Analysis of Engine Radiator Performance at Different Coolant Concentrations and Radiator Materials

Hiyam Adil Habeeb, Ahmed Esmael Mohan, Nor Ayu Mohamad Norani, Mohd Azman Abdullah, Mohd Hanif Harun

Abstract*: Functioning as a cooling system, a radiator is an essential component in reducing the temperature of an internal combustion engine (ICE) of a vehicle by absorbing the heat and dissipated it into the air. With good and effective radiator, the engine will perform at optimized condition. In this study, the performance of radiator was analyzed at different radiator materials and coolant concentrations. A spark ignition (SI) 1.5L engine radiator system was used at 20%, 30%, 40%, 50% and 60% ethylene glycol coolant concentrations. The simulation of heat transfer was performed on different fins material, aluminum, brass and copper using commercial available finite element analysis (FEA) software. Promising results showed that, copper fins was the best among the materials. It is also observed that the lower the coolant concentration, the better the performance of the radiator in reducing the ICE temperature.

Keywords*: Radiator, coolant, SI engine, ethylene glycol, finite element analysis.

I. INTRODUCTION

Radiator technology has grown rapidly since the invention of vehicles. Heat release is one of the important factors that should be taken into consideration in designing an engine. The Internal Combustion Engine, (ICE) is capable of producing maximum temperatures which can cause the engine to overheat. According to [1], about 35% of the energy from the fuel energy is converted into power to drive the vehicle and its accessories, meanwhile another 35% of that energy is released to the atmosphere via exhaust gases. The remaining 30% of the total energy is carried off from the engine by cooling system. The effectiveness of heat transfer is released from engine partitions to the surrounding is important in maintaining the material integrity of the engine as well as enhancing the performance of the engine. In the previous study [2], stated that radiator material, fins, air and coolant flow rate, air temperature, heat exchange period, the coolant used, and coolant inlet temperature are the factor affected the radiator performance. Other than that, many methods have been developed to enhance the overall performance of automobile radiators such as making an attempt to reduce the consuming power, minimize the dimension and result in a minimize of preliminary, operating and maintenance costs [3]. This claim also is supported by [2] that some other methods to optimize the heat transfer performance in the radiator, in design field are increasing the surface area to coolant ratio and core depth, change the fin design, tube type, flow arrangement and flow material. The cooling system must keep up the engine at a constant temperature either in summer or in winter, even under 0°C. If the temperature of the engine is too low, it increases fuel economy as well as pollution. In contrast, when the engine becomes too hot, it harms the engine. The optimum operating temperature for most vehicles is around 212 F which is 100 °C [4]. The higher differential temperature between engine coolant and the outside air allows the heat transfer to occur more efficiently.

The cooling system consists of coolant reservoir, radiator, radiator fan, water pump, heater core, thermostat, radiator pressure cap and necessary hose plumbing for radiator and heater core. According to [5], the coolant media that carried hot temperature is pumped to the radiator through the plane tubes whereas the air is flowing over the fins via pressured convection. The fins are approach to expand the cooling rate of the radiator and also supply a large heat transfer area as nicely as growing the heat transfer convection coefficient.

It is true by having only 100% of water also can keep down the temperature of the engine as water has an excellent relative coefficient of thermal conductivity [6]. However, by looking forward to another aspect that needs to consider, water has a low ability to increase the boiling point. Besides, when it comes to the cooling system that works under pressurized space, the boiling temperature gets higher 100°C. This is the reason why putting 100% of the water solution is not recommended. Furthermore, water freezes at too high temperature to be used in car engines. It only can be considered at a certain place but not in extreme climate location. Other than that, water has no corrosion protection since the molecule ions of water will oxidize the metal system [7].

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Hence, to fulfill the limitation of water properties, a sufficient additive of the antifreeze solution like ethylene glycol is added to water so that the optimum performance of the cooling functioning system can be improved significantly.

As the primary purpose of the antifreeze coolant solution is to keep the engine cold, reduce freezing point and increase boiling point, inhibit corrosion, act as a lubricant coolant pump, and keep system pressure down [8]. In the previous section explains there are different types of coolant percentage, and each of them has different thermophysical properties which only suitable depend on the cooling system of engine requirement, temperature surrounding and protection needed.

There are many types of antifreeze coolant such as ethylene glycol and propylene glycol [9-13]. In this case, by using conventional antifreeze based coolant with a different percentage of volume concentration, different thermophysical properties will be observed in term of thermal conductivity, viscosity, specific heat and density of the fluid.

In the concerns of radiator material, the history of the first era vehicles uses copper/brass radiator because it had been the broadly metal accessible at that time. However, during the oil crisis, major automobile manufacturers in Europe and US have a tendency to invent lighter vehicles to cope with the current situation and reduced oil consumption.

For the relationship between fins materials, copper, brass, and aluminum, these three types of fins material rely on their thermophysical properties as well. These three types of material used to study the relationship reaction between conduction and convection of heat transfer when it attached with aluminum flat tube.

For radiators, this translated to aluminum which is lower in density in contrast to copper and brass, and able to cope with heat fairly well regardless of its manufacturing shortcomings. In addition, aluminum is much cheaper than copper and brass. As a result, for the previous 20 years, aluminum has taken the first place as the steel for radiator for new cars. Various studies were conducted to discover the consequences of some parameters of the design on the overall performance of radiator which is aimed at enhancing cooling effects. Another ways to improve the heat transfer effectiveness in radiator are by increasing the surface area to coolant ratio and core depth, change the fin design, tube type, flow arrangement and flow material [14].

Therefore, in this paper, the analysis of the performance of radiator in spark ignition engine cooling system is performed at difference percentage of coolant (ethylene glycol) concentrations (20, 30, 40, 50 and 60%) and fin materials (Al, Br and Cu)

II. METHODOLOGY AND MATERIALS

According to [10], both of ethylene and propylene are good coolants, but added with glycol, propylene glycol-based coolant is having higher viscosity then ethylene glycol-based coolant (Fig. 1). Hence, ethylene glycol provides better heat transfer. However, when it comes with toxicity concern, propylene glycol is much better since it has lower acute oral toxicity. It is argued that when coolant systems leak or begin discarded, these forms of mixture are less harmful to the environment than ethylene glycol. Improvement of coolant thermophysical properties in vehicle thermal management is important for vehicle performance, operation and safety [7]. In the previous study for the most situations, the minimum recommended concentration is 25% [10]. This is because for glycol concentration below 25%, the inhibitor concentration is too low to a level that may not have protection against corrosion. The suggested limit of glycol concentration is 60% for effective heat transfer and it relies on the types of protection needed. In an observation-based study [12], water is an excellent heat transmission fluid, but it has some weaknesses. As a water has a 0°C freezing point and 100°C boiling temperature. However when is come in a pressurized cooling system, its boiling point will be lower than desired, and without additives it encourage rust and corrosion in many materials. As stated by [13], in order to increase the efficiency of ethylene glycol functioning as antifreeze agent, the coolant must be mixed with water. This is because its act to reduce freezing point and increase boiling point of water. Hence, an adequate volume of glycol must be included in the solution, so that during expansion occur it does not affect the system. This is often critical for systems that stay dormant amid winter shutdown where the temperature may drop below the solution's freezing point.

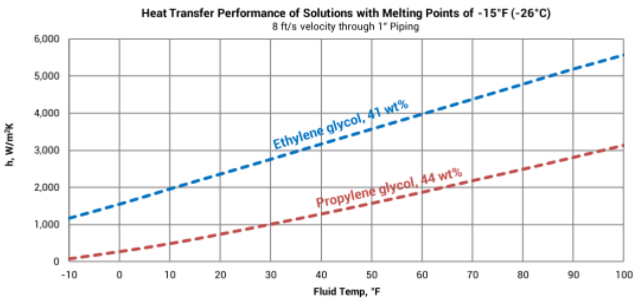

Fig. 1. Heat transfer performance of ethylene glycol and propylene glycol [9]

The radiator specifications are shown in Table I. The radiator consists of an upper header, bottom header, flat tubes and fins. There are 42 aluminum flat tubes with 43 numbers of fins in the actual radiator design model. However due to the number of cells limitation below than 510000 cells, unavailability of high-speed computer and as well as to reduce the computational time and increase in accuracy, the overall radiator design cannot be simulated. Therefore, only one part of flat tube attached with the fins at the both sides tube is simulated the ANSYS Fluent simulation [15-17]. In the simulation, the aluminum material was applied at a flat tube meanwhile different materials used at the fins radiator (aluminum, bras and copper) [18-20]. Fig. 2 shows the detail of flat tube dimension meanwhile Fig. 3 shows the fins mesh and tube. Table II shows the ethylene glycol concentration and Table III shows the fins material properties.

Table I: Radiator Specifications

Parameter	Value
Length	455.6 mm
Width	432 mm
No. of tubes	42
Distance between tubes	8 mm
Tube thickness	0.5 mm
Tube height	2 mm
Tube width	15 mm
Type of tubes	Single, flat
Tube material	Aluminum
Distance between fins	1 mm
Depth of fin	15 mm
Fin material(s)	Aluminum, brass and copper

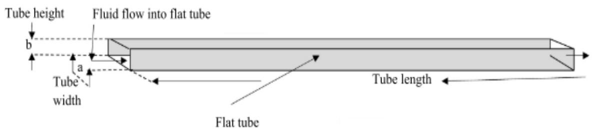

Fig. 2. Flat tube

Fig. 3. Fins mesh and tube

Table II: Ethylene glycol concentration

Property	Concentration (%)				
	20	30	40	50	60
Density (kg/m^3)	1030.95	1048.41	1064.27	1079.32	1093.26
Specific heat (J/kg.K)	3835.11	3663.45	3487.60	3269.89	3098.23
Thermal conductivity (W/m.K)	0.51	0.47	0.43	0.39	0.36
Viscosity (kg/m.s)	0.0012	0.0013	0.0021	0.0027	0.0035

Table III: Material properties

Parameter	Value
Brass	
Specific heat	401.93 J/kg.K
Thermal conductivity	119.91 W/m.K
Density	8470.05 kg/m^3
Aluminum	
Specific heat	871.00 J/kg.K
Thermal conductivity	202.40 W/m.K
Density	2719.00 kg/m^3
Copper	
Specific heat	381.00 J/kg.K
Thermal conductivity	387.60 W/m.K
Density	8978.00 kg/m^3

III. RESULTS

The temperature distribution is shown in Fig. 4. The coolant entering the radiator tube at 368 K (94.85 ^{o}C) and leaving at 321 K (47.85). Fig. 5 to Fig. 8 show the thermophysical properties of the ethylene glycol concentration. The thermophysical properties of this different coolant concentration are usually differs from one other and they have an important impact on heat transfer. These properties were used to measure the heat transfer. As shown in Fig. 5 and Fig. 6, it can be concluded that the percentage of coolant concentration, ethylene glycol leads to an increase in density, and viscosity. Though, for specific heat capacity and thermal conductivity are decrease in Fig. 7 and Fig. 8. A good heat transfer fluid is important to make a better radiator performance. One of the good characteristics of fluids is to have a low viscosity. As show in Fig. 5, the higher percentage of coolant concentration, the higher the viscosity. Hence, it is not good to have a high coolant concentration. One of the significant effects of heat transfer is temperature change. Therefore, it is important to know the amount of heat requires to change the substance's temperature. This specific heat is equivalent to the amount of heat energy transferred to a fluid and resulting an increase in temperature of a system. In Fig. 6 below shows the graph of different coolant concentration versus specific heat. The decrement of this specific heat toward the higher coolant concentration explains that the amount of the heat necessary to change the temperature of 1kg of mass by 1°C. That is means, the higher the specific heat leads to having a good heat transfer fluid. One of the important parameters that describe heat transfer enhancement is thermal conductivity. Fig. 7 shows that thermal conductivity decreases with the increasing percentage of concentration. By referring to this figure, the lowest thermal conductivity of ethylene glycol is at 0.356292 W/mK for the 60% concentration of ethylene glycol and the highest thermal conductivity observed is at 0.511954 W/mK for the 20% concentration of ethylene glycol. In can be concluded that the coolant concentration has decreased the thermal conductivity and increased heat transfer in the radiator. Comparison of the coolant outlet temperature that has been calculated by using effectiveness NTU mathematical calculation. This comparison is needed to prove that the precision of the results obtained from the simulation. Table IV shows the data of coolant output temperature from the calculation compared to the coolant output temperature obtained in simulation. An average percentage error of aluminum, brass and copper fins were 5.47%, 4.65% and 2.35% respectively. This error was mainly due to frictional loss, quality of the mesh, and its accuracy in the ANSYS Fluent software. Thus, it met engineering requirements. So, further analysis had been carried out using the same procedure by changing the material properties. Although water provides the finest heat transfer, ethylene glycol is used for anti-freezing. Generally, when the higher coolant concentration is used for freeze and corrosion protection, secondary cooling system and also prevents bacterial risk contaminant. The concentration would yield a freeze point around 3°C lower than the lowest expected temperature.

It is true that adding slightly more glycol concentration may reduce the heat transfer of the water, nevertheless in most climates and applications, freeze protection is serious. Meanwhile, for bust protection, if there is no problem in slush or ice crystal, it is better not to use high coolant concentration in water. This is because, the more coolant concentration is used, the lower the heat transfer efficiency of the solution.

Furthermore, the copper has the lowest temperature reading since it has a high thermal conductivity which is 387.6 W/m.K compared to aluminum 202.4 W/m.K and brass 119.91 W/m.K. This Fig. 8 also states that the higher the concentration of coolant leads to lower performance. This is because it will low oxidation kinetic and may lead to a significant increase in internal cell resistance. Rust may happen as temperature increase, the rate of chemical reactions similarly increases. The reason corrosion happens belligerently is due to high temperature, the existence of water moisture and oxygen.

In the Table IV below, explains the rate of change of outlet temperature. As all the materials have a positive gradient meaning that it has an increase in rate of change for every 1% of coolant concentration there is rise 0.3567 °C/%, 0.6655 °C/%, and 0.698 °C/% with the respect of copper, aluminum and brass fins. Therefore, the lower rate of change between temperature outlet and percentage of coolant concentration will cause a slight increase in temperature. The copper fins have a good result compare to aluminum and brass fin. By referring Fig. 10 indicates that all the reading here at aluminum flat tube wall that had been attached with a different type of fin materials. The highest heat flux was produced when copper fins is used. That means it can transfer more energy from one substance to another per unit time and denoted by temperature change compared to other materials.

Talking particularly for solids, as the density of copper is higher compared to brass and aluminum, the molecules will be closely packed and hence due to intermolecular vibration the heat transfer due to conduction will be higher.

Generally, there are water coolant ratio is applied to form a solutions. By having a decrement, it indicates that the performance of heat flux is getting slow. So that when it comes to the capability of heat realize through the air, the higher rate of change between total surface heat flux and percentage of coolant concentration is better. Therefore, it can be concluded from this aspect, brass fins with 745.19W/m2% is a good heat transfer to the air compare to copper (737.03 W/m2%) and aluminum (686.022 W/m2%).

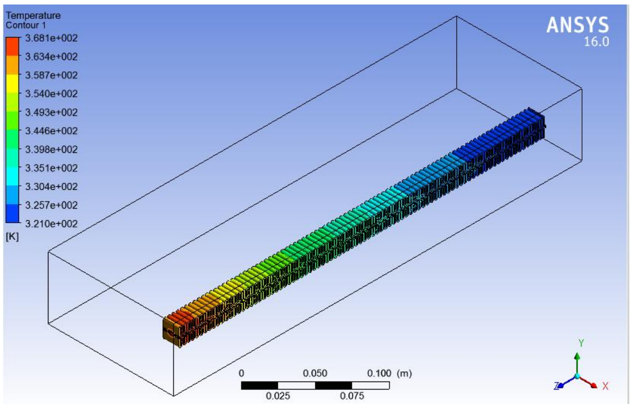

Fig. 4. FEA simulation of radiator tube and fins

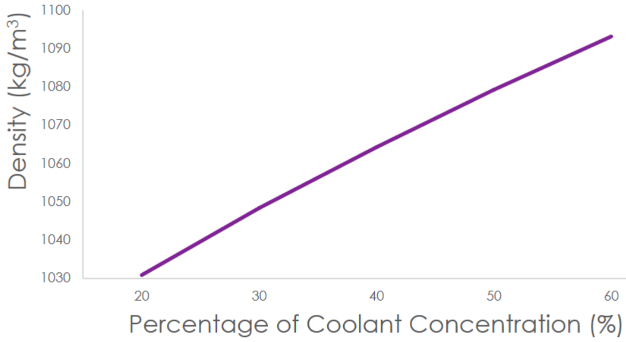

Fig. 5. Density of coolant at difference concentration

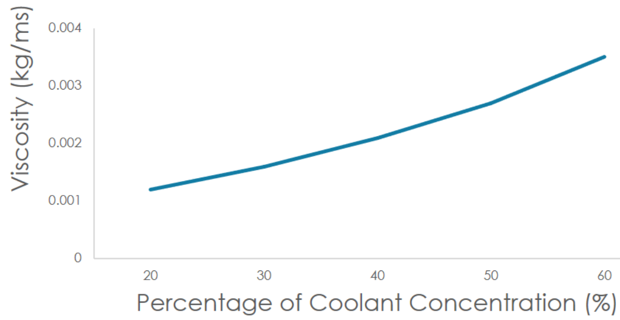

Fig. 6. Viscosity of coolant at different concentration

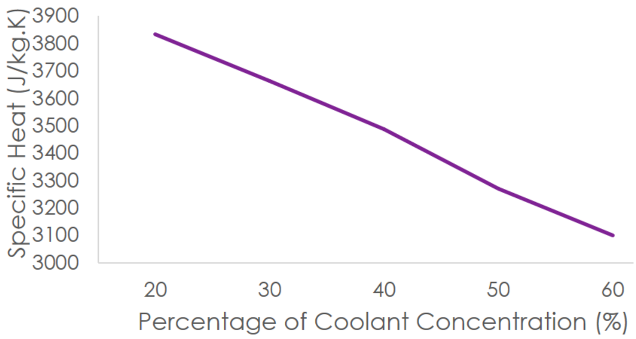

Fig. 7. Specific heat of coolant at difference concentration

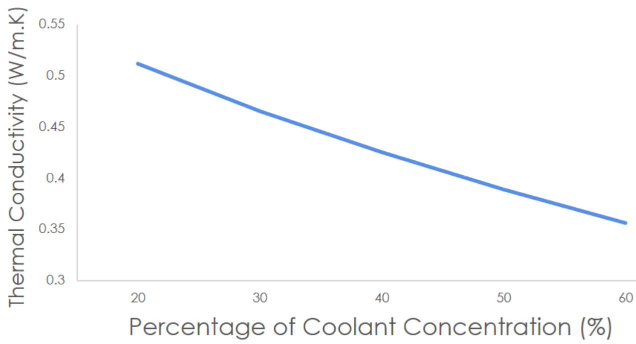

Figure 8: Thermal conductivity of coolant at different concentration

Fig. 9 shows the percentage of coolant concentration against temperature outlet for aluminum, brass and copper fins. All the trend line mark show the increment of the temperature. This is because of the characteristics of coolant itself. As the ethylene glycol concentration gets higher, it tends to reduce heat transfer abilities. This is the reason for coolant needed to be mixed with water due to good heat transfer ability of the water.

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Table IV: Outlet temperature of the radiator

Coolant (%)	Outlet temperature					
	Theoretical			*Simulation*		
	Al-Al	Al-Br	Al-Cu	Al-Al	Al-Br	Al-Cu
20	47.60	48.20	43.40	47.39	45.56	44.57
30	48.20	49.40	44.60	49.44	50.90	45.04
40	47.00	48.50	43.10	49.41	48.19	45.69
50	46.40	47.00	45.20	49.89	49.64	46.14
60	45.20	45.80	45.80	50.49	49.69	45.80

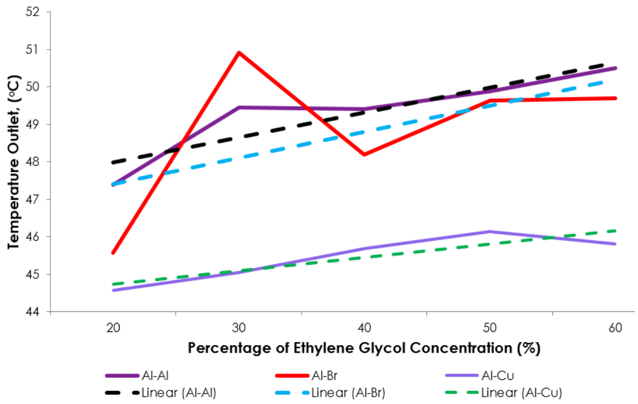

Fig. 9. Radiator outlet temperatures

Table V tabulates the rate of change of outlet temperature and heat flux per unit percentage of coolant concentration. As all the materials have positive gradient, they have an increasing in rate of change for every 1% of coolant concentration, 0.3567, 0.6655, and 0.698 for copper, aluminum and brass fins respectively. Therefore, the lower rate of change between temperature outlet and percentage of coolant concentration will cause a slight increase in temperature. The copper fins have a good result compare to aluminum and brass fin. In this case, the linear graphs having a negative gradient (Fig. 10). By having a decrement, it indicates that the performance of heat flux is getting slow. When it comes to the capability of heat releasing through the air, the higher rate of change between total surface heat flux and percentage of coolant concentration is better. Therefore, it can be concluded from this aspect, aluminum fins is better for good heat transfer.

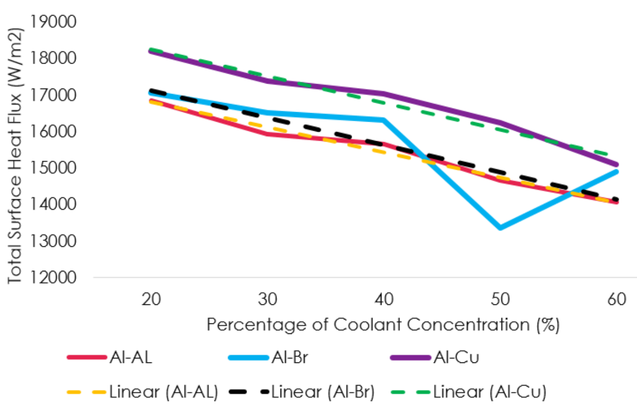

Fig. 10. Surface heat flux of the radiator

Table V: Rate of temperature and heat flux

Material	Rate of temperature outlet (°C/%)	Rate of heat flux (W/m^2%)
Al-Al	0.6655	-686.02
Al-Br	0.6980	-745.19
Al-Cu	0.3567	-737.03

IV. CONCLUSION

In this research, the radiator performance had been simulated by using ANSYS Fluent software. This simulation involving two working fluids namely air and ethylene glycol as a function of 20%, 30%, 40%, 50% and 60% concentration. In this simulation also the performance of aluminum, brass and copper fins material were determined and compared against each other. It is found that the copper fins with low coolant concentration improves the heat transfer rate in the vehicle radiator compared to the aluminum and brass fins.

It is also can be concluded that by reducing coolant concentration, heat transfer efficiency is improved while achieving satisfactory freeze protection. For burst protection, it is not necessary to add coolant concentration if slush or ice crystal in the fluid is acceptable. The coolant concentration is affective to be mixed with water in order to eliminate the rust from occurring.

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