

Cooling Loss Reduction of Highly Dispersed Spray Combustion with Restricted In-Cylinder Swirl and Squish Flow in Diesel Engine

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ABSTRACT

In diesel engines with a straight intake port and a lipless cavity to restrict in-cylinder flow, an injector with numerous small-diameter orifices with a narrow angle can be used to create a highly homogeneous air-fuel mixture that, during PCCI combustion, dramatically reduces the NO_x and soot without the addition of expensive new devices.

To further improve this new combustion concept, this research focused on cooling losses, which are generally thought to account for 16 to 35% of the total energy of the fuel, and approaches to reducing fuel consumption were explored. First, to clarify the proportions of convective heat transfer and radiation in the cooling losses, a Rapid Compression Machine (RCM) was used to measure the local heat flux and radiation to the combustion chamber wall. The results showed that though larger amounts of injected fuel increased the proportion of heat losses from radiation, the primary factor in cooling losses is convective heat transfer. Next, 3D simulations were used to predict the cooling loss behavior over the entire combustion chamber, and in conjunction with local heat flux measurements on an actual engine, an analysis was performed to determine where cooling losses are significant and when these cooling losses occur. The results showed that because of the convective heat transfer from the reversed squish flow while the piston is descending, the cooling losses were greatest along the side wall of the cavity to the squish region.

Based on the findings above, a piston cavity was designed that suppresses reversed squish flow. The shape of this shallow-dish open-chamber cavity suppressed reversed squish flow including local flow, resulting in reduced fuel consumption.

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INTRODUCTION

Recently, there has been an increasing awareness of environmental and energy problems, which are global in scale. Diesel engines have better fuel consumption than gasoline engines, and there are great hopes for them because they are more flexible in terms of fuel diversification. However, diesel engines have more NO_x and smoke than gasoline engines, and thus require expensive fuel injection components and emission control devices to clean these emissions.

Inagaki et al. [1] proposed a new combustion concept that reduces NO_x significantly below the Euro6 standard by operating PCCI (Premixed Charge Compression Ignition) in diesel engines that have highly dispersed spray from injectors with numerous small-diameter orifices with a narrow angle combined with low in-cylinder flow. A schematic diagram of an engine for the new combustion concept is shown in [Figure 1](#), and the basic specifications of the engine are shown in [Table 1](#). The engine is based on a direct-injection diesel engine found in commercially available vehicles in Europe. A

low pressure loop (LPL) EGR system was added to the original engine, which has a conventional high pressure loop (HPL) EGR system. The engine for the new combustion concept is using conventional diesel engine injection components to control costs, and have multi-orifice nozzles with orifices that are smaller than in conventional diesel engines. This type of nozzles with numerous small-diameter orifices can form the highly dispersed spray which can promote the entrainment under the restricted in-cylinder flows. One of an image of the highly dispersed spray is shown in [Figure 1](#). However, this type of nozzles has increased smoke because of the weak penetration of the spray; leading to decreased overall load performance. To resolve this problem, the compression ratio was decreased to 14:1. The low compression ratio makes diffusive combustion phasing advance with early injection timing. This results in lower soot emissions because enough time is created to oxidize soot before the end of combustion. Further, to restore the poor cold startability due to the decreased compression ratio, a straight intake port was adopted to achieve a near-zero swirl ratio. A lipless shallow-cavity (referred to below as the “standard cavity”) was also adopted to suppress squish flow. This cavity suppressed convective heat transfer and achieved the required in-cylinder temperature to restore the poor cold startability.

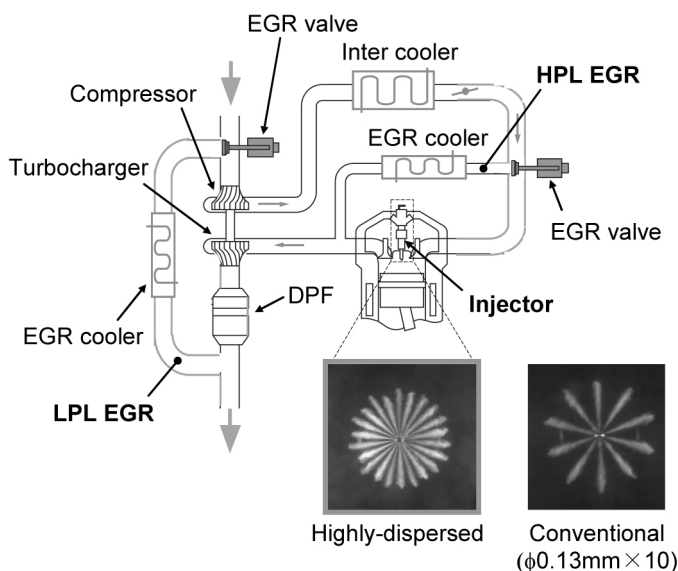


Figure 1. Schematic diagram of engine and highly-dispersed spray by numerous small-diameter orifices

Table 1. Specifications of engine

Engine type	4-cylinder DI Diesel (2AD-FHV, TOYOTA)
Bore × Stroke (mm)	86 × 96
Displacement (cm ³)	2231
Compression ratio	14.0 : 1
Swirl ratio	0.3
Combustion chamber	Lip-less Shallow
Diameter of piston bowl (mm)	φ58
Fuel injection system	Common rail (DENSO)
Discharge coefficient of orifice	0.94
Orifice diameter (mm)	φ0.08
Number of orifice	18
Include angle	140deg.

[Figure 2](#) shows a trade-off curve between NO_x emission and fuel consumption in an equivalent New European Driving Cycle (NEDC) [2]. The new combustion concept can offer less than a half of NO_x of Euro6 standard. On the other hand, the new concept increases unburned fuel (HC and CO), which is a characteristic of PCCI combustion; fuel consumption is about the same as conventional diesel combustion. [Figure 3](#) shows a comparison of the heat balance between conventional and new combustion concept in the equivalent NEDC [2]. The unburned fuel loss of the new concept is larger than that of conventional diesel combustion. However, the exhaust loss of the new concept is lower than that of conventional diesel combustion, because PCCI combustion can offer a high degree of constant volume energy release, which results in lower exhaust gas temperature. Because the lower gas temperature causes a lower intake pressure which increases the fuel consumption on PCCI combustion [3], the intake pressure is optimized by a variable geometry turbocharger. In addition, the restricted in-cylinder flows can suppress convective heat transfer to the combustion chamber wall; the cooling loss of the new concept is about the same as conventional diesel combustion. As a result, the new combustion concept can achieve low NO_x without deteriorating fuel consumption.

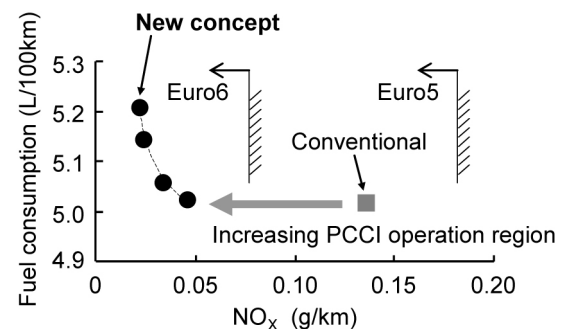


Figure 2. Trade-off curve between NO_x emission and fuel consumption in equivalent NEDC [2]

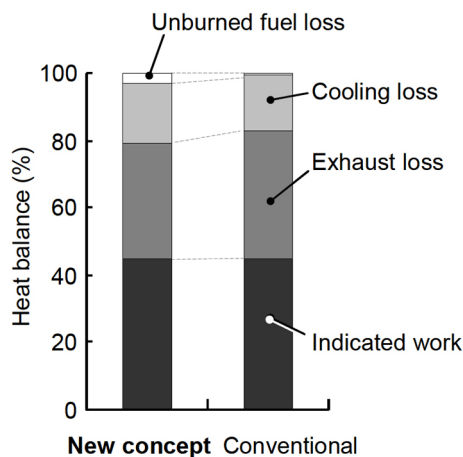


Figure 3. Heat balance in equivalent NEDC [2]

Hashizume et al. [4] investigated the mechanism of the emission of unburned fuel and explored ways to decrease fuel consumption by reducing the amount of unburned fuel. The results showed that the primary factor for the emission of unburned fuel during PCCI combustion is incomplete combustion of the combustion chamber space (bulk), and though unburned fuel can be reduced by suppressing the amount of EGR gas, there is an issue with worsened combustion noise. Thus there is a need to develop technologies to decrease fuel consumption working from new perspectives.

This research focuses on cooling losses to explore new ways to decrease fuel consumption. Cooling losses are thought to account for 16 to 35% of the total energy of the fuel [5]. As CO₂ restrictions grow more stringent going forward, the development of technologies to reduce cooling losses is necessary [6] to further decrease the fuel consumption of diesel engines. The cooling loss of the new concept still accounts for about 20% and has some leeway to reduce fuel consumption. Generally, combustion in diesel engines is promoted by the mixture of the fuel spray with air through in-cylinder flow, and combustion occurs diffusively. Poor local mixing of fuel and air leads to soot particles and a luminous flame. Because of this, diesel engines have significant radiation from luminous flames, and it is said that the contribution of radiation in cooling losses cannot be ignored. Because of this, the proportion of radiation in cooling losses have been investigated by many researchers, and the estimates vary widely from about 10% [7][8] to over 30% [9][10]. The combustion in the new concept is combined PCCI with the diffusive diesel combustion at a high load, although it is just PCCI combustion at a low load. Therefore, there is a possibility that radiation is increasing by a luminous flame at a high load.

This research started by using a Rapid Compression Machine (RCM) to analyze the local heat flux and radiation to the combustion chamber wall during this combustion. This revealed the contribution of radiation in cooling losses on the

new combustion concept. Next, 3D simulations were carried out in addition to measurements of instantaneous heat flux to the piston wall, cylinder head wall, and cylinder block wall using thin-film thermocouples in order to determine where there are significant cooling losses in the cylinder and when these cooling losses occur. Based on these findings, the cooling loss mechanism resulting from this new combustion concept was observed, and approaches to improving fuel efficiency by decreasing cooling losses were explored.

EXPERIMENTAL APPARATUS

In this research, both convective and radiant heat transfer are measured in the RCM, and convective heat transfer is also measured in a test engine, which is same as the engine presented in the introduction section. In addition, 3D simulation is used to predict the cooling loss behavior over the entire combustion chamber.

RAPID COMPRESSION MACHINE (RCM)

Figure 4 shows the RCM, which was used to measure local heat flux and radiant heat flux to the combustion chamber wall. A high-temperature, high-pressure atmosphere is created when a cam linked to an air cylinder is rapidly driven using compressed air, and the curved surface of the cam drives the piston, which compresses the in-cylinder air in the combustion chamber and makes it flow [11].

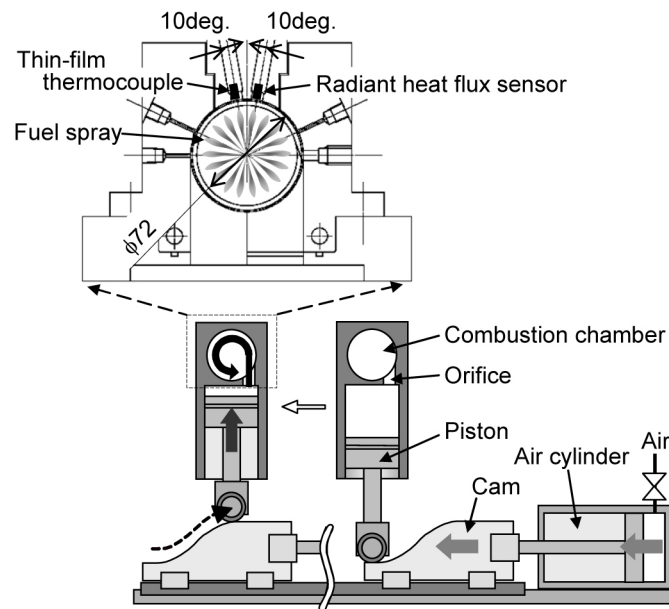


Figure 4. Schematic diagram of Rapid Compression Machine

The RCM combustion chamber is a cylinder 20mm high with a diameter of 72mm, and differs from an actual engine with cavity. Also, there is no expansion stroke, and the in-cylinder flow behavior differs from that of an actual engine. However, the RCM has a quartz observation window through

which the entire combustion chamber can be viewed. The advantage of this is that the combustion behavior can be observed and the local heat flux and radiant heat flux can be measured simultaneously. Because of this, this research used this RCM to analyze the contribution of radiation in cooling losses.

The thin-film thermocouples for measuring the local heat flux and radiant heat flux sensors were installed in the RCM combustion chamber. Though the radiant heat flux is homogeneously distributed even if the flame is not homogeneously distributed [7], local heat flux depends on the state of the flame, so the effect of the measurement location is significant [12]. Thus in this research, the radiant heat flux sensors were installed where the spray collides with the combustion chamber wall, and the thin-film thermocouples used to measure local heat flux were installed in bilaterally symmetric locations with respect to the center axis of the spray. Also, a pressure transducer (Kistler 6125B) was installed in the combustion chamber wall to measure the combustion pressure. The signals from the thin-film thermocouples and radiant heat flux sensors are amplified 500 times by the DC amplifier (Kyowa Electronic Instruments DA-510B), and, together with the signal from the pressure transducer, are acquired by the data recorder (Yokogawa Electric DL-1640). In addition to the measurements of local heat flux and radiant heat flux, a high-speed camera (Photron FASTCAM SA1.1) was used to visually record the combustion behavior. The speed of the camera is 20,000fps, and the resolution is 512×512 pixels.

SENSORS FOR MEASURING HEAT FLUX

The local heat flux was measured by thin-film thermocouples employing the method used by Enomoto et al. [13]. The structure of the thin-film thermocouples, which are custom-made, are shown in Figure 5. To decrease the heat capacity and increase the response time of the surface temperature-measuring junction, the junction was formed by sputtering a thin layer of gold between 0.13mm diameter Constantan wire inserted in the center of the sensor to the body of the sensor. The back temperature-measuring junction is formed from 0.13mm diameter Constantan wire and Chromel wire. The directions of heat conduction were taken into consideration before installing the thin-film thermocouples. The local heat flux to the combustion chamber was calculated by setting the surface and back temperature measurements as the boundary conditions and using numerical analysis to find the first-order temperature distribution within the thin-film thermocouple [14]. The thickness of the gold layer is around $5\mu\text{m}$ to $7\mu\text{m}$, which impacts a response time of the thin-film thermocouple. The measurements of the local heat flux shown below include less than 0.5ms delay in the response. However, no compensation was applied in this research because validation results of the

instantaneous heat flux between measurement and 3D simulation were favorable.

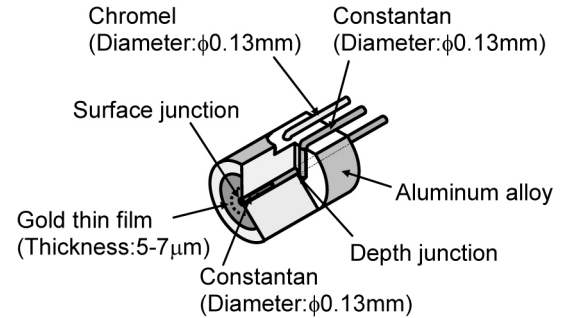


Figure 5. Thin-film thermocouple for heat flux measurement

The local heat flux obtained from the thin-film thermocouples was made up of the convective heat transfer and radiant heat flux. Thus, radiant heat flux was measured at the same time to determine the contribution of radiation in cooling losses.

The structure of the radiant heat flux sensor is shown in Figure 6. The radiant heat flux sensor has a detector (Captec Enterprise RFD03) comprised of areas with two different emissivity characteristics, and the radiant heat flux is measured based on the temperature difference. A sapphire window was used to protect the detector from the combustion flame, which is the method used by Oguri et al. [15]. The transmissivity of the sapphire window is changing with temperature of an emitter. Figure 7 shows the relationship between temperature of an emitter and transmissivity of a sapphire. The sapphire window transmits 85% of the radiant heat flux emitted by the luminous flame. The measurements shown below have been compensated using this value. The transmissivity of the sapphire decreases less than 800K. It means that the radiation from the wall, whose temperature is 433K, cannot transmit the sapphire window.

However, this does not impact the measurement. Because, according to Stefan-Boltzmann law, radiation from luminous flame is much larger than radiation from the chamber wall. In addition, the radiant heat flux sensor's detector has a 60ms delay. Thus the measurements shown below have been compensated using Equation (1).

$$V_{inst} = V_{raw} + C \frac{dV_{raw}}{dt} \quad (1)$$

where V_{inst} is the instantaneous radiant heat flux, V_{raw} is the experimental raw value of the radiant heat flux, and C is the delay of the radiation sensor. The radiant heat flux compensated using Equation (1) was also validated by two color temperature radiometry.