and nanoparticles, respectively. "φ_v" is the nanoparticles volume concentration.

The specific heat of the nanofluids was calculated using the equation given by Xuan and Roetzel [45] which assumes a thermal equilibrium between the base fluid and the nanoparticles. The equation is:

$$C_{p,nf} = \frac{(1-\varphi_v)\rho_w C_{p,w} + \varphi_v \rho_p C_{p,p}}{\rho_{nf}} \tag{2}$$

The viscosity (μ_{nf}) (Pa.s) and the effective thermal conductivity (W/m.k) of the nanofluids (k_{nf}) are calculated from the following equations, respectively:

$$\mu_{nf} = \mu_w \left(123\varphi_v^2 + 7.3\varphi_v + 1\right) \tag{3}$$

$$k_{nf} = \frac{k_p + (n-1)k_w - \varphi_v (n-1)(k_w - k_p)}{k_p + (n-1)k_w + \varphi_v (k_w - k_p)} k_w \tag{4}$$

In these equations, factor of empirical shape is shown by "n" which is calculated by n = 3/ψ, and the particle sphericity is shown by "ψ" . This is considered as the ratio of the surface area of a sphere to the surface area of the particle, where, both possess the same volume. In addition, "*n*" is considered as 3 in the current research work. To interpret the results better, changing in dimensionless physical properties of the nanofluids are depicted in Figure 4. In this figure, the ratios of physical properties of the prepared Ag/Water nanofluids to those of the pure water as the base fluid are exhibited as a function of nanoparticles concentration. It is obvious that adding small amount of silver nanoparticles can make changes in the physical properties of the base fluid significantly.

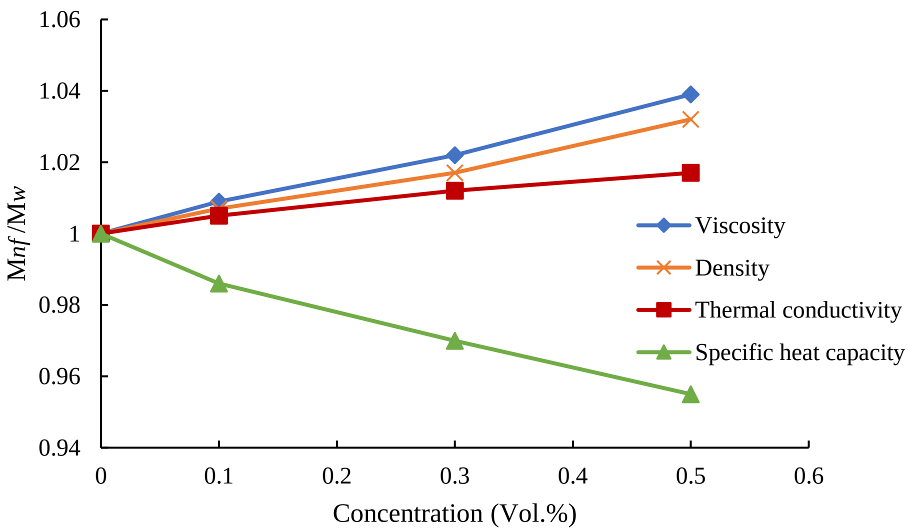

Figure 4. Dimensionless physical properties of nanofluid in comparison with those of pure water

Calculation of convection heat transfer coefficient

In order to obtain the convection heat transfer coefficient and Nusselt number, the following calculations were done. According to Newton's cooling law:

$$Q = h_{exp} A(T_b - T_{wall}) \tag{5}$$

The heat transfer rate can be calculated as:

$$Q = \dot{m} C_p (T_{in} - T_{out}) \tag{6}$$

Considering the equality of "*Q*" (W) in the above equations, the heat transfer coefficient and respective Nusselt numbers of the nanofluids can calculated:

$$h_{exp} = \frac{\dot{m} C_p (T_{in} - T_{out})}{A(T_b - T_{wall})} \tag{7}$$

$$Nu_{exp} = \frac{h_{exp} D_h}{k_{nf}} = \frac{\dot{m} D_h C_p (T_{in} - T_{out})}{A k_{nf} (T_b - T_{wall})} \tag{8}$$

where the mean Nusselt number of the whole radiator is indicated by "Nu_{exp}", mass flow rate (kg/s) is shown by "$\dot{m}$" which is obtained by multiplying density by volume flow rate of fluid, "C_p" denotes fluid specific heat capacity (J/kg.K), "T_{in}" and "T_{out}" show inlet and outlet temperatures (K), respectively, "A" refers to peripheral area of radiator tubes (m^2), and "T_b" shows bulk temperature (K). This is considered as the mean values of inlet and outlet temperature of the working fluid which moves inside the radiator. Moreover, average value of two surface thermocouples is shown by "T_{wall}" (K). In addition, in the Eq. 8 fluid thermal conductivity and hydraulic diameter of the tube are indicated by "k_{nf}" and "D_h", respectively. In all experiments, for calculating the physical properties, fluid bulk temperature was considered.

RESULTS

Convection Heat Transfer Coefficient of Pure Water

Prior to starting the experiments regarding the application of the prepared nanofluids in the car radiator, some experimental runs were performed by using pure water, so that the reliability and accuracy of the setup was checked and controlled. Experimental results of water flow through radiator at constant inlet temperature of 85°C are shown in Figure 5. As expected, by increasing the Reynolds number of the coolant, the Nusselt number was increased. The Experimental results were compared with the following empirical equation suggested by Seider–Tate [43] for laminar flow:

$$Nu_{th} = 1.86 \left(\mathrm{Re}_{nf} \, \mathrm{Pr}_{nf} \, \frac{D}{L} \right)^{1/3} \left(\frac{\mu_{nf}}{\mu_{wnf}} \right)^{0.14} \tag{9}$$

"μ_{wnf}" is nanofluid viscosity at tube wall temperature and "Pr" is Prandtl number of nanofluid. As shown in Figure 5, there is a good agreement between experimental data and the results obtained from Seider–Tate [43] equation which confirms the accuracy and reliability of the experimental data which have been used for further experiments.

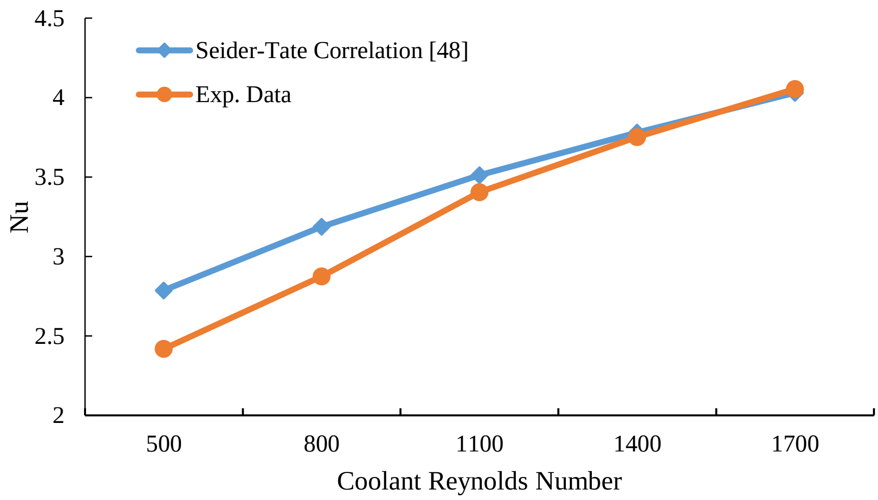

Figure 5. The results of pure water in comparison with the Seider–Tate correlation [43]

Convection Heat Transfer Coefficient of nNanofluid

Effect of fluid temperature

Results obtained by investigating the effect of temperature variations (80 to 90°C) on the heat transfer performance of the car radiator at nanoparticles concentration of 0.5 vol.% and fixed average air and coolant Reynolds numbers of 4500 and 500, respectively, are presented in this section. Figure 6 shows the changes of the heat transfer coefficient as a function of temperature for Ag/water nanofluid and pure water. As it is clear, by increasing the inlet temperature the convection heat transfer coefficient was increased. At inlet temperatures of 80, 85, and 90°C convection heat transfer coefficients of the nanofluids were enhanced by 21.8%, 21.7% and 20.3% relative to that of pure water, respectively. It is thought that this improvement of heat transferring capability can be attributed to impact of temperature on the physical properties and Brownian motion.

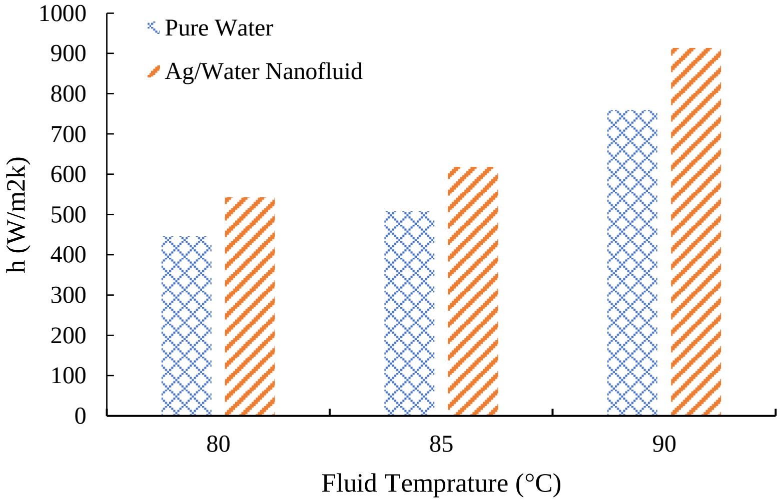

Figure 6. Variations of convection heat transfer coefficient at different temperatures (at the nanoparticles concentration of 0.5 vol.%)

Effect of coolant Reynolds number

In this section, analysis of the coolant Reynolds number $(500 \langle Re \langle 1700)$ of the car radiator at a fixed inlet temperature (85°C) and an air Reynolds number of 4500 with varying silver nanoparticles volume fraction is incorporated. Coolant Reynolds number plays a vital role in determining the radiator's thermal performance. Inappropriate Reynolds number of coolant might cause the engine might be overcooled or overheated. The radiator can ensure optimum temperature operation of the engine by adjusting Reynolds numbers of the coolant and air. Although coolant pumping is performed by an engine, thermostat also plays a determining role in controlling the Reynolds number of the coolant [33].

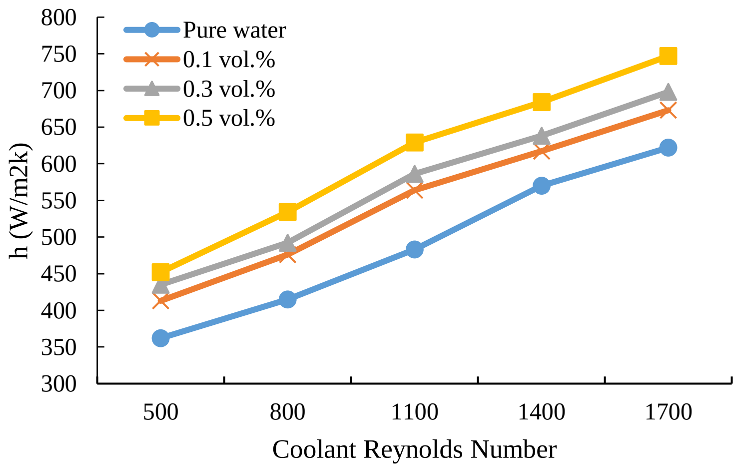

Figure 7. Effect of coolant Reynolds number on convection heat transfer coefficient of the car radiator

Convection heat transfer coefficient of the car is shown in Figure 7. Naturally, the convection heat transfer coefficient increases by increasing the coolant Reynolds number. For example, by adding 0.5% Vol.% Silver nanoparticles, convection heat transfer coefficient was improved by 30.2% at inlet temperature of 85°C and Reynolds numbers of 1100 and 4500 for coolant and air, respectively. Figure 7 also shows that heat transfer performance of the car radiator containing nanofluid is higher than that of the car radiator using pure water.

Effect of air Reynolds number

In this section, it is discussed how the air Reynolds number can affect the heat transferring capability of the car radiator. Coolant's volumetric and mass flow rates, Prandtl and Nusselt numbers did not experience any changes since the coolant Reynolds number was kept fixed at 1100. However, concentration of Silver nanoparticles and air Reynolds number were increased from 0 to 0.5 vol.% and 4000 to 5000, respectively. Nanofluids with higher Silver volume fraction provide higher convection heat transfer coefficient than that of the base fluid. The same scenario happened for the heat transfer of car radiator where it is proportional to air Reynolds number as shown in Figure 8. By adding 0.5 vol.% Silver nanoparticles at average inlet temperature (85°C), coolant and air Reynolds number (1100 and 5000, respectively), about 23.3% improvement in convection heat transfer coefficient can be achieved. Moreover, the results of experiments exhibited that higher air Reynolds number leads to better heat dissipation process, however, by considering the design of the car radiator it must be ensured that the engine operates at optimum temperature. Driving conditions or its speed and engine load must be considered. For instance, while driving uphill the engine must operate at higher load and due to lower air velocity, the air Reynolds number should be low. Hence, in this condition the engine might get overheated. However, when driving downhill an engine only needs to be operated at lower load and at the same time high air Reynolds number is observed, so engine might be overcooled. Therefore, these aspects must be taken into consideration when designing automotive radiator [33].

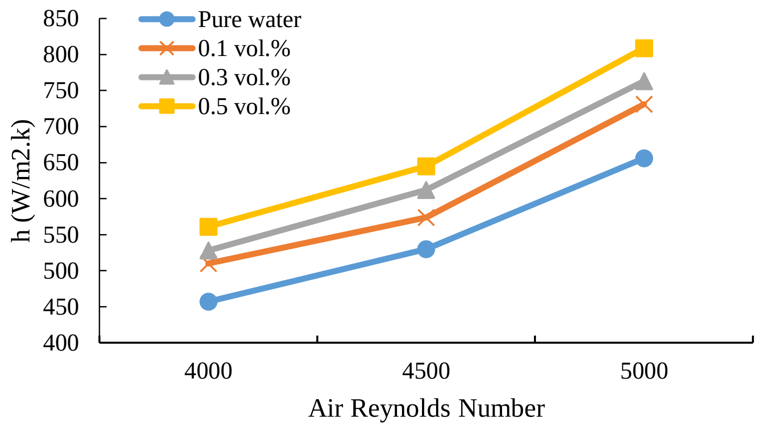

Figure 8. Effect of air Reynolds number on convection heat transfer coefficient of the car radiator

Effect of volume fraction of Silver nanoparticles

In this part, effect of Silver nanoparticles volume concentration on heat transfer capability of the car radiator is discussed. According to above results, the best conditions for highest heat transfer rate are temperature of 90°C, and Reynolds number of 600 and 5000 for coolant and air, respectively. For evaluating the effect of Ag volume fraction, the nanofluids were prepared using different Ag concentrations of 0.1, 0.3, and 0.5 vol.%. Figure 9 depicts changing of heat transfer performance at various nanoparticle concentrations. As can be seen, the ratio of the nanofluid Nusselt number to the water Nusselt number (Nunf/Nuw) has been increased by increasing nanoparticles concentration. By adding only 0.5 vol.% Ag nanoparticles to water, Nusselt number was increased by about 24% compared with that of the pure water. Additionally, at different fluid inlet temperatures of 80 and 85°C, the trend same as at 90°C was observed.

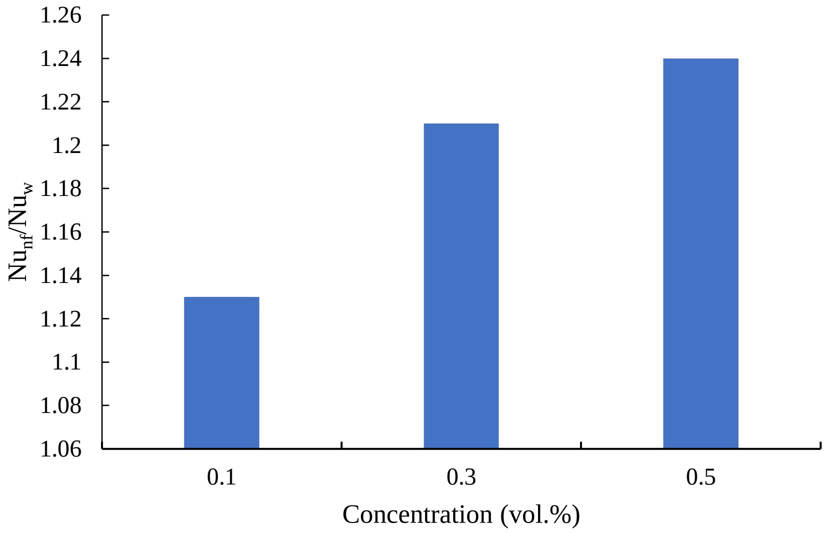

Figure 9. Effect of Silver volume fraction on heat transfer coefficient of the car radiator at constant temperature, and constant air and coolant Reynolds numbers

Considering the results which have been obtained from this study, it was observed that when low amount of silver nanoparticles is added to water, thermal conductivity increases slightly, specific heat decreases, and also viscosity and density increase sharper. For better understanding, Figure 4 illustrates variations of physical properties of the prepared Ag/Water nanofluid. However, these variations are negligible (of about 3.5%) which can't be considered for explaining heat transfer enhancement of up to 30.2% obtained in this study. Thus, it can be concluded that by employing the prepared Ag/water nanofluids in car radiator, its efficiency can be enhanced considerably. In literature, it has been suggested that Brownian motion and formation of nanolayer are among the most determining factors in enhancing the heat transfer performance. As reported in literature, the thickness of thermal boundary layer, due to application of silver nanoparticles and the random motion of the nanoparticles within the base solution, is decreased [46]. This greatly affects the heat transfer performance and enhances the heat transfer capability [46]. Regarding the accidental movement of nano-scale particles, between solid particles and fluid medium, a slip velocity can be formed [50]. Moreover, it has been suggested [46] that small variations in temperature and velocity might affect the Brownian motion.

The higher convection heat transfer coefficients provided by employing the prepared nanofluid, allowed the working fluid in the car radiator to be cooler. Adding nanoparticles to water for producing an efficient nanofluid can enhance engine efficiency by improving the cooling rates and also reducing the radiator size. Adopting nanofluids which leads to smaller coolant systems provides possibility of using smaller and lighter radiators which amends vehicle performance and leads to more efficient fuel economy [41].

CONCLUSIONS

In the current research work, effects of some variables on heat transfer performance of the car radiator have been investigated. For this end, the nanofluids which were prepared by water and silver nanoparticles were adopted. Moreover, nanoparticles volume fraction, temperature, air and coolant Reynolds numbers were varied in order to determine the heat transfer performance of the radiator by using nanofluids. After preforming the experiments by using the nanoparticle silver/water, the following conclusions were observed:

1) The results confirmed that by increasing the working fluid temperature in the car radiator (ranging from 80 to 90°C), the convection heat transfer coefficient is increased. In this respective, at 90°C, about 20.3% heat transfer enhancement was achieved by adding 0.5 vol.% Silver nanoparticles at 500 and 4500 Reynolds numbers for coolant and air, respectively.
2) Moreover, it was concluded that by raising the Reynolds number, the heat transfer performance of the car radiator can be enhanced. In addition, by increasing the coolant Reynolds number from 500 to 1700, about 71.8% and 65.3% heat transfer enhancement were observed for pure water and water containing 0.5 vol.% Silver nanoparticles, respectively.
3) By raising air Reynolds number (or equally speed of fan) from 4000 to 5000, about 43.5% and 44.2% heat transfer enhancement were observed for pure water and water with 0.5 vol.% Silver nanoparticles, respectively.
4) In general, presence of silver nanoparticles in water for preparing a stable nanofluid could enhance the heat transfer performance of the car radiator. Heat transfer enhancement level is dependent on amount of nanoparticles which is added to pure water. Consequently, the best results were obtained at 90°C, Reynolds numbers of 500 and 5000 for

coolant and air, respectively, and by adding 0.5 vol.% Ag nanoparticles to base fluid which yielded the heat transfer enhancement of 30.2% compared to pure water.

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REFERENCES

[1] S. Choi, D. Singer, and H. Wang, "Developments and applications of non-Newtonian flows," *Asme Fed*, vol. 66, pp. 99-105, 1995.

[2] S. U. Choi and J. A. Eastman, "Enhancing thermal conductivity of fluids with nanoparticles," Argonne National Lab., IL (United States), 1995.

[3] S. U. S. Choi, Z. G. Zhang, W. Yu, F. E. Lockwood, and E. A. Grulke, "Anomalous thermal conductivity enhancement in nanotube suspensions," (in English), *Applied Physics Letters,* vol. 79, no. 14, pp. 2252-2254, Oct 1 2001, doi: Doi 10.1063/1.1408272.

[4] W. Yu, D. M. France, S. U. Choi, and J. L. Routbort, "Review and assessment of nanofluid technology for transportation and other applications," Argonne National Lab.(ANL), Argonne, IL (United States), 2007.

[5] Y. M. Xuan and Q. Li, "Investigation on convective heat transfer and flow features of nanofluids," (in English), *Journal of Heat Transfer-Transactions of the Asme,* vol. 125, no. 1, pp. 151-155, Feb 2003, doi: 10.1115/1.1532008.

[6] R. Sadri *et al.*, "A facile, bio-based, novel approach for synthesis of covalently functionalized graphene nanoplatelet nano-coolants toward improved thermo-physical and heat transfer properties," *J Colloid Interface Sci,* vol. 509, pp. 140-152, Jan 1 2018, doi: 10.1016/j.jcis.2017.07.052.

[7] Y. L. Zhai, L. Li, J. Wang, and Z. H. Li, "Evaluation of surfactant on stability and thermal performance of Al2O3-ethylene glycol (EG) nanofluids," (in English), *Powder Technology,* vol. 343, pp. 215-224, Feb 1 2019, doi: 10.1016/j.powtec.2018.11.051.

[8] A. S. Dalkılıç *et al.*, "Experimental study on the thermal conductivity of water-based CNT-SiO2 hybrid nanofluids," *International Communications in Heat and Mass Transfer*, vol. 99, pp. 18-25, 2018/12/01/ 2018, doi: https://doi.org/10.1016/j.icheatmasstransfer.2018.10.002.

[9] A. H. Rasheed, H. B. Alias, and S. D. Salman, "Experimental and numerical investigations of heat transfer enhancement in shell and helically microtube heat exchanger using nanofluids," *International Journal of Thermal Sciences,* vol. 159, p. 106547, 2021/01/01/ 2021, doi: https://doi.org/10.1016/j.ijthermalsci.2020.106547.

[10] C. Liu, T. Zhang, B. Lv, Y. Qiao, and Z. Rao, "Preparation and thermo-physical properties of stable graphene/water nanofluids for thermal management," *Journal of Molecular Liquids,* vol. 319, p. 114165, 2020/12/01/ 2020, doi: https://doi.org/10.1016/j.molliq.2020.114165.

[11] B. Kristiawan, A. I. Rifa'i, K. Enoki, A. T. Wijayanta, and T. Miyazaki, "Enhancing the thermal performance of TiO2/water nanofluids flowing in a helical microfin tube," *Powder Technology,* vol. 376, pp. 254-262, 2020/10/01/ 2020, doi: https://doi.org/10.1016/j.powtec.2020.08.020.

[12] E. O. I. Ettefaghi, H. Ahmadi, A. Rashidi, A. Nouralishahi, and S. S. Mohtasebi, "Preparation and thermal properties of oil-based nanofluid from multi-walled carbon nanotubes and engine oil as nano-lubricant," (in English), *International Communications in Heat and Mass Transfer,* vol. 46, pp. 142-147, Aug 2013, doi: 10.1016/j.icheatmasstransfer.2013.05.003.

[13] S. Askari, R. Lotfi, A. M. Rashidi, H. Koolivand, and M. Koolivand-Salooki, "Rheological and thermophysical properties of ultra-stable kerosene-based Fe3O4/Graphene nanofluids for energy conservation," (in English), *Energy Conversion and Management,* vol. 128, pp. 134-144, Nov 15 2016, doi: 10.1016/j.enconman.2016.09.037.

[14] S. Mukherjee, S. Jana, P. Chandra Mishra, P. Chaudhuri, and S. Chakrabarty, "Experimental investigation on thermo-physical properties and subcooled flow boiling performance of Al2O3/water nanofluids in a horizontal tube," *International Journal of Thermal Sciences,* vol. 159, p. 106581, 2021/01/01/ 2021, doi: https://doi.org/10.1016/j.ijthermalsci.2020.106581.

[15] J. Ding, H. Zhao, and H. Yu, "Graphene nanofluids based on one-step exfoliation and edge-functionalization," *Carbon,* vol. 171, pp. 29-35, 2021/01/01/ 2021, doi: https://doi.org/10.1016/j.carbon.2020.08.068.

[16] F. Soltani, D. Toghraie, and A. Karimipour, "Experimental measurements of thermal conductivity of engine oil-based hybrid and mono nanofluids with tungsten oxide (WO3) and MWCNTs inclusions," (in English), *Powder Technology,* vol. 371, pp. 37-44, Jun 30 2020, doi: 10.1016/j.powtec.2020.05.059.

[17] A. Asadikia, S. A. A. Mirjalily, N. Nasirizadeh, and H. Kargarsharifabad, "Characterization of thermal and electrical properties of hybrid nanofluids prepared with multi-walled carbon nanotubes and Fe2O3 nanoparticles," *International Communications in Heat and Mass Transfer,* vol. 117, p. 104603, 2020.

[18] E. Sadeghinezhad, A. R. Akhiani, H. S. C. Metselaar, S. T. Latibari, M. Mehrali, and M. Mehrali, "Parametric study on the thermal performance enhancement of a thermosyphon heat pipe using covalent functionalized graphene nanofluids," (in English), *Applied Thermal Engineering,* vol. 175, p. 115385, Jul 5 2020, doi: ARTN 11538510.1016/j.applthermaleng.2020.115385.

[19] G. Huminic, A. Huminic, F. Dumitrache, C. Fleaca, and I. Morjan, "Study of the thermal conductivity of hybrid nanofluids: Recent research and experimental study," (in English), *Powder Technology,* vol. 367, pp. 347-357, May 1 2020, doi: 10.1016/j.powtec.2020.03.052.

[20] L. D. Tijing, B. C. Pak, B. J. Baek, and D. H. Lee, "A study on heat transfer enhancement using straight and twisted internal fin inserts," (in English), *International Communications in Heat and Mass Transfer,* vol. 33, no. 6, pp. 719-726, Jul 2006, doi: 10.1016/j.icheatmasstransfer.2006.02.006.

[21] P. Naphon, "Effect of coil-wire insert on heat transfer enhancement and pressure drop of the horizontal concentric tubes," (in English), *International Communications in Heat and Mass Transfer,* vol. 33, no. 6, pp. 753-763, Jul 2006, doi: 10.1016/j.icheatmasstransfer.2006.01.020.

[22] B. Sahin and A. Demir, "Performance analysis of a heat exchanger having perforated square fins," (in English), *Applied Thermal Engineering,* vol. 28, no. 5-6, pp. 621-632, Apr 2008, doi: 10.1016/j.applthermaleng.2007.04.003.

[23] Z. Zhnegguo, X. Tao, and F. Xiaoming, "Experimental study on heat transfer enhancement of a helically baffled heat exchanger combined with three-dimensional finned tubes," *Applied Thermal Engineering,* vol. 24, no. 14, pp. 2293-2300, 2004/10/01/ 2004, doi: https://doi.org/10.1016/j.applthermaleng.2004.01.012.

[24] M. Y. Wen and C. Y. Ho, "Heat-transfer enhancement in fin-and-tube heat exchanger with improved fin design," (in English), *Applied Thermal Engineering,* vol. 29, no. 5-6, pp. 1050-1057, Apr 2009, doi: 10.1016/j.applthermaleng.2008.05.019.

[25] S. H. Hashemabadi and S. G. Etemad, "Effect of rounded corners on the secondary flow of viscoelastic fluids through non-circular ducts," (in English), *International Journal of Heat and Mass Transfer,* vol. 49, no. 11-12, pp. 1986-1990, Jun 2006, doi: 10.1016/j.ijheatmasstransfer.2006.01.014.

[26] S. H. Hashemabadi, S. G. Etemad, M. R. G. Naranji, and J. Thibault, "Laminar flow of non-Newtonian fluid in right triangular ducts," (in English), *International Communications in Heat and Mass Transfer,* vol. 30, no. 1, pp. 53-60, Jan 2003, Doi 10.1016/S0735-1933(03)00007-1.

[27] K. Yakut and B. Sahin, "Flow-induced vibration analysis of conical rings used for heat transfer enhancement in heat exchangers," (in English), *Applied Energy,* vol. 78, no. 3, pp. 273-288, Jul 2004, doi: DOI 10.1016/j.apenergy.2003.09.001.

[28] S. Laohalertdecha and S. Wongwises, "Effects of EHD on heat transfer enhancement and pressure drop during two-phase condensation of pure R-134a at high mass flux in a horizontal micro-fin tube," (in English), *Experimental Thermal and Fluid Science,* vol. 30, no. 7, pp. 675-686, Jul 2006, doi: 10.1016/j.expthermflusci.2006.01.003.

[29] J. S. Paschkewitz and D. M. Pratt, "The influence of fluid properties on electrohydrodynamic heat transfer enhancement in liquids under viscous and electrically dominated flow conditions," (in English), *Experimental Thermal and Fluid Science,* vol. 21, no. 4, pp. 187-197, Apr 2000, doi: Doi 10.1016/S0894-1777(00)00002-9.

[30] N. Umeda and M. Takahashi, "Numerical analysis for heat transfer enhancement of a lithium flow under a transverse magnetic field," (in English), *Fusion Engineering and Design,* vol. 51-52, pp. 899-907, Nov 2000, doi: Doi 10.1016/S0920-3796(00)00424-5.

[31] D. P. Kulkarni, R. S. Vajjha, D. K. Das, and D. Oliva, "Application of aluminum oxide nanofluids in diesel electric generator as jacket water coolant," (in English), *Applied Thermal Engineering,* vol. 28, no. 14-15, pp. 1774-1781, Oct 2008, doi: 10.1016/j.applthermaleng.2007.11.017.

[32] K. Y. Leong, R. Saidur, S. N. Kazi, and A. H. Mamun, "Performance investigation of an automotive car radiator operated with nanofluid-based coolants (nanofluid as a coolant in a radiator)," (in English), *Applied Thermal Engineering,* vol. 30, no. 17-18, pp. 2685-2692, Dec 2010, doi: 10.1016/j.applthermaleng.2010.07.019.

[33] S. Devireddy, C. S. R. Mekala, and V. R. Veeredhi, "Improving the cooling performance of automobile radiator with ethylene glycol water based TiO2 nanofluids," *International communications in heat and mass transfer,* vol. 78, pp. 121-126, 2016.

[34] G. A. Oliveira, E. M. C. Contreras, and E. P. Bandarra, "Experimental study on the heat transfer of MWCNT/water nanofluid flowing in a car radiator," (in English), *Applied Thermal Engineering,* vol. 111, pp. 1450-1456, Jan 25 2017, doi: 10.1016/j.applthermaleng.2016.05.086.

[35] H. M. Ali, H. Ali, H. Liaquat, H. T. Bin Maqsood, and M. A. Nadir, "Experimental investigation of convective heat transfer augmentation for car radiator using ZnO-water nanofluids," (in English), *Energy,* vol. 84, pp. 317-324, May 1 2015, doi: 10.1016/j.energy.2015.02.103.

[36] A. M. Hussein, R. A. Bakar, K. Kadirgama, and K. V. Sharma, "Heat transfer enhancement using nanofluids in an automotive cooling system," (in English), *International Communications in Heat and Mass Transfer,* vol. 53, pp. 195-202, Apr 2014, doi: 10.1016/j.icheatmasstransfer.2014.01.003.

[37] M. M. Elias *et al.*, "Experimental investigation on the thermo-physical properties of Al2O3 nanoparticles suspended in car radiator coolant," (in English), *International Communications in Heat and Mass Transfer,* vol. 54, pp. 48-53, May 2014, doi: 10.1016/j.icheatmasstransfer.2014.03.005.

[38] S. M. Peyghambarzadeh, S. H. Hashemabadi, M. S. Jamnani, and S. M. Hoseini, "Improving the cooling performance of automobile radiator with Al2O3/water nanofluid," (in English), *Applied Thermal Engineering,* vol. 31, no. 10, pp. 1833-1838, Jul 2011, doi: 10.1016/j.applthermaleng.2011.02.029.

[39] S. M. Peyghambarzadeh, S. H. Hashemabadi, S. M. Hoseini, and M. S. Jamnani, "Experimental study of heat transfer enhancement using water/ethylene glycol based nanofluids as a new coolant for car radiators," (in English), *International Communications in Heat and Mass Transfer,* vol. 38, no. 9, pp. 1283-1290, Nov 2011, doi: 10.1016/j.icheatmasstransfer.2011.07.001.

[40] B. C. Pak and Y. I. Cho, "Hydrodynamic and heat transfer study of dispersed fluids with submicron metallic oxide particles," (in English), *Experimental Heat Transfer,* vol. 11, no. 2, pp. 151-170, Apr-Jun 1998, doi: Doi 10.1080/08916159808946559.

[41] R. J. Moffat, "Describing the Uncertainties in Experimental Results," (in English), *Experimental Thermal and Fluid Science,* vol. 1, no. 1, pp. 3-17, Jan 1988, doi: Doi 10.1016/0894-1777(88)90043-X.

[42] W. Duangthongsuk and S. Wongwises, "Effect of thermophysical properties models on the predicting of the convective heat transfer coefficient for low concentration nanofluid," (in English), *International Communications in Heat and Mass Transfer,* vol. 35, no. 10, pp. 1320-1326, Dec 2008, doi: 10.1016/j.icheatmasstransfer.2008.07.015.

[43] E. N. Sieder and G. E. Tate, "Heat transfer and pressure drop of liquids in tubes," *Industrial & Engineering Chemistry,* vol. 28, no. 12, pp. 1429-1435, 1936.

[44] S. S. Harandi, A. Karimipour, M. Afrand, M. Akbari, and A. D'Orazio, "An experimental study on thermal conductivity of F-MWCNTs-Fe3O4/EG hybrid nanofluid: Effects of temperature and concentration," (in English), *International Communications in Heat and Mass Transfer,* vol. 76, pp. 171-177, Aug 2016, doi: 10.1016/j.icheatmasstransfer.2016.05.029.

[45] Y. M. Xuan and W. Roetzel, "Conceptions for heat transfer correlation of nanofluids," (in English), *International Journal of Heat and Mass Transfer,* vol. 43, no. 19, pp. 3701-3707, Oct 2000, doi: Doi 10.1016/S0017-9310(99)00369-5.

[46] S. E. Maiga, S. J. Palm, C. T. Nguyen, G. Roy, and N. Galanis, "Heat transfer enhancement by using nanofluids in forced convection flows," (in English), *International Journal of Heat and Fluid Flow,* vol. 26, no. 4, pp. 530-546, Aug 2005, doi: 10.1016/j.ijheatfluidflow.2005.02.004.