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ANALYSIS OF THE EFFECT OF ULTRASONIC VIBRATION ON NANOFLUID AS COOLANT IN ENGINE RADIATOR

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The paper discusses the combined methods of increasing heat transfer, effects of adding nanofluids and ultrasonic vibration in the radiator using radiator coolant (RC) as a base fluid. The aim of the study is to determine the effect of nanoparticles in fluids (nanofluid) and ultrasonic vibration on the overall heat transfer coefficient in the radiator. Aluminum oxide nanoparticles of 20–50 nm in size produced by Zhejiang Ultrafine powder & Chemical Co, Ltd China were used, and the volume concentration of the nanoparticles varied from 0.25 %, 0.30 % and 0.35 %. By adjusting the fluid flow temperature of the radiator from 60 °C to 80 °C, the fluid flow rate varies from 7 to 11 lpm. The results showed that the addition of nanoparticles and ultrasonic vibration to the radiator coolant increases the overall heat transfer coefficient by 62.7 % at a flow rate of 10 liter per minute and temperature of 80 °C for 0.30 % particles volume concentration compared to pure RC without vibration. The effect of ultrasonic vibration on pure radiator coolant without vibration increases the overall heat transfer coefficient by 9.8 % from 385.3 W/m^2·°C to 423.3 W/m^2·°C at a flow rate of 9 liter per minute at a temperature of 70 °C. The presence of particles in the cooling fluid improves the overall heat transfer coefficient due to the effect of ultrasonic vibrations, nanofluids with a volume concentration of 0.25 % and 0.30 % increased about 10.1 % and 15.7 %, respectively, compared to no vibration. While, the effect of nanoparticles on pure radiator coolant at 70 °C enhanced the overall heat transfer coefficient by about 39.6 % at a particle volume concentration of 0.35 % compared to RC, which is 390.4 W/m^2·°C to 545.1 W/m^2·°C at 70 °C at a flow rate of 10 liter per minute

Keywords: nanofluid, aluminum oxide, radiator coolant, ultrasonic vibration, overall heat transfer coefficient

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1. Introduction

In the past decades, research efforts have been conducted to improve the performance of cooling systems in cars, specifically radiator and coolant fluid. The cooling system maintains the proper engine working temperature. The component of the cooling system is a radiator and cooling fluid (pure water) as a medium for transferring heat from the engine to the air. Typically, vehicle coolant is pure water, but in countries with extreme weather, it is very dangerous [1]. Recently, engine coolants consist of a mixture of ethylene glycol with additive packages and some water is called radiator coolant (RC). The correct type and mixture of coolant should provide lower freezing point and increased boiling point of the cooling fluid and protect the engine from potential damage. But, this reduces the heat dissipation properties. One way to solve this problem is to add nanometer-sized solid particles called nanofluids. Since its first introduction to actual engineering applications [2–5], nanofluid has been successfully applied to enhance heat transfer in many applications.

The potential nanofluids as cooling fluids compared to conventional fluids (i.e. water, ethylene glycol, and oils) reported by numerous researchers have extended the concept of their use in multifarious systems. The thermal and hydrodynamic behavior of nanofluids makes them the best candidate to be used in automotive thermal management. This method can increase the thermal performance of radiators [6]. By using nanofluids as a coolant and simultaneously vibrating in ultrasonic waves, the dimensions of automotive cooling systems can be reduced due to increased radiator performance. Many researchers suggested different types of nanoparticles to enhance the heat transfer in automotive radiators including metal (copper, aluminum, nickel), oxides (iron oxide, titanium, alumina, silica, copper oxide) and solid particles such as silicon carbide, carbon nanotube, graphene, calcium carbonate, titanium and nanotubes [7].

2. Literature review and problem statement

It has been reported that a cooling system is very important. One method for the engine cooling system, using nanoparticles dispersed in a conventional cooling radiator to increase the thermal conductivity of a liquid is called the passive method. The researchers state that optimal cooling system performance can be achieved at low volume concentrations of nanoparticles (<1 %) [8]. At high volume concentrations of nanoparticles, the viscosity of nanofluids will increase, which is undesirable in energy efficiency systems.

Investigations have been carried out on a car radiator using nanofluid with aluminum oxide particles and base fluid using a mixture of water and ethylene glycol with a volume ratio of 50:50 (Nanofluid aluminum oxide/Water-Mono Ethylene Glycol). The volume fraction of nanoparticles used ranged from 0.2–0.8 %, the coolant flow rate was 4–9 liters per minute and the inlet temperature was 65–85 °C. The results showed that the heat transfer performance of the radiator was improved by using nanofluids compared to conventional coolers. The nanofluid with the lowest volume fraction of 0.2 % increases the heat transfer by 30 % [9]. This heat transfer improvement is relatively low to achieve an optimal engine cooling system. Simulation was performed using a mixture of ethylene glycol and water with aluminum oxide and copper oxide nanoparticles as a radiator cooling fluid. The results showed that the addition of 0.3 % aluminum oxide particles increased the thermal conductivity of the cooling radiator from 0.415 W/m·°C to 1.287 W/m·°C, while copper oxide particles increased to 1.241 W/m·°C. The addition of 0.3 % aluminum oxide nanoparticles could increase the heat transfer coefficient from 13.145.95 W/m^{2}·°C to 31.005.9 W/m^{2}·°C, while 0.3 % volume concentration copper oxide particles increased to 6384.41 W/m^{2}·°C [10]. The simulation results show that aluminum oxide particles provide better heat transfer improvement than copper oxide particles. Experimental investigation of nanofluid as a coolant for a car radiator with graphene as nanoplatelets at a volume concentration of 0.5 % and a mixture of water-ethylene glycol (70:30 by volume) was used as the base fluid. The overall heat transfer coefficient increased by 81 % at a mass flow rate of 62.5 kg/s at a working temperature of 45 °C. Meanwhile, the nanofluid pressure drop increases with the increase in mass flow rate [11]. The improvement of heat transfer should not be accompanied by an increase in pressure drop because this will increase the pumping power to circulate the fluid, and it is not desirable.

Ultrasonic vibration investigations in heat transfer applications have shown very high performance improvements and have been carried out by many researchers. The application of ultrasound can improve the performance of the heat exchanger due to the propagation of ultrasonic waves in the liquid resulting in the effects of acoustic flow, acoustic cavitation, and oscillation of fluid particles responsible for the intensification of heat transfer [12]. Experimental investigation on the presence of acoustic streaming in a closed cylindrical enclosure filled with water induced by the vibration ultrasonic using transducer of the lower plate was carried out. The results show that the increase in heat transfer coefficient is proportional to ultrasonic wave and inversely proportional to the distance between the center of the wave and the source of the heat energy. The highest increase by 390 % was observed at a frequency of 18 kHz for power between 56–158 Watt [13]. Experimental investigation of convection heat transfer in a dual-pipe heat exchanger using pure water was performed. The ultrasonic wave source was placed in the middle of the heat exchanger at a frequency of 35 kHz. The highest heat transfer enhancement by 150 % occurred in laminar flow, while turbulent flow had no effect [14].

All this suggests that it is advisable to conduct a study on the effect of ultrasonic vibration on nanofluid on the overall heat transfer coefficient. This research will be carried out by combining passive and active methods – vibrating at the ultrasonic frequency of nanofluids on the radiator.

3. The aim and objectives of the study

The aim of the study is to identify the effect of ultrasonic vibrations on nanofluids in a radiator, by adding nanoparticles to the base fluid/coolant fluid, namely radiator coolant.

To achieve the aim, the following objectives have been set:

– to analyze the effect of ultrasonic vibration on the overall heat transfer coefficient of pure radiator coolant;

– to analyze the effect of nanoparticles on the overall heat transfer coefficient of pure radiator coolant;

– to analyze the effect of ultrasonic vibration on the overall heat transfer coefficient of nanofluid coolant.

4. Materials and methods

In this study, 20–50 nm γ-aluminum oxide nanoparticles purchased from Zhejiang Ultrafine powder&Chemical Co, Ltd China were used. The nanofluid was prepared by dispersing aluminum oxide nanoparticles in different volume concentrations in radiator coolant as the base fluid**.**

The experimental setup is shown in Fig. 1, consisting of a heating tank, pump, flow meter and fan. The heating tank serves to replace the heat from the engine with temperature variations ranging from 60 *°C* to 80 *°C* by using controlled heating. The pump is used to circulate the coolant fluid, the flow meter to measure the flow of fluid flowing with a variation of 7–11 lpm and the fan to cool the radiator surface. Data were collected in stable conditions, with and without ultrasonic waves vibrations. After recording the data at each flow rate, the fluid temperature was varied from 60 to 80 °C with an interval of 10 °C. Four pieces of ultrasonic transducers are installed on the four sides of the radiator, which convert electrical signals into mechanical energy. An ultrasonic wave generator is mounted on four transducers with a frequency of 40 kHz.

Heat transfer coefficient calculation was carried out with changing the fluid flow rate and the temperature of the radiator inlet and outlet. The temperature is measured using a type K thermocouple connected to the data logger. The logarithmic mean temperature is calculated using (1) to obtain the overall heat transfer coefficient.

$$\Delta T_{LMTD} = \frac{\left(T_{hi} + T_{co}\right) - \left(T_{ho} - T_{ci}\right)}{\left(T_{hi} + T_{co}\right) / \left(T_{ho} - T_{ci}\right)}. \tag{1}$$

The flow rate of heat fluid is based on (2):

$$Q_h = m_h C_h \left(T_{hi} - T_{ho}\right). \tag{2}$$

While the flow rate of cold fluids or heat received by air is:

$$Q_c = m_c C_c \left(T_{co} - T_{ci}\right). \tag{3}$$

The average flow rate of heat and cold fluids is:

$$Q_{av} = \frac{Q_h + Q_c}{2}. \tag{4}$$

The overall heat transfer coefficient U is calculated by (5):

$$U = \frac{Q_{avc}}{A \times \Delta T_{LMTD}}. \tag{5}$$

The total thermal resistance *R*, as in Fig. 2, consists of fluid thermal resistance (convection) in the inner and outer duct, thermal resistance on the wall (conduction). The total thermal resistance *R* is the sum of each thermal resistance in (6).

$$R = R_1 + R_2 + R_3. \tag{6}$$

The relationship between total thermal resistance and overall heat transfer coefficient (7)

$$R = \frac{1}{U \times A}. \qquad (7)$$

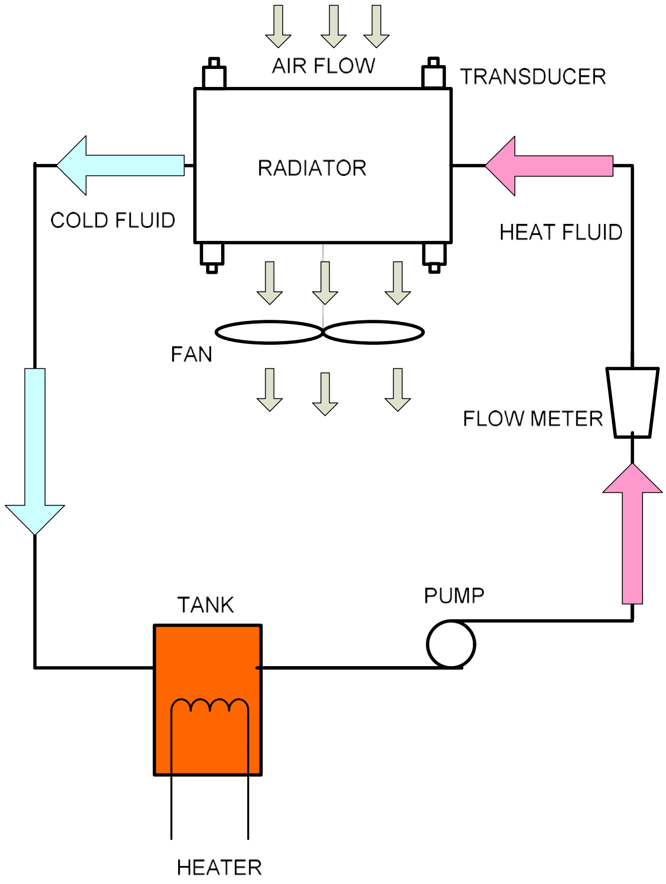


Fig. 1. Experimental setup

Heat transfer can be analogous to electric current, temperature difference as voltage and thermal resistance as resistance. From the above formula, it can be explained that the smaller the thermal resistance, the greater the heat transfer.

5. Results of studying the effect of ultrasonic vibration on nanofluids in the radiator

5. 1. Effect of ultrasonic vibration on pure radiator coolant

Fig. 3 shows experimental results of the effect of ultrasonic vibration on pure radiator coolant at a temperature of 60 °C, 70 °C and 80 °C, respectively. Analysis of variance is a significant statistical tool and it was used in this study, and the confidence level of 95 % was maintained to analyze the data. Table 1 describes the calculation results for a two-way ANOVA, where the rows is the treatment with ultrasonic vibrations (without vibration and with vibration) and the columns is the treatment with variations in working temperature at a flow rate of 10 liter per minute.

The effect of ultrasonic vibration on increasing the total heat transfer coefficient is very significant. It is proven that the value of $F_{\text{calculate}}$ is greater than F_{critical} (21.471>18.5128). The highest increase in the overall heat transfer coefficient of the effect of ultrasonic vibration on pure radiator coolant was from 386.42 $\text{W/m}^2\cdot{}^\circ\text{C}$ to 431.19 $\text{W/m}^2\cdot{}^\circ\text{C}$ or an increase of about 11.58 % at a flow rate of 10 liter per minute at a temperature of 60 °C (Fig. 3). The lowest increase in the overall heat transfer coefficient is about 5.22 % at a flow rate of 9 liter per minute (353.62 $\text{W/m}^2\cdot{}^\circ\text{C}$ to 372.11 $\text{W/m}^2\cdot{}^\circ\text{C}$) at the same temperature.

The average increase in the overall heat transfer coefficient (U) due to ultrasonic vibration is by 8.06 % at 60 °C, 8.15 % at 70 °C and 7.06 % at 80 °C at the same flow rate from 7 lpm to 11 lpm (Fig. 3). The increase in the overall heat transfer coefficient is almost the same for the three temperature variations.

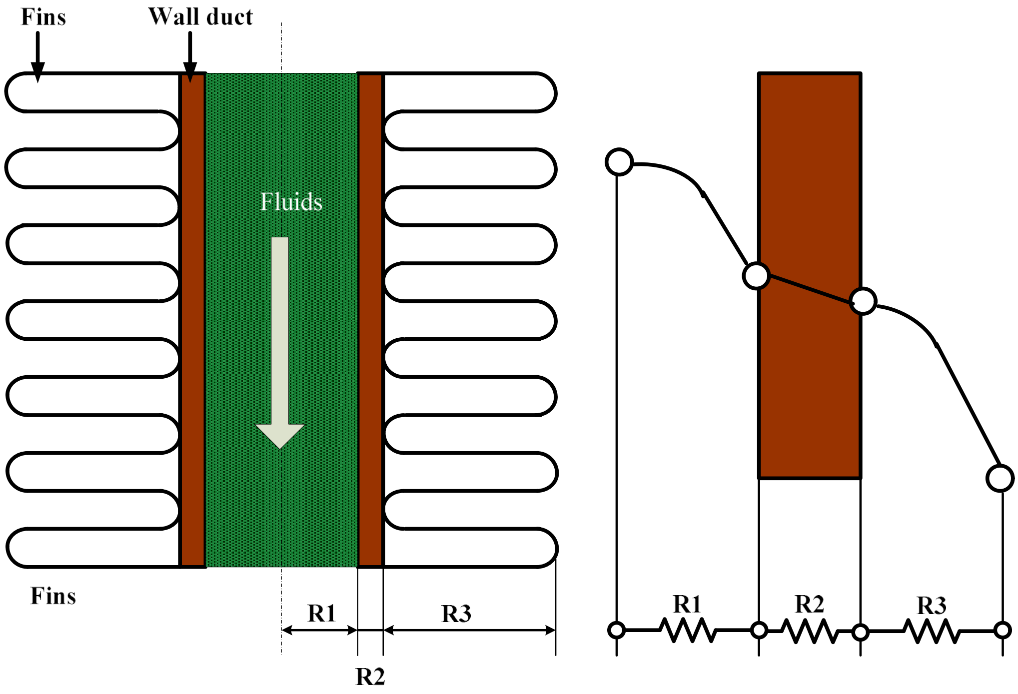


Fig. 2. Thermal resistance of the radiator

Table 1

Analysis of variance (two-way ANOVA) of the effect of ultrasonic vibration on pure radiator coolant

Source of Variation	*SS*	*df*	*MS*	*F*	*P*-value	*F* crit
Rows	1466.751	1	1466.751	21.471	0.043553	18.512
Columns	44.167	2	22.083	0.323	0.755697	19
Error	136.621	2	68.310	–	–	–
Total	1647.539	5	–	–	–	–

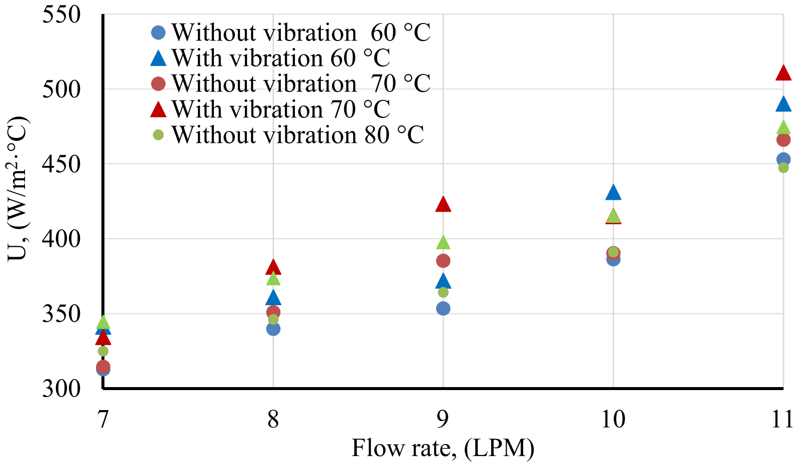


Fig. 3. Effect of ultrasonic vibration on pure RC at 60 °C, 70 °C and 80 °C

This is in accordance with the ANOVA analysis in Table 1, where $F_{\text{calculate}}$ is smaller than F_{critical} (0.233<19). This means that the Ho hypothesis is accepted, the overall heat transfer coefficient is the same for all temperature varaiations.

5. 2. Effect of nanoparticles on radiator coolant nanofluid without vibration

Fig. 4 shows experimental results of the effect of nanoparticles on pure radiator coolant at 70 °C (nanofluid). The presence of nanoparticles in the radiator coolant increases the rate of heat transfer. According to the two-way ANOVA analysis, the effect of nanoparticles significantly changes the heat transfer coefficient, which shows that calculated $F_{\text{calculate}}$ is greater than F_{critical} (11.621>3.006) (Table 2). This means that the Ho hypothesis is rejected, the all of overall heat transfer coefficient different of particle concentrations variation.

The highest increase in the overall heat transfer coefficient is around 39.64 % at a particles volume concentration of 0.35 % compared to pure radiator coolant or RC (0 %), which is 390.4 W/m^2·°C to 545.1 W/m^2·°C at 70 °C at a flow rate of 10 liter per minute.

This shows that nanofluids are very effective in increasing the overall heat transfer coefficient that has been carried out on a radiator. As shown in Fig. 4, the improvement of the heat transfer coefficient is proportional to volume particles concentration.

An increase of 16.2 % is due to the addition of 0.25 % particle volume concentration, an increase of 24.6 % – the addition of 0.3 % particle volume concentration and an increase of 39.06 % – the addition of 0.35 % particle volume concentration, compared to pure radiator coolant for a flow rate of 10 liters per minute. As shown in Fig. 4, the higher the particle volume concentration, the greater the overall heat transfer coefficient.

The effect of flow rate of the cooling fluids is also significant for the improvement of the overall heat transfer coefficient. As can be seen in Table 2, calculated $F_{\text{calculate}}$ is greater than F_{critical} (11.621>3.006). This means that the Ho hypothesis is rejected, the all of overall heat transfer coefficient different for flow rate variations. For example, an increase of the overall heat transfer coefficient was 3.24 % for the flow rate of 8 liter per minute, 5.91 % for the flow rate of 9 liter per minute, 21.13 % for the flow rate of 10 liter per minute and 28.93 % for the flow rate of 11 liter per minute, compared to the flow rate of 7 liter per minute. As shown in Fig. 4, the higher the flow rate, the greater the overall heat transfer coefficient.

Table 2

Analysis of variance (two-way ANOVA) of the effect of nanoparticles

Source of Variation	*SS*	*df*	*MS*	*F*	*P*-value	*F crit*
Rows	38368.23	4	9592.058	11.62192	0.000128	3.00691
Columns	762064.3	4	190516.1	230.8329	6.28E-14	3.00691
Error	13205.47	16	825.3418	–	–	–
Total	813,638	24	–	–	–	–

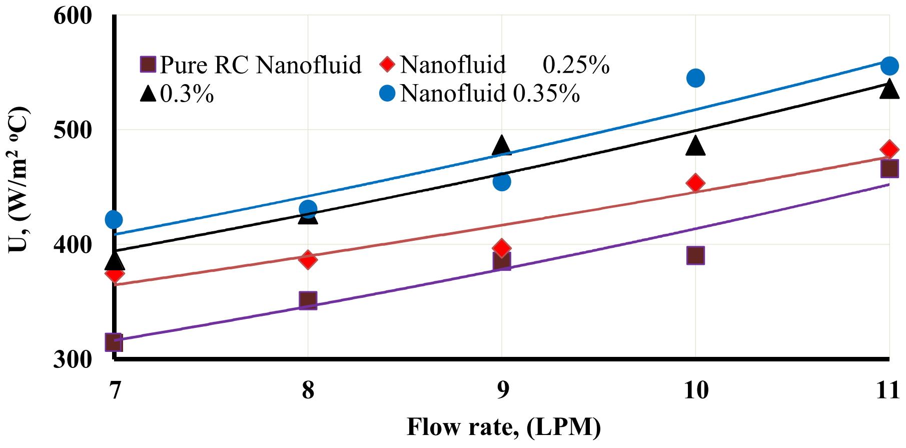


Fig. 4. Effect of nanoparticles on pure RC at 70 °C without vibration

5. 3. Effect of ultrasonic vibration on nanofluid

Fig. 5 shows the experimental results for nanofluids subjected to ultrasonic vibrations. The presence of ultrasonic vibration increases the overall heat transfer~~,~~ coefficient. According to the two-way ANOVA analysis, the effect of ultrasonic vibration significantly changes the overall heat transfer coefficient, which shows that calculated $F_{\text{calculate}}$ is greater than F_{critical} (4.60>4.25) (Table 3). This means that the Ho hypothesis is rejected, the all of overall heat transfer coefficient different of ultrasonic vibration methods. It can be seen that the highest increase in the overall heat transfer coefficient is around 15.7 % at a temperature of 80 °C and a flow rate of 10 liter per minute, which is 543.2 W/m^2·°C without vibration and 628.5 W/m^2·°C at the same volume concentration of 0.30 %. The increase in the overall heat transfer coefficient is 62.7 % when compared to pure RC without vibration (391.2 W/m^2·°C to 628.5 W/m^2·°C).

Table 3

Analysis of variance (two-way ANOVA) of the effect of ultrasonic vibration on nanofluid

Source of Variation	*SS*	*df*	*MS*	*F*	*P*-value	*F crit*
Sample	19977.17539	1	19977.17539	4.60358	0.04223	4.25967
Columns	3402.18520	2	1701.09260	0.39200	0.67994	3.40282
Interaction	102.61996	2	51.30998	0.01182	0.98825	3.40282
Within	104147.5166	24	4339.47985	–	–	–
Total	127629.4972	29	–	–	–	–

Meanwhile, for the particle volume concentration of 0.25 %, the increase in the overall heat transfer coefficient is relatively low at 10.2 % for the same temperature and flow rate. The presence of particles in the cooling fluid improves the heat flow rate due to the effect of ultrasonic vibrations.

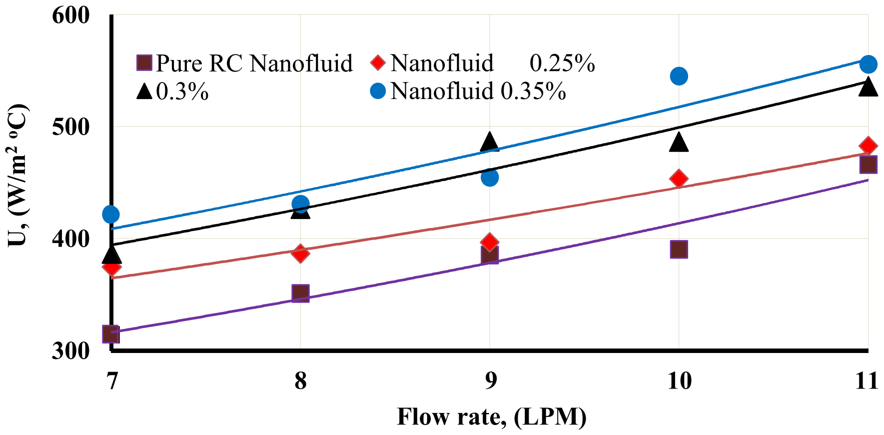


Fig. 5. Effect of ultrasonic vibration on nanofluid at 80 °C

The transfer rate in the radiator consists of three heat transfer~~s~~ processes, convection inside the duct, conduction on the duct wall and convection outside the duct, which is in contact with the outside air through the fins (Fig. 2). Table 1 shows the comparison of thermal resistance between nanofluid with a particle volume concentration of 0.30 % and pure RC. The thermal resistance of pure RC is higher than that of nanofluid, and is inversely proportional to the overall heat transfer coefficient value.

Table 4

Effect of ultrasonic vibration on the thermal resistance of nanofluid of 0.30 % at a temperature of 80 °C for the flow rate of 9 liter per minute

Parameter	Pure RC	Nanofluid 0.35 %
Overall heat transfer coefficient (*U*)	390.8 W/m^2·°C	554.4 W/m^2·°C
Thermal resistance, R_1	0.031778 °C/W	0.030254 °C/W
Thermal resistance, R_2	0.000143 °C/W	0.000143 °C/W
Thermal resistance, R_3	0.111767 °C/W	0.063183 °C/W
Total thermal resistance, *R*	0.143689 °C/W	0.093580 °C/W

Total thermal resistance is the sum of convection thermal resistance inside the duct, thermal resistance on the duct wall and convection thermal resistance outside the duct. The total thermal resistance decreased from 0.143689 °C/W to 0.093580 °C/W (34.9 %). The greatest decrease in thermal resistance outside the duct is convective heat transfer in the fins from 0.111767 °C/W to 0.063183 °C/W (34.8 %) is the thermal resistance of convection heat transfer between fins and air. Thermal resistance inside the duct decreased from 0.031778 °C /W to 0.030254 °C/W (5.0 %) i.e. convection heat transfer inside the duct, is a convection heat transfer between fluid (nanofluid) and the duct wall. This thermal resistance shows the heat transfer coefficient at each position, the convection heat transfer coefficient inside the duct and the convection heat transfer coefficient outside the duct. The percentage of the decrease in the thermal resistance ratio is high because it is influenced by the convection surface area, the surface area of the channel on the inside is relatively smaller than the surface area of the outside, namely the surface area of the fins, so the value is very small.

6. Discussion of the effect of ultrasonic vibration as a coolant in the engine radiator

The effect of ultrasonic vibration increases the overall heat transfer coefficient for pure radiator coolants (RC). Water is a natural heat transfer fluid, a liquid used since the dawn of time to heat and cool. It freezes at 0 °C and boils at 100 °C. To extend the liquid range, other chemicals are added such as ethylene glycol, namely radiator coolant. Ethylene glycol has two –OH groups, both of which can form hydrogen bonds. For this reason, the boiling point of ethylene glycol is much higher, which makes it more viscous than water. Water also contains O-H groups, which makes a "hydrogen bond" to each other, causing water to have a very high boiling point for a molecule of its size. Thus, ethylene glycol and water molecules can form hydrogen bonds to each other, which means that they mix freely, in all proportions, as shown in Fig. 6 below.

Ultrasonic waves passing through a liquid medium can induce the occurrence of a phenomenon known as acoustic cavitation. During the ultrasonic wave rarefaction phase, instantaneous local pressures in liquid become negative when the acoustic pressure amplitude is larger than the ambient pressure. As a result, gases dissolved in the liquid appear as gas bubbles because gases can no longer be dissolved in the liquid under negative pressures. During the compression phase of the ultrasonic wave, some of the bubbles violently collapse leading to shock wave being emitted into the liquid [15]. The phenomenon of the bubbles formation and subsequent violent collapse of the bubble under an acoustic wave (ultrasound) is called acoustic cavitation [12]. The growth and collapse of bubbles in acoustic cavitation and release of large amounts of energy are shown in Fig. 7. Bubbles collapse in liquids created unique high energy. Experimental results have shown that temperatures and pressures approaching 5,000 °K and 2,000 atm are produced during this collapse with a very short lifetime [12].

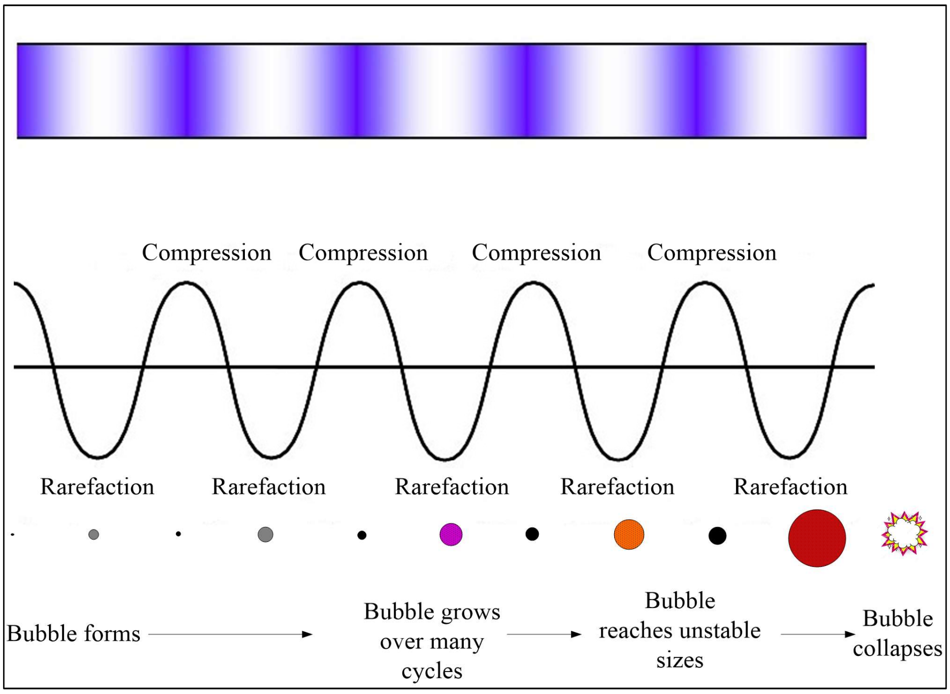


Fig. 7. Acoustic wave in liquid forming bubbles and destruction of the boundary layer on the surface improve heat and mass transfer

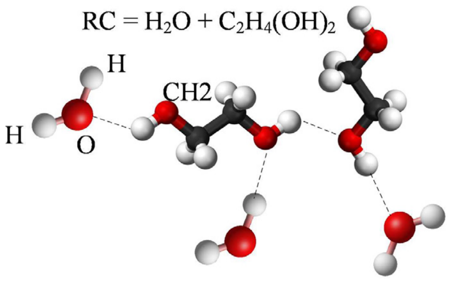


Fig. 6. Radiator coolant (RC) is a mix of water and ethylene glycol

Unlike cavitation bubble collapse in the bulk liquid, the collapse of a cavitation bubble on or near the surface is unsymmetrical because the surface provides resistance to liquid flow from that side. The result is an inrush of liquid predominantly from the side of the bubble remote from the surface resulting in a powerful liquid jet being formed, targeted at the surface. A bubbles collapse near the solid-liquid interface disrupts thermal and velocity boundary layers, reducing thermal resistance and creating micro turbulence. For this reason, ultrasonic vibration on liquid increases convection heat transfer, the growth and collapse of bubbles and collapsing bubbles near the surface are shown in Fig. 8.

This effect can also be used for cleaning, because high-pressure jetting can be sufficiently powerful to cause pitting of the surface (erosion).

The improvement of the overall heat transfer coefficient of pure RC is very small about 6.3 % at 70 °C and 6.0 % at 80 °C (Fig. 3). The reason is that the method of vibrating the radiator is not perfect and the power to generate ultrasonic waves is very small.

The improvement of the overall heat transfer coefficient by adding nanoparticles without vibration is about 39.6 % (Fig. 4) compared to pure RC. This increase in the overall heat transfer coefficient is due to the addition of nanoparticles into the radiator coolant according to the existing reference. The overall heat transfer coefficient increased by 42.5 % for alumina particles for the same base fluid is radiator coolant. The presence of a 1 % volume concentration of alumina nanoparticles in ethylene glycol enhanced heat transfer up to 40 %. The increase of the overall heat transfer coefficient for RC nanofluids occurred because of Brownian motion, a random movement of nanoparticles suspended in fluids (radiator coolant) resulting from the impact of molecules of the surrounding medium. Brownian motion decreases when the particle size is bigger, because the motion of fluid molecules is not able to push solid particles. But if the particle size is smaller, the Brownian motion is higher. The presence of nanoparticles in the radiator coolant (Fig. 9, *a*) and move due to the collision of the radiator coolant molecules and nanoparticles zig-zag motion path (Fig. 9, *b*).

The thermophoretic process also contributes to this increase. The temperature gradient between the pipe wall and the fluid will cause particle migration from high temperature to low temperature and also cause variations in particle concentration. For nanoparticles, the Brownian force and thermophoretic force are the significant slip mechanisms in the heat transfer process. The thermophoretic force causes a non-uniform particle distribution, while Brownian forces take the particles in the opposite direction of the particle concentration gradient, trying to make the particles more homogeneous. The Brownian force and thermophoretic force oppose and affect each other. In the cooling process, the migration of particles tends to the duct wall, and at the same time the acoustic cavitation takes place due to ultrasonic vibrations (Fig. 10, *b*). The nanoparticles move randomly near the wall, which serves as a carrier of heat energy towards the wall. This will disturb the fluid flow velocity profile and change it, thereby increasing the heat flow rate (Fig. 10, *c*) and before was velocity boundary layer profile as shown in (Fig. 10, *a*).

The highest improvement of the overall heat transfer coefficient due to ultrasonic vibration and presence of nanoparticles is about 15.7 % compared to without vibration at 0.3 % particles volume concentrations at a temperature of 80 °C and flow rate of 10 liter per minute (Fig. 5). When compared to a pure radiator coolant without vibration, the increase is 62.7 %, this improvement is very small when compared to the references.

The limitation of this research is the technique or method of producing imperfect ultrasonic vibrations, radiator vibrations are not measured, so the frequency is not detected. The weakness in this study is that the flow rate is relatively small, while in actual conditions the flow at the radiator is quite high. In the future, it is necessary to increase the flow rate to approach the actual conditions.

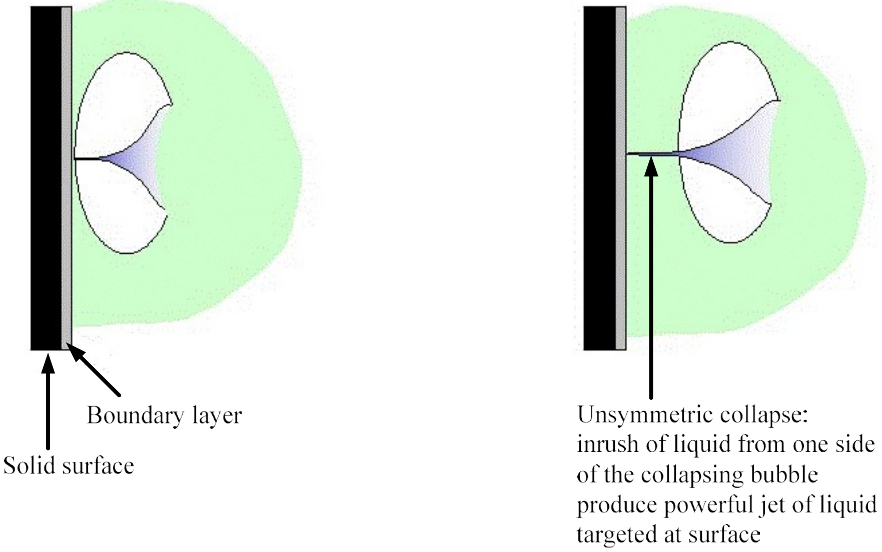
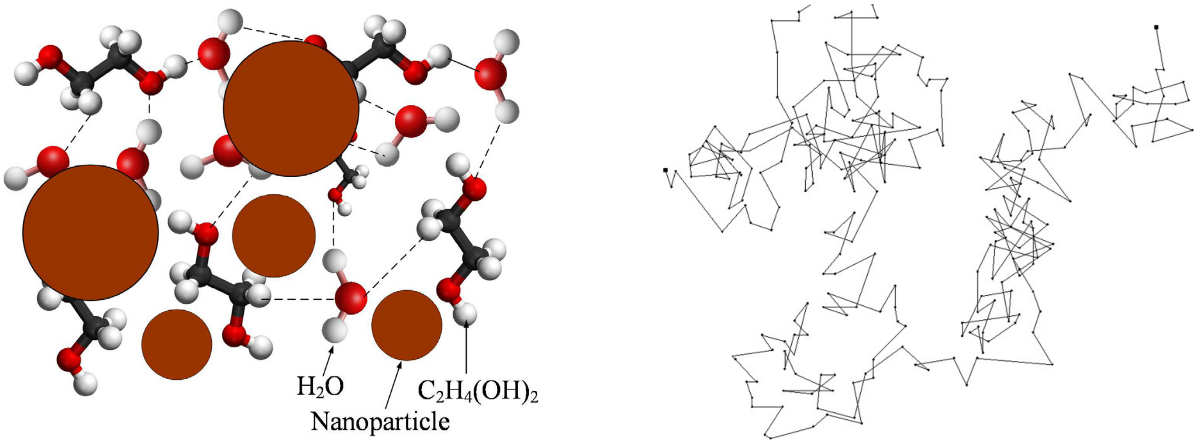
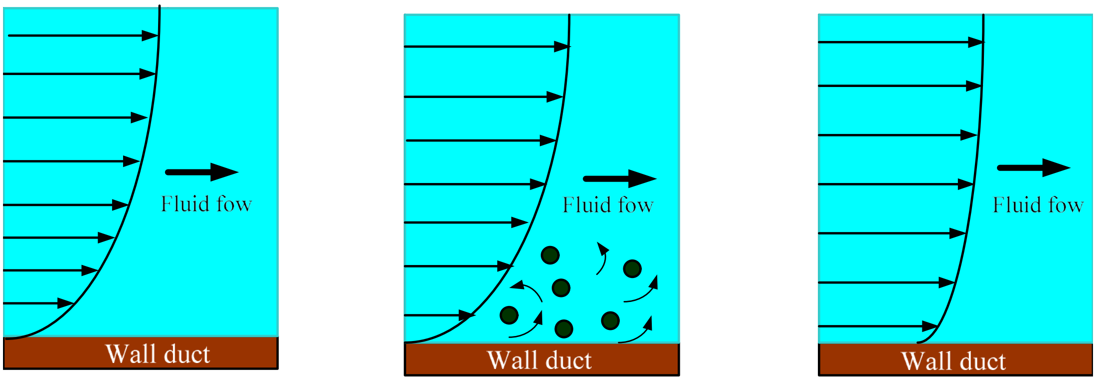


Fig. 8. Formation of a jet through acoustic cavitation in a liquid near the surface and destruction of the boundary layer on the surface improve heat and mass transfer



a *b*

Fig. 9. Brownian motion is the motion of nanoparticles due to collisions with radiator coolant molecules: *a* – Nanoparticle in radiator coolant; *b* – The zig-zag motion path of nanoparticles due to radiator coolant molecule collisions



a *b* *c*

Fig. 10. Mechanism of heat transfer enhancement by acoustic cavitation and presence of nanoparticles in fluids: *a* – typical velocity boundary layer; *b* – acoustic cavitation; *c* – modified velocity boundary layer profile

The difficulty in this experiment requires a larger vibrator power in order to perfectly vibrate the radiator. In future research, it is better to use the simulation method or reduce the radiator size.

7. Conclusions

1. Ultrasonic vibration can increase the overall heat transfer coefficient on pure RC but is very low by 9.8 %, which indicates that the results of this study are not optimal. The overall heat transfer coefficient increases from 385.3 W/m^2·°C to 423.3 W/m^2·°C at a flow rate of 9 liter per minute at a temperature of 70 °C.

2. The addition of nanoparticles to pure radiator coolant (RC) as a cooling fluid can increase the heat transfer coefficient by 39.6 % from 390.4 W/m^2 °C to 545.1 W/m^2 °C at a flow rate of 10 liter per minute at a temperature of 70 °C.

3. The effect of ultrasonic vibration on nanofluid increases the heat transfer coefficient by 39.6 % at a particle volume concentration of 0.35 % compared to pure radiator coolant (RC).

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