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ENGINE CYLINDER HEAD COOLING ENHANCEMENT BY MIST COOLING – A SIMULATION STUDY

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Abstract

Among the two types of engine cooling, liquid-cooling and air-cooling, liquid cooling is widely used due to its capability to reject a larger amount of heat and air-cooling is preferred for small capacity engines in which cooling systems are much simpler in design and low in cost. In practice, piston-seize in air-cooled engines is common during long hours of operation or at higher engine speeds. The current work proposes mist cooling as a way to overcome this problem. A feasibility study is conducted where the temperature distribution in an array of plate fins, similar to fins on an engine cylinder head, is measured. The fins are subjected to constant heat flux at the base and cooled by airflow, simulating actual conditions on a cylinder head. Experiments were conducted for several air velocities ranging from 21.5 m/s to 40.4 m/s. The temperature distribution in the fin was measured at several locations simultaneously to calculate the amount of heat being transferred. These experiments were repeated with the injection of mist to compare the augmentation of heat transfer. The heat transfer coefficients increased between 200 and 400% and the surface temperatures were depressed. This proves that mist-cooling can be adopted to enhance heat transfer and lower the temperatures in air-cooled systems during critical conditions.

Keywords: engine cooling, heat transfer enhancement, mist-cooling

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1. Introduction

Fuel combustion in the engine cylinder releases a large amount of heat. Part of the heat is lost through exhaust gases, while some of the heat flows into the cylinder wall, cylinder head and the piston itself. This heat must be rejected to prevent these parts from overheating. Without adequate means of disposing of the excess heat, the lubricating properties of the oil film would be lost resulting in engine failure. Even before piston seizing occurs, there can be other serious difficulties in the engine. The spark plug would be so hot that it would ignite the air-fuel mixture prematurely. This condition could also cause engine failure, because pre-ignition can melt holes in pistons and cause other internal damage. To prevent such events, the role of the engine cooling system is critical.

Two basic types of engine cooling systems in practice are air-cooling and liquid-cooling. In the case of small capacity engines such as those in motorcycles, air-cooling system is satisfactory. Air-cooling systems are simple in design and relatively low in cost. They feature finned cylinder heads to provide a maximum surface area for heat transfer.

Engine failures due to piston-seize in air-cooled systems are still reported in many cases, particularly in 2-stroke engines. The main factor which can be associated with this phenomenon is inadequate engine cooling due to poor heat transfer rates from the engine. The current work details the feasibility study carried out to improve air-cooled systems by means of mist cooling on the fin surfaces of an engine cylinder head. The wide potential of this method as indicated in literature studies suggests its use for the current application.

2. Literature Review

Heat transfer affects engine performance, efficiency and emission. For a given mass of fuel within the cylinder, higher heat transfer to the combustion chamber walls will lower the average combustion gas temperature and pressure, and reduce the work per cycle transferred to the piston. In contrast, low heat transfer will result in a serious temperature rise and may lead to engine failure and poor emission [1].

Generally, small engines like motorcycles as well as heavy machinery and other stationary equipment use air-cooling system. Though air is not the most efficient medium for heat transfer, it is plentiful and usually provides a sufficient ΔT with the engine block, in order to dissipate heat. The main advantage of this cooling is that it doesn’t need to carry any additional load on the engine. So, the engines are lightweight and simple compared to the liquid cooling system engines. Furthermore, the engine is rather a self-contained unit, as it requires no external components like radiator, etc. In this type of cooling system, most heat is removed by convection, followed by exhaust gases, radiation from engine components and also by lubrication system [2].

Mist-cooling or spray cooling is a technique of increasing interest for electronic cooling and other high heat flux applications and is characterized by high heat transfer, uniformity of heat removal, small fluid inventory, low droplet impact velocity and no temperature overshoot. The mechanisms by which heat is removed during mist cooling are, however, poorly understood due to its dependence on many parameters that are not easily varied independently and predictive capabilities are quite limited [3]. Mist cooling is a very efficient means for dissipating high heat fluxes with low coolant mass fluxes at low wall superheats. It is used in a wide range of applications from metal quenching, to cooling of high power electronics to medical treatments [4,5].

In some cases, liquid cooling of high heat flux thermal designs are necessary to maintain lower operating temperatures, which will increase the reliability and performance of the components. Possible liquid cooling technologies include single-phase liquid cooling in microchannels, immersion flow boiling, mist cooling, jet impingement cooling and heat pipes. Of the above cooling technologies, mist cooling appears to offer the best balance of high heat removal capability, isothermality and low fluid inventory [3].

Mist cooling occurs when liquid is forced through a small orifice, shatters into a dispersion of fine droplets, which then impact a heated surface. The droplets spread on the surface and evaporate or form a thin liquid film, removing large amounts of energy at low temperature differences due to the latent heat of evaporation in addition to substantial single-phase liquid convection effects. Other advantages include the possibility of uniformly cooling large surfaces, low droplet impact velocity and no temperature overshoot. Some disadvantages include the need for pumps, filters, and in some cases, the need to transport excess liquid and vapor to a condenser [3].

3. Methodology

Since conducting experiments on an actual engine will be tedious and costly, a simulation method is adopted to study mist cooling. This method provides better control on measured parameters while maintaining accuracy. The experimental set-up and determination of heat transfer coefficient are described in the following section.

3.1 Experimental Set-up

The experimental setup consists of an array of aluminum fins, which simulate the fins on an air-cooled engine cylinder head. The base of the fin is heated electrically for constant heat flux. Thermocouples measure air and fin surface temperatures while air velocity is measured using a hot-wire anemometer. A 3 HP centrifugal blower is used to generate air velocity up to 150km/h to simulate ram air blowing on the hot fin surfaces. A mist generator unit consisting filter, water pump and nozzle is used to generate mist. *Figures 1, 2* and *3* show the schematic diagram and the actual experimental set-up respectively.

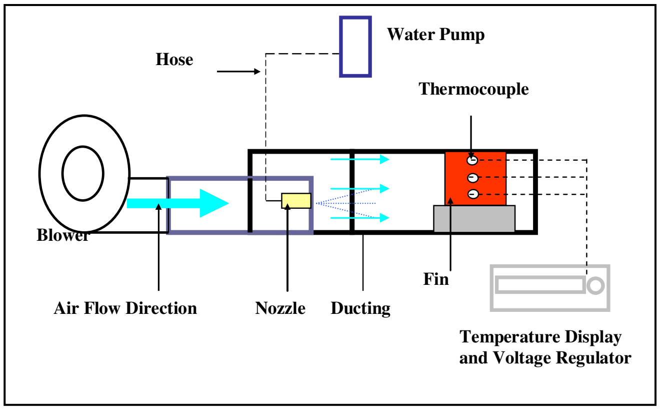

Figure 1: Schematic Diagram of the Experimental Set-up

Figure 2: Experimental Set-up

Figure 3: Fin Array and Thermocouple Locations

2.2 Determination of Heat Transfer Coefficient, h

A method to determine the average heat transfer coefficient values, *h*, is required to characterize the effect of cooling by both air and mist respectively. These h values will indicate the amount of heat transferred by both means of cooling, thus enabling us to draw a conclusion on the heat transfer augmentation. In the analysis, the flows on the fin surfaces may be treated as flow between parallel plates. But since the gap between the fins is significantly large and the flow length is comparatively short, the boundary layers will not converge and full development of flow will not occur. Hence it is more appropriate to treat the flow as one over flat plates. By conducting experiments in such a way that steady-state conditions are obtained, the heat transfer coefficient values may be determined by using the well known Nusselt correlation for flow of fluid over a flat plate.

However, this approach is not used in the present study, as the surface temperature distribution on the fin surfaces does not play any role in the calculation. Therefore, the adiabatic fin approach is adopted. By treating the fin as fins with adiabatic tip and neglecting temperature variation along the fin thickness, i.e. lumped system assumption, the temperature variation from the base to the fin tip is given by the expression:

$$\frac{\theta}{\theta_b} = \frac{T(x) - T_\infty}{T_b - T_\infty} = \frac{\cosh m(L-x)}{\cosh mL} \qquad (1)$$

$$\text{where } m = \sqrt{hp / kA_c} \qquad (2)$$

p = fin perimeter; k = fin thermal conductivity

The values of m are calculated from the above equation (1) for three different locations along the fin height from the base towards the fin tip direction by incorporating temperature values that were measured at respective locations. The local values of h are then determined from equation (2). These h values at all three locations are then averaged to get a single value of h_{avg} for analysis. In this method of heat transfer coefficient determination, the principal assumptions made are:

a) The fins are equal in dimension with same open area for air flow.
b) The fins have same thickness from the base to the tip.
c) Temperature variation in the direction of air flow is negligible.
d) The thermal conductivity of the fin is constant.
e) Temperature variation along the fin thickness is negligible.

4. Results and Discussion

Experiments are conducted for four different velocities of air and repeated with the injection of mist. The summary of the results is presented in *Table 1* below:

Table 1: Average Heat Transfer Coefficient Value, h_{avg} for Different Velocity of Air

V=40.4m/s	**V=37.8m/s**	**V=32.1m/s**	**V=21.5m/s**
Without mist **h=262.67 W/m^2K**	*Without mist* **h=153.17 W/m^2K**	*Without mist* **h=106.37 W/m^2K**	*Without mist* **h=58.70 W/m^2K**
With Mist **h=528.29 W/m^2K**	*With Mist* **h=389.79 W/m^2K**	*With Mist* **h=312.6 0 W/m^2K**	*With Mist* **h=292.10 W/m^2K**
Increase of "h" value: **50.3%**	Increase of "h" value: **61.0%**	Increase of "h" value: **66.0%**	Increase of "h" value: **80.1%**

The results above are then plotted on graphs as in *Figure 4* and *5* to visually identify and distinguish the heat transfer augmentation with the presence of mist.

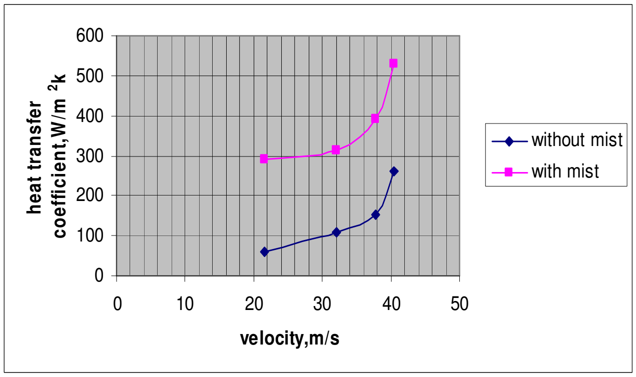

Figure 4: Average Heat Transfer Coefficient vs Air Velocity

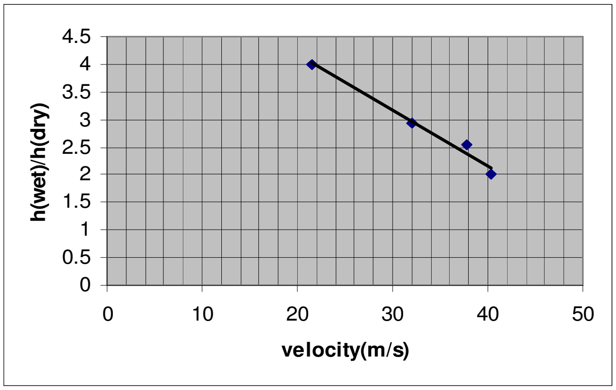

Figure 5: Non-Dimensional Heat Transfer Coefficient Ratio, h_{mist} / h_{dry}

Both *Table 1* and *Figure 4* clearly indicate a significant increase of average heat transfer coefficient with the presence of mist. The increases are from 50.3% up to 80.3%. The trend shows that both air-cooling and mist-cooling become even more significant at higher air velocities, owing to the increase of forced convection. However, the percentage of increase of average heat transfer coefficient becomes lower at higher air velocities. A non-dimensional plot of average heat transfer coefficient ratio between mist-cooling and air-cooling is presented in *Figure 5*. The ratio reduced linearly with velocity increase.

In the velocity range studied, a maximum ratio of 4 obtained, indicating mist-cooling can enhance air-cooling by four times. This finding yields that mist-cooling is particularly suited for low velocities of air and high engine outputs as in climbing a grade. The mechanism that contributes to heat transfer increase during mist-cooling is the fact that mist actually creates a thin layer of water film during the spray. This no-slip layer of water film increases thermal conductivity in this region by several times and consequently results in the increase of the average heat transfer coefficient.

3. Conclusion

The objective of the study has been successfully achieved. Although mist cooling with a fine spray of air-water is not new, the application towards augmenting heat transfer on fins of air-cooled engine cylinder heads is novel. The adiabatic fin method can be well applied to estimate the average heat transfer coefficient increase. The study also concludes that mist cooling is a very complex situation for analysis due to several factors. The complexity arises from the increase of heat transfer coefficient, *h* of water vapor as compared to dry air. The mist with droplets of water which hits the surfaces are impossible to be quantified, which at the same time forms a thin water film to increase the heat transfer from the fin. The total heat transfer is actually the combined effect due to the increase of h values and temperature difference, ΔT. Furthermore, it is not possible to isolate the individual contribution of various effects but the overall effect is determined.

In a nutshell, it can be concluded that it is useful to employ mist cooling so as to enhance cooling on air-cooling system, such as the cylinder head of an engine, at low air-velocities and particularly at high engine output.

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