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The Water-Cooled Engine System Performance

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Abstract

Efficient cooling systems are really important to avoid unnecessary problem to the engine. The cooling system will help in maintaining the engine to operate at its most efficient temperature. Overheated and overcooling, both will cause damage to the vehicle. In this experiment, to analyze the effect of varying engine speed (1500, 2000, 2500 and 3000 rpm) and engine load (1, 2, 3 and 4 kg) to the temperature profile and heat dissipation of the engine. The result show that increasing engine load and engine speed, the heat transfer within the engine will also increase.

Keyword*: water-cooled, radiator, gasoline engine, heat transfer.*

1. Introduction

Heat will produced inside the internal combustion engine either inside or outside the engine. For inside the engine, the heat produced inside the combustion chamber, where the detonation process occurs. The product that produced from the detonation process contain energy include heat. The product will be released to the environment as the exhaust gases. Some internal combustion used the exhaust gases to form another energy that used to improve the performance of the engine (Yoo *et al*., 2000).

The internal combustion engines remove this waste heat through the cool intake air, hot exhaust gases, and explicit engine cooling. This heat, if un-removed, will become excess and cause the engine in overheated state. This will cause damage to the metal parts of the engine. In the worst case, overheated may cause the metal to melt. This is why cooling system is one of the vital systems in automotive vehicle in ensuring the efficiency of the vehicle. The main purpose of engine cooling system is to maintain metal temperatures within its safe limits by removing excess heat produced by the engine. If an engine is allowed to run without external cooling, the cylinder walls, cylinder and pistons will tend to assume the average temperature of the gases to which they are exposed, which may be of the order of 1000 to 1500^{o}C (Rajput, 2007)

Basically, there are two types of cooling system that have been used in an internal combustion engine which are air cooling system and water cooling system. In air cooling system, heat is carried away by the air flowing over and around the cylinder. While, in water cooling system, the heat is transferred from cylinder walls to the liquid. The water-cooled engine system consists of the water jacket, water pump, cooling fan, thermostat, connecting hoses, heater core, radiator and radiator pressure cap. In this method of cooling engines, the cylinder walls and head are provided with jackets through which the cooling liquid can circulate. The heat is transferred from cylinder walls to the liquid by convection and conduction. The liquid becomes heated in its passage through the jackets and is itself cooled by means of an air-cooled radiator system. The heat from liquid in turn is transferred to the air. The waste heat of the engine is dissipated into the engine cabin's flow field through radiators and surface through convective heat transfer. If the dissipation of waste heat is not timely, it will make the high surface temperature, and affects engine cooling performance. Therefore, the cabin heat flow field has an important impact on the engine cooling systems. In fact, this impact is reflected in the aspect of convective heat transfer characteristics (Cai et al., 2012).

The main limitation of heat transfer in a cooling system is in the transfer from the radiator to the air. Heat transfer from the water to the fins as much as seven times faster than heat transfer from the fins to the air, assuming equal surface exposure. The radiator must be capable of removing an amount of heat energy approximately equal to the heat energy of the power produced by the engine. Each horsepower is equivalent to 42 Btu (10800 calories) per minute (Halderman, 2009). The heat-removing the requirement of the cooling system will increase when the engine power is increased. Recent trends to enhance the power output of engines with a turbocharger or supercharger have increased the demand on engine cooling systems more than ever. While reducing the cooling system size and weight, several efforts have been attempted to handle the increased heat load on the system with innovative cooling strategies such as reverse cooling, split cooling, and nucleate boiling cooling (Kim et al., 2010). A number of researchers have also proposed replacing the conventional water pump with an electrically-driven pump that can actively control the coolant flow rate based on the optimum driving temperature (Vegenas *et al*., 2004; Hnatczuk *et al.*, 2000; Page, *et al.*, 2005; Cho *et al.*, 2005; Cho *et al.*, 2007; Kim *et al*., 2009).

Therefore, engine cooling is really important to keep the temperature of the engine low in order to avoid loss of volumetric efficiency and hence the power, engine seizure, and danger of the failure of the engine. This paper is focused on the temperature profile and heat dissipation at various engine speeds and loads.

2. Effect of Engine Speed and Loads

There are many engine variables that may affect the magnitude of the heat transfer within the engine and the temperature dissipation of the components in the engines system which are engine speed, engine load, overall equivalence ratio, compression ratio, spark or injection timing, swirl and squish motion, mixture inlet temperature, coolant temperature and composition, wall material and wall deposits. In this study we will only consider the effect of the engine speed and loads.

Gas flow velocity into and out of the engine will be increased when engine speed is increased. This will cause a rise in turbulence and convection heat transfer coefficient. Thus, the heat transfer that happens during the intake and exhaust strokes; and also during the early part of the compression stroke will be increased.

The gas velocities in the cylinder are comparatively independent of engine speed during combustion and power stroke. However, gas velocities are depending by swirl, squish and combustion motion. The convection heat transfer coefficient and convection are therefore fairly independent of engine speed at this time. Besides that, radiation heat transfer is only essential during this portion of the cycle, is also independent of engine speed.

The rate of heat transfer (kW) during this part of the cycle is thus constant, but less heat transfer per cycle (kJ/cycle) occurs because the time of the cycle is less at higher speed. This gives the engine a higher thermal efficiency at higher speed. Moreover, more cycles per unit time occur at higher speed but each cycle lasts at lesser time. The net result is slightly ascended in heat transfer loss per time (kW) from the engine. This may occur due to the higher heat losses in some part of the cycle, but it is mostly due to the higher steady-state (pseudo-steady-state) losses that the engine establishes at higher speeds.

The mass flow of gas through an engine increases with speed, with a net outcome of less heat loss per unit mass (kJ/kg). All steady-state temperature within an engine increase as engine speed increases. Heat transfer to the engine coolant also increases with higher speed.

To keep the engine speed constant as the load on the engine is increased, the throttle must be further opened. This will cause less pressure drop across the throttle and higher pressure and density in the intake system. Therefore, mass flow rate of air and fuel will increase with load at a given speed. Heat transfer within the engine will also increase.

3. Experimental Parameters

3.1. Mass and Volume Flow Rate

Mass flow rate can be defined as the amount of mass flowing through a cross section per unit time, whereas, the volume of the fluid flowing through a cross section per unit time is called volume flow rate. The mass and volume flow rate are related by (Cengel and Boles, 2007):

$$\dot{m} = \rho\dot{V} = \frac{\dot{V}}{v} \tag{1}$$

where $\dot{m}$ is mass flow rate (kg/s), ρ is coolant density (kg/m^3), $\dot{V}$ is volume flow rate (m^3/s) and v is specific volume (m^3/kg).

3.2. Air Specific Heat

Specific heat is defined as the energy required raising the temperature of a unit mass of a substance by one degree. There are two kinds of specific heats which are specific heat at constant volume, c_v and specific heat at constant pressure, c_p. Both specific heats can be expressed as (Cengel and Boles 2007):

$$c_v(T) = \frac{du}{dT} \tag{2}$$

and

$$c_p(T) = \frac{dh}{dT} \tag{3}$$

where du is internal energy change (kJ/kg), dh is enthalpy change (kJ/kg) and dT is temperature change (K).

The relationship between c_p and c_v is expressed as follows.

$$c_p = c_v + R \tag{4}$$

and

$$\bar{c}_p = \bar{c}_v + R_u \tag{5}$$

where R is gas constant (0.2870 kJ/kg·K) = R_u/Molar mass, R_u is universal gas constant (8.31447 kJ/kmol·K), $\bar{c}_p$ is constant pressure specific heat on molar basis and $\bar{c}_v$ is constant volume specific heat on molar basis.

The $\bar{c}_p$ can be expressed in the form of a third-degree polynomial as shown below.

$$\bar{c}_p = a + bT + cT^2 + dT^3 \tag{6}$$

where: a = 28.11, b = 0.1967 x 10^{-2}, c = 0.4802 x 10^{-5} and d = -1.966 x 10^{-9}

3.3. Heat Capacity Rate

The heat capacity rate of a fluid stream represents the rate of heat transfer needed to change the temperature of the fluid stream by 1^{o}C as it flows through a heat exchanger (radiator). The heat capacity rate of the coolant and air can be expressed as follows (Cengel, 2006).

$$C_{coolant} = \dot{m}_{coolant} c_{p,coolant} \tag{7}$$

and

$$C_{air} = \dot{m}_{air} c_{p,air} \tag{8}$$

where $C_{coolant}$ is coolant heat capacity rate (kW/^{o}C), C_{air} is air heat capacity rate (kW/^{o}C), $\dot{m}_{coolant}$ is mass flow rate of the coolant (kg/s), $\dot{m}_{air}$ is mass flow rate of the air (kg/s), $c_{p,coolant}$ is coolant specific heat (kJ/kg· ^{o}C) and $c_{p,air}$ is air specific heat (kJ/kg· ^{o}C).

3.3. Heat Transfer Effectiveness

Heat transfer effectiveness, ε can be defined as (Cengel, 2006):

$$\varepsilon = \frac{\dot{Q}}{\dot{Q}_{max}} \tag{9}$$

The $\dot{Q}$ and $\dot{Q}_{max}$ parameters can be expressed as

$$\dot{Q} = C_{coolant}\left(T_{coolant,out} - T_{coolant,in}\right) \tag{10}$$

$$= C_{air}\left(T_{air,in} - T_{air,out}\right)$$

and

$$\dot{Q}_{max} = C_{min}\left(T_{air,in} - T_{coolant,in}\right) \quad (11)$$

where: $C_{coolant}$ is Coolant heat capacity rate (kW/^{o}C), C_{air} is Air heat capacity rate (kW/^{o}C), $T_{coolant,out}$ is Coolant outlet temperature (^{o}C), $T_{coolant,in}$ is Coolant inlet temperature (^{o}C), $T_{air,out}$is Air outlet temperature (^{o}C), $T_{air,in}$ is Air inlet temperature (^{o}C) and C_{min} is the smallest of C_{air} and $C_{coolant}$.

4. Experimental Setup

The experiment is carried out using a Proton Perdana V6 petrol engine. The engine is directly coupled to a dynamometer to measure the output power of the engine. The petrol engine had been equipped with electronic sensors to measure several engine parameters. Thus, several output data could be taken directly from the monitoring system of the engine. All the apparatus used in this experiment is shown on Figure 1.

Dynamometers are used to measure torque and power over the engine operating ranges speed and load. In this experiment, we will be using a hydraulic dynamometer. The specifications of the dynamometer are: DPX2 Model, Hydraulic break Type, and 150 bhp maximum powers at 4000 rpm. The general specification of the test engine are V6, 24V, DOHC, 2.0 L, 110 kW (147 bhp) at 6750 rpm with MPI (Multiple-Point Fuel Injection). The Pico USB TC-08 is used to detect the temperature within the engine cooling system. Several thermocouples are connected to the Pico USB TC-08, and then connected to the computer. The temperature reading will be taken automatically. The thermocouple used in this experiment is the type K. This type of thermocouple is having the range of temperature between -200^{0}C (-328^{0} F) to 1250^{0}C (2282^{0}C). The standard limit of error for it is greater of 2.2^{0}C or 0.75%. In this experiment, it is placed to the upper hoses and lower hoses of the radiator to measure the inlet and outlet temperature of the coolant. While another, two of the thermocouple is used to measure the inlet and outlet temperature of the air through the radiator.

Air blower is used to give and inlet air to the radiator. The air from the blower is continuously supplied in order to prevent the temperature of the air to become close to the coolant temperature. When these things happen, the heat transfer will become very slow. The vane anemometer is used to measure the velocity of the inlet air and outlet air. This anemometer used a small vane turbine whose rotation rate is measured to determine air velocity. The velocity is then used to calculate the mass flow rate of the air. The unit is in meter per second.

The main objective of this study is to determine the temperature profile and heat dissipation at various engine speeds and loads by mean of the experiment. The experiment that had been conducted is the constant load test and constant speed test. Discussion had been made to study the effect of varying, engine speeds and engine loads of the heat transfer in the engine cooling system.

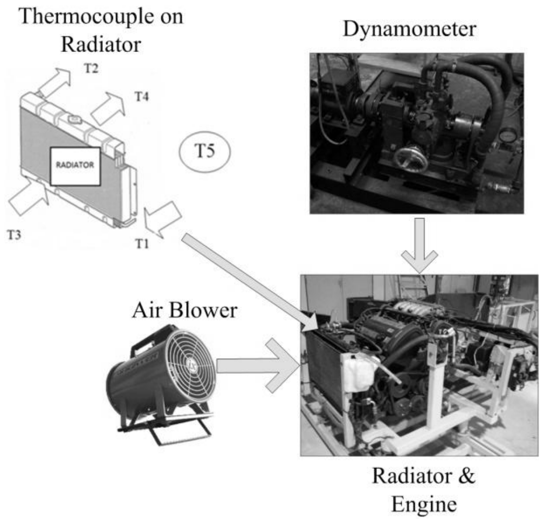

Figure 1. The experimental setup

5. Results and Discussion

5. 1. Effect of Engine Speeds to Water Temperature Difference

Figure 2 shows that, when engine speed increase, water temperature difference is decreased. The water enters the engine at higher temperature and will lose it heats to air via heat transfer, thus it will exit the engine at low temperature. However, when engine speed is increased, the heat in engine will also increase, so, the water outlet temperature will still be hot because water will absorbs more heat from the engine, thus, the difference between the outlet and inlet temperature will decrease. The figure also shows that at higher load, the water temperature difference is higher than at lower load.

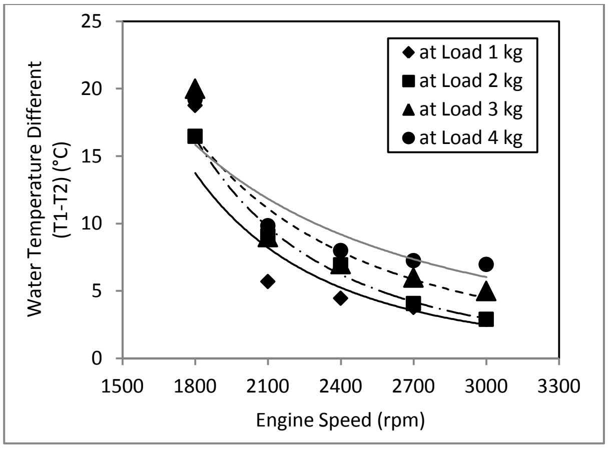

Figure 2. Water temperature different against engine speed

5. 2. Effect of Engine Speeds to Air Temperature Difference

Figure 3 shows that, when engine speed is increased, the air temperature difference will increase. The air enters the engine through the radiator at low temperature, and exit the engine at high temperature. The air temperature increase after flow through the engine is because of a temperature difference between water and air. Water enters the engine at high temperature whereas, the air enters at low temperature. To achieve equilibrium, heat transfer occurs between air and water. So, the air absorbs the heat from the water caused the exit air temperature increase. When engine speed increase, the heat within the engine will increase also, thus the air needs to absorb more heat and it had caused the increase in exit air temperature, and thus leads to the increase of the temperature difference. From the figure also, it shows that at higher load, air temperature difference will also be higher because the heat within the engine is increased.

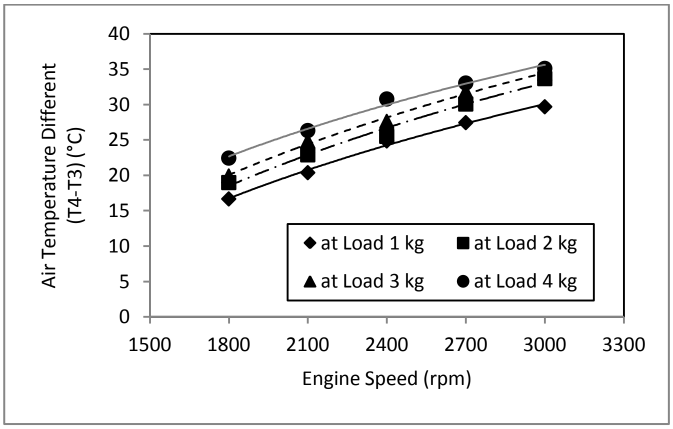

Figure 3. Air temperature different against engine speed

5. 3. Effect of Engine Speeds to Heat Transfer Rate for Water

Figure 4 shows that, generally, when engine speed is increased, the heat transfer rate from the air to the water will increase. It is because, even though the temperature difference of water is decreasing with increasing engine speed, the mass flow rate of water is still increasing with increasing engine speed. When the engine speed is increased, the heat within the engine will increase, so, the water that flow through the system will increase its volume flow rate to ensure the system has enough water to absorb the heat from the system without the temperature increasing to boiling temperature. The figure also shows that at higher load, the heat transfer rate of water is higher because of increasing in temperature within the engine. However, at some point, the heat transfer rate of water is decreasing because of when the engine speed increase, the heat within the engine instead of being absorbed by the water; the heat is converted to power to cope with high speed. At higher loads, the heat transfer rate of water also higher.

5. 3. Effect of Engine Speeds to Heat Transfer Rate for Air

Figure 5 shows that, when engine speed is increased, the heat transfer rate from water to air is also increased. It is because when engine speed is increase the air temperature difference will increase thus increasing the heat transfer rate of air. When the engine speed increase, the heat within the engine is increased, then, the heat absorbs by water from the engine will increase, thus the heat absorbs by air from the water will also increase. The air enters the engine in low temperature, so, when air absorbs more heat, the air exit temperature will increase, caused the difference between the inlet and outlet temperature of air increase, thus lead to increase in heat transfer rate of air. From the figure also shows that at higher load, the heat transfer rate of air is also higher compared to lower load.

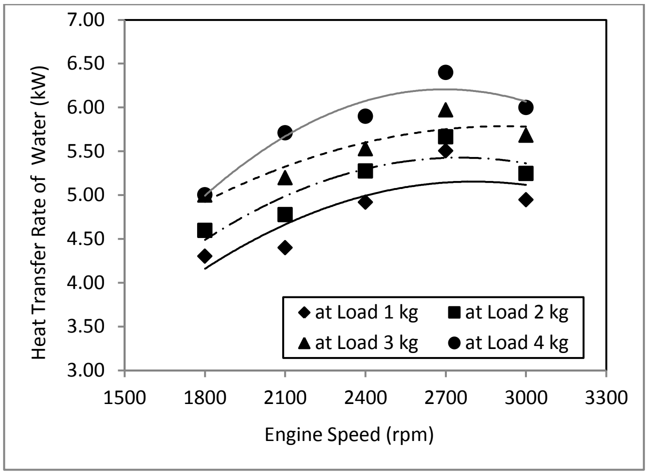

Figure 4. Heat transfer rate of water against engine speed

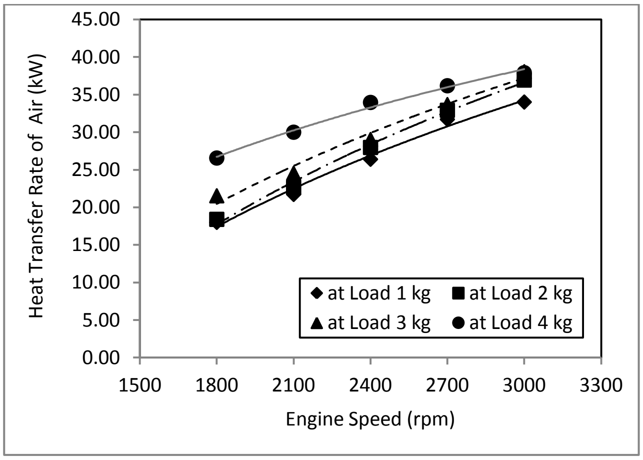

Figure 5. Heat transfer rate of air against engine speed

5. 4. Effect of Engine Speeds to Heat Transfer Effectiveness

Figure 6 shows that the relationship between heat transfer effectiveness against engine speeds. From the figure, the effectiveness generally is decreasing when engine speed increase. The heat transfer effectiveness is defined as the ratio of the actual heat transfer that occurs to the maximum possible heat transfer. The decreasing occurs because of, at higher engine speed, the heat within the engine is converted to power to cope with the high speed, so the heat absorbs by water is less. From the figure, it shows that at a low engine speed, the effectiveness is the highest. When the effectiveness is high, it means that the actual heat transfer that occurs in the radiator is nearing the maximum possible heat transfer.

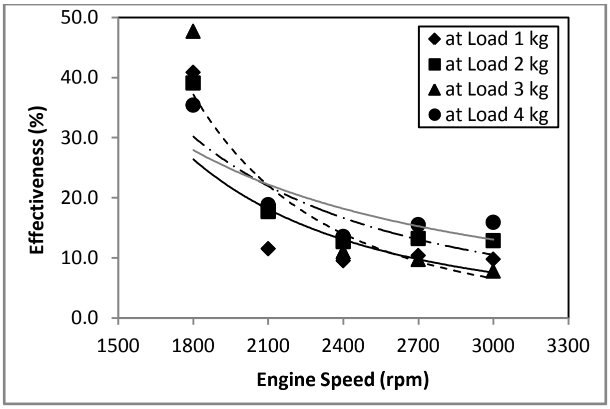

Figure 6. Heat transfer effectiveness against engine speed with loads variation

6. Conclusion

As a conclusion, the experiment has been successfully done to achieve its objective that is to determine the temperature profile and heat dissipation at various engine speeds and loads. The performance characteristic study of the engine cooling system is carried out by means of experiment. The heat transfer performance of the engine is determined by varying engine variables that are engine speed and engine load that enter the radiator. In order to determine the heat transfer between the air and the water, some parameters need to be measured such as the temperature of the inlet and outlet of the water and air, water flow rate and the air velocity.

We can conclude that when engine speed is increase, the heat transfer within the engine will also increase. However, at some point when the engine speed is too high, the heat transfer within the engine will be decreased. This is because, when the engine speed is too high, the piston speed will also increase. The engine needs to generate optimum power at high engine speed. So, the heat that supplied from the combustion will be used to cope with the high speed. This is also to ensure complete burning in the combustion chamber and also to maintain the combustion pressure at a level which provides for optimum engine performance.

On the other hand, when the engine load is increased the heat transfer within the engine will also increase. However, with the same condition as when engine speed is increasing, after some point, when the load is too high and the engine speed also too high, the heat transfer with the engine will decrease. This is also because the engine needs to generate optimum power at high load, so the heat supplied from the combustion will be used to cope with the high speed.

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