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DEVELOPMENT OF AN EVAPORATIVE COOLING SYSTEM FOR SMALL FOUR-STROKE ENGINES

S.C. Lee*, J.Y. Kim*, B.H. Han, T.M. Choi*** and S.H. Bae*****

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A new evaporative cooling system for small four-stroke engines has been developed. Performance tests of a four-stoke single cylinder engine equipped with this evaporative cooling system have been carried out in the laboratory. Air removal rates from the closed coolant loop during the starting stage of the engine have been monitored for various engine operating conditions. In addition, data of the brake horsepower, the specific fuel consumption, heat loss to the coolant, cylinder-liner wall temperature and the wall heat flux have been obtained and were compared to those of the identical engine equipped with a conventional liquid cooling system. At a fixed air fuel ratio and under the MBT condition, the brake horsepower of the engine for the evaporative cooling system is enhanced compared to that for the liquid cooling system. The heat loss through the cylinder liner is decreased when the evaporative cooling system is adopted. The test result indicates several benefits of the evaporative cooling system such as faster warm up, better fuel economy and greater engine durability.

Key Words : Evaporative Cooling System, Engine Performance, Heat Release, Temperature and Heat Flux Measurement, SI Engine

1. INTRODUCTION

Efforts have been ceaselessly made to improve the performance of engines in the automobile industry. As part of these efforts, attention has been focussed on the reduction of heat loss from engines which takes place inevitably during the compression and expansion processes. Engines operating at higher temperatures may gain an advantage of better fuel economy (Taylor, 1966). This can be achieved by substituting conventional liquid cooling systems for evaporative cooling systems.

Evaporative cooling systems remove heat from the engine by vaporizing the liquid coolant at its saturation temperature. The heat transfer mechanism at the liquid jacket is convective boiling rather than forced convection in conventional cooling systems. Thus, this mechanism permits the vapor cooled engines to run at relatively high and uniform temperatures regardless of engine operating conditions.

Several studies of the evaporative cooling system have been carried out particularly in the recent years (Leshner., 1983; Kubozuka et al., 1987; Watanabe et al., 1987). These works have dealt with engine performance, combustion chamber corrosion and deposit, exhaust emissions and heat transfer mechanism characteristics. Various advantages of the evaporative cooling system such as faster warmup, reduced friction, greater engine durability have been revealed in the studies.

*Mechanical Engineering Department, Yeungnam University, Gyongsan 713-748, Korea
**Department of Automobile, Yeungnam Junior, College of Technology, Taegu 705-037, Korea
***Dae Woo HMS Industries Co. Dalsung, 711-855, Korea

The present work involves a fundamental study of the evaporative cooling system as well as a small four-stroke engine with this system. Behaviour of air removal from the cooling system during the starting stage of the engine have been investigated. Several parameters representing the engine performance have been monitored and were compared to those of the identical engine with a conventional liquid cooling system. In addition, tests of heat release from the engine have been carried out in order to analyse the thermal performance of the cooling system as well as the engine.

2. DEVELOPMENT OF EVAPORATIVE COOLING SYSTEM

The evaporative cooling system used in the present study is sketched in Fig. 1. The system basically consists of an internal combustion engine, a condenser, a circulating pump, a thermostatic air vent and an air reservoir.

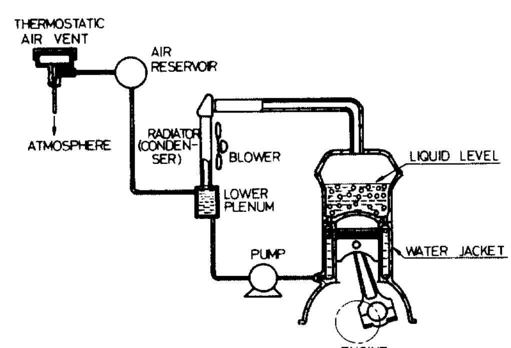

Fig. 1 Schematic diagram of an evaporative cooling system

The coolant is introduced as a liquid phase into the coolant jacket of the engine and is then discharged as a vapor phase to the condenser. Heat is transferred from the cylinder wall to the coolant by convective boiling in the coolant jacket. The heat is removed to the atmosphere by liquefying the vapor coolant in the condenser. Condensate which is collected at the bottom of the condenser is returned to the cooling jacket at or near its saturation temperature by a circulating pump. The liquid level in the system during normal operation is shown in Fig. 1. This indicates that the surface area of heat generation in the jacket is always wetted by the liquid phase coolant to avoid an overheating of the engine.

The system is always maintained at or slightly above the atmospheric pressure either in operation or at rest. Air which is drawn in the coolant circulation loop when the engine is not in operation, is pushed by the vapor ahead of it and is discharged through the condenser to the atmosphere during normal operation of the cooling system. The air vent is temperature-controlled and is closed to prevent the coolant from escaping into the atmosphere when the hot coolant contacts the capsule of the air vent. As the operation of the engine is ceased, air moves back to the system through the air vent to maintain the atmospheric pressure inside the coolant loop.

3. ENGINE PERFORMANCE TEST

Performance tests of a single-cylinder four-stroke engine equipped with the evaporative cooling system and with a conventional liquid cooling system have been carried out in the laboratory. A schematic diagram of the experimental apparatus is shown in Fig. 2. It is composed of a test engine, an engine cooling system, air and fuel supply system and exhaust pipe system. The specification of the test engine is summarized in Table 1. The radiator (condenser) in the engine cooling system is of corrugated fin-and-tube type and has a size of 420 (mm) × 300 (mm) × 33 (mm). Measurement of the intake air flowrate and temperature, the intake and exhaust pressure, fuel consumption, revolution count and torque of engine shaft has been taken to evaluate the engine performance.

Engine dynamometer used in the present study is of air-cooled eddy current type and has a maximum absorbing power of 10 (Ps) and a maximum revolution count of 4000 (rpm). The engine speed was electronically controlled and was measured on a digital tachometer. Temperatures of the intake air, the coolant and the cylinder wall were measured by means of the copper-constantan thermocouples. The air flowrate and the coolant flowrate were measured by means of an orifice and a venturi, respectively, which were connected to pressure transducers.

The signals from the thermocouples, pressure transducers, and flowmeters are processed by a microcomputer interfaced with a multichannel A/D converter. This computer-based data acquisition system has a maximum scan rate of approximately 8kHz and a maximum scan repeat rate of 400Hz.

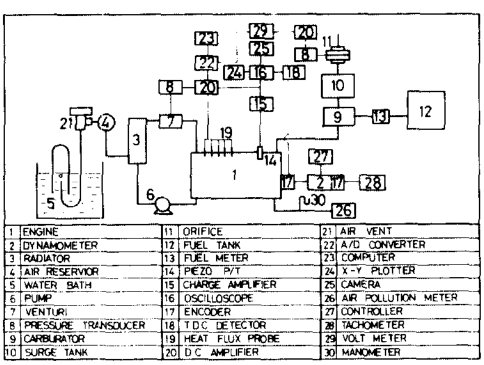

Fig. 2 Schematic diagram of the experimental apparatus

Table 1 Specification of test engine

Number of cylinders	Single
Bore × Stroke	90 (mm) × 105 (mm)
Displacement	667 (cc)
Compression ratio	4.5

4. AIR REMOVAL IN THE EVAPORATIVE COOLING SYSTEM

Time history of air removal percentage by weight in the evaporative cooling system was monitored for several engine operating conditions as shown in Fig. 3. The air removal percentage here represents a ratio of the amount of air-removed from the system to the total amount of air contained initially inside the loop. The amount of air removed from the coolant circulation loop was measured by using and inverted mass cylinder immersed in the water as shown in Fig. 2. It is indicated that more than 97 percent of air by weight could be removed as the system operating condition reaches the steady state. It has been reported that the influence of non-condensible gas on the condensation heat transfer coefficient is not significant as long as the air content in the vapor is very small (ASHRAE 1985). Thus, the present cooling system appears to be satisfactory in regard to the capability of air removal.

Under full throttle conditions, 3∼5 minutes are taken to reach the steady state after the vapor is produced in the jacket and an increase of engine speed results in a decrease of time required to get to this state. For idle condition, approximately 50 minutes is needed to get to this state. This is mainly because the amount of the vapor generated in the coolant jacket is much smaller compared to that of full throttle conditions.

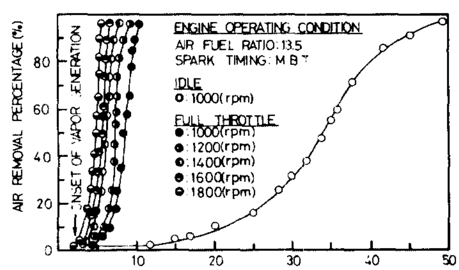

Fig. 3 Time history of air removal percentage in the evaporative cooling system

5. INFLUENCE OF AIR CONTENT ON ENGINE PERFORMANCE

Air content in the vapor phase may significantly affect the condensation process partly because it may form an insulation layer across the heat transfer surfaces. It should be also noted that unlike vapor, the air carries no useful heat, so that the heat content of air and vapor mixtures is reduced. Thus, the presence of a considerable amount of noncondensible gas in the coolant circulation loop may alter the heat transfer characteristics of the evaporative cooling system, resulting in degradation of engine performance.

It is of practical interest to investigate the effect of air content in the vapor on the engine performance in order to examine the importance of a proper design of air removal device in the evaporative cooling system. Figs. 4 and 5 shows the brake horsepower(BHP), the torque and the brake specific fuel consumption(BSFC) of the engine for various air content percentages in the coolant circulating loop. These tests have been performed by artificially controlling air removal percent in the system.

It is obvious from the figures that the brake horsepower and the engine torque tend to decrease as the amount of air content remained in the system becomes larger, whereas an opposite trend is found for specific fuel consumption curves. As the air removal percentage drops from 97% to 58%, the brake horsepower is reduced by approximately 9% and the specific fuel consumption is increased significantly. It has been observed that the knock phenomenon takes place due to rising of the temperatures of the cylinder and combustion chamber walls as the air removal percentage drop below 50%. From these results one may assume that an effective air removal from the coolant circulating loop in normal operation is essential in the evaporative cooling system. It should be noted, however, that the present evaporative cooling system has a capability of eliminating more than 97% of air initially contained in the coolant loop while the system is in operation.

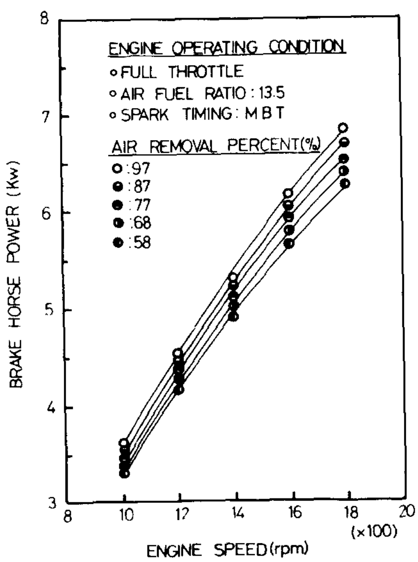

Fig. 4 Full throttle power-speed curve for engine with the evaporative cooling system

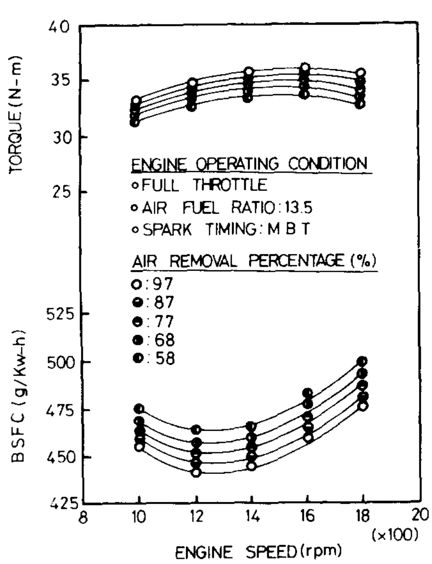

Fig. 5 Full throttle torque and speciffic fuel consumption for engine with the evaporative cooling system

6. COMPARISION OF ENGINE PERFORMANCES BETWEEN EVAPORATIVE COOLING SYSTEM AND LIQUID COOLING SYSTEM

The full-throttle torque-speed curve, power-speed curve and specific fuel consumption-speed curve are of great importance in evaluating the engine performance. Figures 6 and 7 show these curves obtained for the test engine equipped with the evaporative cooling system and with a liquid cooling system. Data of the liquid-cooled engine have been obtained by regulating the liquid flowrate at a fixed inlet temperature of 50(℃) and outlet temperature of 80(℃),

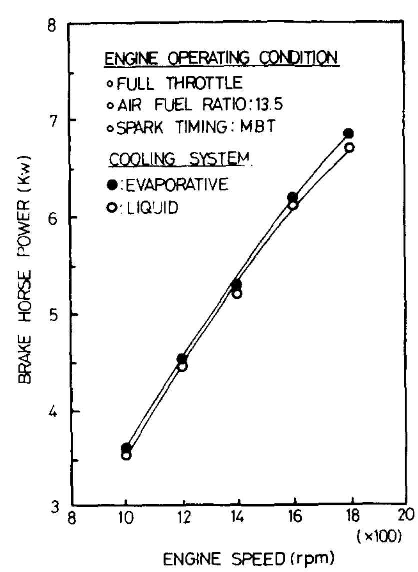

Fig. 6 Comparison of power curves for engine with evaporative cooling systemand with liquid cooling system

regardless of engine operating conditions. The coolant used in the present study is pure water. The operation pressure is atmospheric pressure for the evaporative cooling system. All curves plotted in the Fig. 6 and 7 illustrate typical features of spark-ignition engine performance. The brake horsepower tends to increase as the engine speed is increased and, however, the increment becomes weak. The torque-speed curve shows a peak value around the middle of the speed range and a considerable falling off at maximum speed. The brake specific fuel consumption has a minimum value around 1200(rpm).

It is interesting to note that the engine performance with the evaporative cooling system is better than that of liquid-cooled engine. The brake horsepower for the evaporative cooling system is increased by 3~4% compared to that for the liquid cooling system under identical engine operating conditions. The specific fuel consumption is accordingly reduced for the evaporative cooling system leading to a better fuel economy. The improvement of fuel economy is thought to be achieved due to the elevation of coolant temperature in the evaporative cooling system.

Figure 8 shows the effect of spark timing on the break horsepower for several engine operating conditions. The brake horsepower has a maximum value around 30~40 degree BTDC depending upon the engine speed. The horsepower of the engine equipped with the evaporative cooling system is always greater than that of the liquid cooled engine under identical operating conditions.

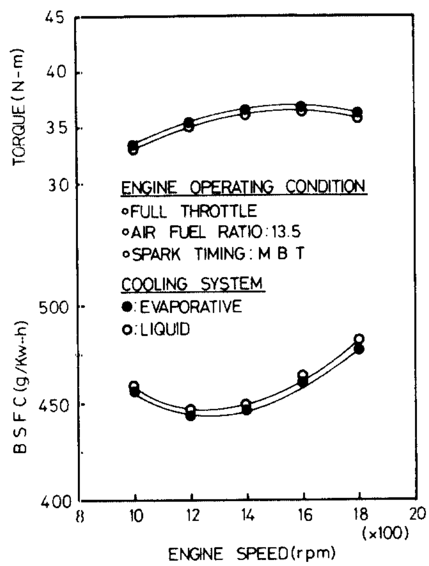

Fig. 7 Comparison of torque and specific fuel consumption curves for engine with evaporative cooling system and with liquid cooling system

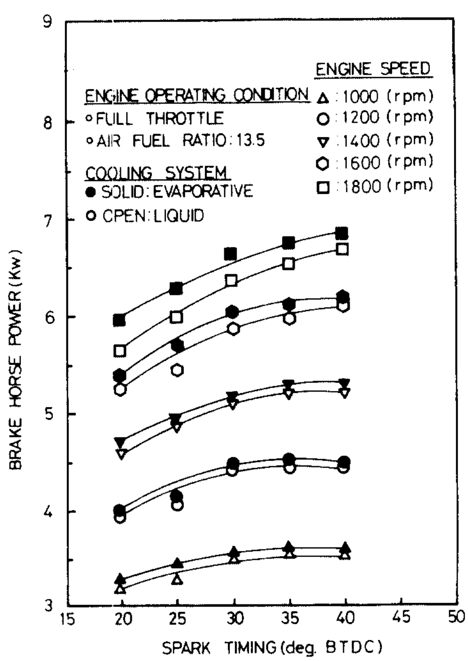

Fig. 8 Effect of spark timing on power

7. HEAT LOSSES TO THE COOLANT

A significant amount of heat is transferred to the cylinder structure, thence to the coolant, during the operating of engines. The heat loss to the coolant was calculated based on measurement of the coolant flowrate and the inlet and outlet temperature of the coolant in the liquid jacket for the evaporative cooling system and the liquid cooling system, respectively. Figure 9 shows a comparision of heat losses for both cooling systems under full throttle conditions. The heat loss is in general reduced when the evaporative cooling system is substituted for the liquid cooling system. This reduction in heat release through the coolant appears to account for the enhancement of the break horsepower as shown in Fig. 4.

8. TEMPERATURE AND HEAT FLUX MEASUREMENT IN THE CYLINDER WALL

The temperature and the heat flux in the cylinder wall have

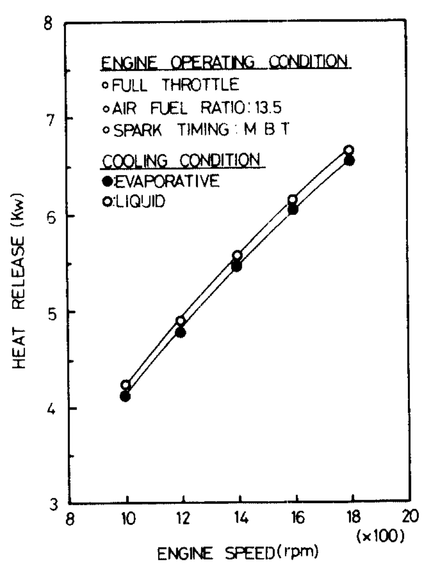

Fig. 9 Comparison of heat losses from engine with evaporative cooling systemand with liquid cooling system

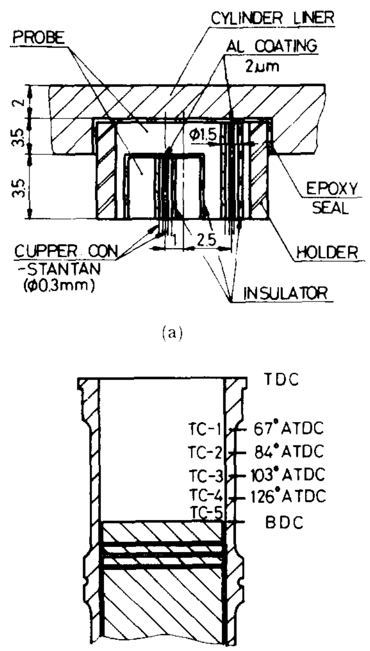

Fig. 10 Heat flux measurement system : (a) Probe assembly ; (b) location of probes

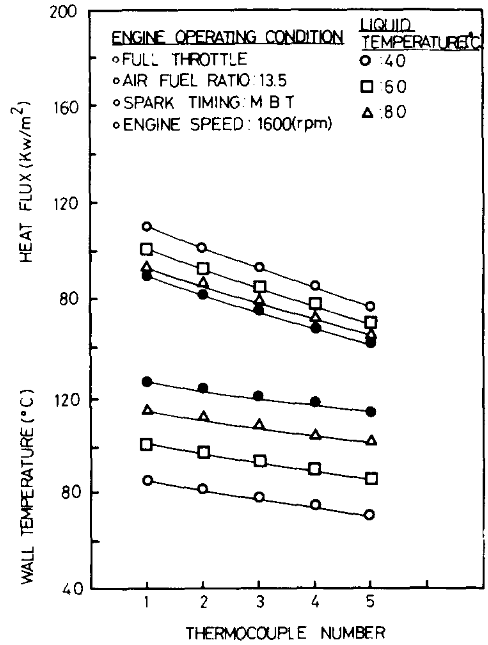

Fig. 11 Heat flux and wall temperature distributions in the cylinder liner (solid symbol : evaporative cooling system ; open symbol : liquid cooling system)

been measured to compare heat transfer characteristics of the engine with the evaporative cooling system and with the liquid cooling system. It has been accomplished by means of heat flux probes as shown in Fig. 10(a). The probe consists of two flat plate juctions, electrical insulation, and a holder. The junctions are made of copper-constantan thermocouples with a diameter of 0.3(mm) and are 3.5(mm) apart. A very thin layer of aluminum with a thickness of 2(μm) was coated onto the surface to form the junctions by vapor deposition technique.

A calibration to check the sensitivity of the junctions has been carried out following Enomoto(1985), resulting in a satisfactory effect with this thickness. The holder provided a thermal insulation layer, so that heat flow between the junctions could be considered to be reasonably one-dimensional. The heat flux probes were embedded into the cylinder wall at five locations as shown in Fig. 10(b). The hot junctions are 2 (mm) away from the inner surface of the cylinder wall.

Data of temperatures and heat fluxes at each location are shown in Fig. 11. Engine operating condition is full throttle and the engine speed was fixed at 1600(rpm). Data of the liquid cooling system were taken for three different coolant outlet temperatures of 40(℃), 60(℃) and 80(℃), and are compared with those of the evaporative cooling system. It is shown in the figure that the cylinder wall temperature is increased as the coolant temperature rises whereas the heat flux has an opposite trend. The heat fluxes for the evaporative cooling system are lower compared to those for the liquid cooling system.

This fact coincides well with the result of the heat release to the coolant mentioned in a previous section. The wall temperatures for the evaporative cooling system are much higher than those for the liquid cooling system. Higher cylinder wall temperature leads to higher oil temperature, which accordingly results in lower oil viscosity. Thus, it may be assumed that the engine horspower is enhanced partly due to reduced friction as the evaporative cooling system is substituted for the conventional liquid cooling system. This fact can be confirmed from the result of the present study shown in Fig. 4 as well as the work of Leshner(1983). It has been reported that the wall temperature of the cylinder block for the evaporative cooling system is relatively uniform compared to that for the liquid cooling system(Leshner, 1983). The result in Fig. 11 seems to ascertain in part this fact although the present data is limited to the cylinder liner.

9. SUMMARY AND CONCLUSIONS

Performance tests of a four-stroke single cylinder engine equipped with a new evaporative cooling system have been carried out. Air removal from the coolant circulating loop during normal operation of engine shows a satisfactory result. The brake horsepower and the specific fuel consumption of the engine with the evaporative cooling system is enhanced compared to those of the engine with the conventional liquid cooling system. The heat release to the coolant as well as the heat flux through the cylinder wall has been obtained for both cooling systems. These values for the evaporative cooling system become lower compared to those for the conventional liquid cooling system. This difference appears to account for the improvement of the engine horsepower. The test result illustrates several benefits of the evaporative cooling system such as better fuel economy and greater engine durability.

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