

A New Piston Insulation Concept for Heavy-Duty Diesel Engines to Reduce Heat Loss from the Wall

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ABSTRACT

To reduce heat transfer between hot gas and cavity wall, thin Zirconia (ZrO_2) layer (0.5mm) on the cavity surface of a forged steel piston was firstly formed by thermal spray coating aiming higher surface temperature swing precisely synchronized with flame temperature near the wall resulting in the reduction of temperature difference. However, no apparent difference in the heat loss was analyzed. To find out the reason why the heat loss was not so improved, direct observation of flame impingement to the cavity wall was carried out with the top view visualization technique, for which one of the exhaust valves was modified to a sapphire window. Local flame behavior very close to the wall was compared by macrophotography. Numerical analysis by utilizing a three-dimensional simulation was also carried out to investigate the effect of several parameters on the heat transfer coefficient. From the observation of wall impinged flame, it was revealed that a kind of thermal boundary layer with Zirconia coating was thinner than the baseline, which could be resulted in the increase in heat transfer coefficient. Furthermore, the numerical simulation results suggested that higher wall surface temperature swing with Zirconia coating is not the main cause of thinner boundary layer, but surface roughness and/or porous structure is. To confirm the hypothesis, new pistons with different insulating structures were then experimented. Even though the heat loss was not so improved because of the limited area of insulation, the potential for BTE improvement was confirmed.

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INTRODUCTION

Thermal efficiency improvement is a primary target for the current engine developments, in order to meet both customer and social demands for energy consumption reduction, even for diesel engines. To achieve higher thermal efficiency, one may look to reduced losses in the exhaust energy losses, wall heat losses, mechanical losses and pumping losses. Wall heat loss reduction reminds a priority issue, since there is little influence by current state of the art emission reduction technologies represented by aftertreatment catalysts and/or turbocharging. Previous studies have confirmed several effective wall heat loss reduction approaches; those are temperature difference (ΔT) from in cylinder gas to the cylinder wall reduction by decreasing in-cylinder gas temperature [1], heat transfer coefficient reduction by lower in-cylinder gas velocity [2], and reduction in spray flame impingement on the combustion chamber wall. On the other hand, increased gas temperatures associated with a reduction in wall heat losses are not always effectively transformed into the brake or indicated work [3]. From these results, thermodynamic cycle efficiency (or work extraction efficiency) impact is needed to consider when wall heat loss reduction is achieved, in order to obtain further thermal efficiency improvement. However, if the geometric compression ratio is increased to achieve higher thermodynamic cycle efficiency, heat loss to the wall would be increased even further.

One of the options to reduce the heat loss is to suppress the spray flame impingement to the wall by narrower nozzle orifice and wider chamber diameter. But the recent design trend towards smaller bore diameter and cylinder volume (engine downsizing) and higher injection pressure, could make it difficult. The other option is to insulate heat flux at the wall surface. Several decades ago, diesel engines made by ceramics were studied to reduce heat transfer from in-cylinder gas [4]. At that time, however, heat loss was not so improved even with higher wall temperature (lower ΔT), rather combustion and emissions characteristics were seriously deteriorated [5]. In comparison with the past approach, new approach (i.e. SiRPA [6]; TOYOTA's new insulating technique) based on aluminum piston is to reduce ΔT by increasing wall temperature swing precisely synchronized with the gas temperature swing during the entire cycle, resulting in the heat loss improvement.

In our previous study, the piston with shallow toroidal cavity was utilized to investigate the potential to reduce heat loss from the wall by the low thermal conductivity material. At first, Zirconia was coated only on the piston cavity surface intended to reduce the heat loss by the direct impingement of spray flame. The piston, of which cavity surface was thermal spray coated with thin Zirconia layer, was compared with that for baseline piston [7]. And, it was revealed from microscopic observation that Zirconia coated piston showed lower

flame tip temperature drop in the impingement area compared to the baseline steel piston. The thickness of Zirconia coating was designed to achieve such surface temperature swing by zero-dimensional non-steady thermal conductivity calculation. It was considered that this was due to differences in wall temperature and degree of heat insulation effect.

MOTIVATION AND PURPOSE OF THIS STUDY

Nevertheless, there were no improvements in cycle-averaged wall heat loss by the heat balance analysis [8] based on the same engine experiments with Zirconia coated piston and the baseline piston as shown in Fig. 1. On the contrary, BTE was deteriorated by the increase in energy losses. Furthermore, by means of the iron coated piston made with the same thermal spraying process, heat loss was deteriorated about 2 points even though the thermal characteristics of the material is almost the same with the baseline piston. These results were not consistent with the trend of flame tip temperature variation in the previous study. Serrano et al. [9] also experimentally revealed null or negative effect of piston insulation with Zirconia coating on the specific fuel consumption by utilizing multiple-cylinder heavy-duty diesel engine, even though the thickness and/or other specifications of Zirconia layer may be different from us.

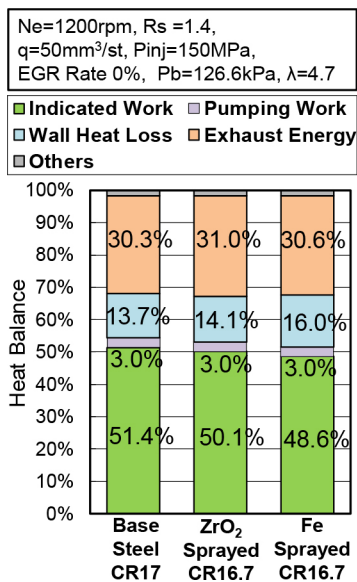


Figure 1. Comparison of Heat Balance for Zirconia and Cast Iron Spray Coated Pistons with That for Baseline Piston

From this result, it should be noted that the major factor of heat loss is not only the insulating material at the spray flame impinging point, but others, e.g. surface structure, instantaneous surface temperature variation, gas flow velocity at very close to the wall, and so on. In order to obtain a fundamental knowledge about the heat loss phenomena with the wall impinged spray flame for evolving cutting-edge technologies, local flame behavior near the piston cavity circumference wall was firstly observed and heat loss variation with various boundary conditions of the wall including surface roughness and averaged surface temperature was then investigated by a three-dimensional numerical simulation (AVL FIRE™).

The purpose of this study is to provide a new in-cylinder surface insulating technique for reducing heat loss effectively. Two options of revised heat insulating piston were designed based on the findings from the combustion observation and the numerical simulation analysis. The experimental results of both two pistons indicated the heat loss reduction not only part load conditions, but higher load conditions. Furthermore, BTE was simultaneously, but still slightly improved by one of them.

EXPERIMENTAL APPARATUS

Engine and Fuel Specifications

The engine used for this study was based on a single cylinder direct-injection, heavy-duty diesel engine, with detailed specifications shown in Table 1. The engine equipped with a forged steel piston with a shallow toroidal type cavity as a baseline specification. The cross section of the piston is shown in Fig. 2. The engine is also equipped with an electronically controlled high pressure common rail fuel injection system with a maximum injection pressure of 300MPa (Denso G4S modified) and an electronically controlled hydraulically driven variable valve actuation system (Sturman Industries, DHVVA.) The test system layout is shown in Fig. 3. This engine system includes an idealized turbocharged/intercooled intake system, as well as a high pressure EGR system using both an externally driven intake supercharging device and an EGR pumping device. The system is capable of independent control of intake pressure, exhaust pressure, EGR rate, and intake temperature. A standard configuration used in this study was to match the exhaust back pressure to the intake boost pressure to eliminate external boost work, pressure drop in the EGR line, turbocharging efficiency variations, and also to minimize detriments associated with single exhaust valve operation. The fuel was low sulfur diesel fuel sold in the market (JIS No.2, 6 ppm of sulfur content) and the engine oil was also low sulfur content (JASO DH-2).

Table 1. Engine and Fuel Specifications

Engine Type	DI Single Cylinder 4 Valve
Displaced volume	2004 cc
Stroke	140 mm
Bore	135 mm
Maximum Engine Speed	2000 rpm
Swirl Ratio	1.4
Fuel Injector	Common Rail System (Maximum injection Pressure: 300 MPa)
Nozzle Orifice	Minisac Type, Φ0.181 mm x 9 holes, Spray Angle: 150°, Flow Rate: 1750 cm ³ /minute
Piston Type	Forged Steel Piston
Combustion Chamber	Shallow Toroidal (Cavity Diameter: Φ98 mm)
Compression Ratio	18:1
Valve Actuation	Camless VVA (Sturman Industries DHVVA)
Air Charging System	External Supercharger
Test Fuel	Diesel Fuel JIS #2, Cetane Number 47.0, Sulfur Content 6 ppm



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The most engine tests and numerical simulations were carried out at the baseline operating point as shown in Table 2. This part load test condition was chosen from several test cycles, e.g. WHTC, WHSC, and JE05 as the typical point of most frequent real-world operating condition of current heavy-duty commercial vehicles (having a major contribution for vehicle fuel economy.) Furthermore, at this operating point, many parameters' effects are extensively evaluated by the engine without any constraints defined by the engine design limits. For the EGR rate in this study, we selected 0% to maximize the wall heat loss, aiming to find out the effective measures under the critical conditions for reducing it.

Table 2. Baseline Engine Operating and Numerically Simulated Condition

Engine Speed	1200 rpm
Fuel Injection Quantity	120 cm ³ /st (about 0.8MPa BMEP)
Fuel Injection Pressure	200 MPa
EGR Rate	0 %

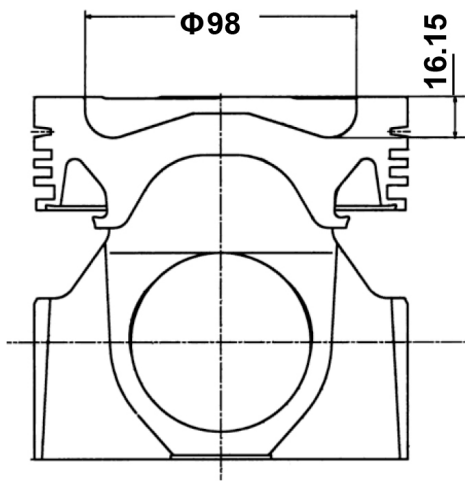


Figure 2. Cross-Section of the Piston and Combustion Chamber Shape (Compression ratio of 18:1)

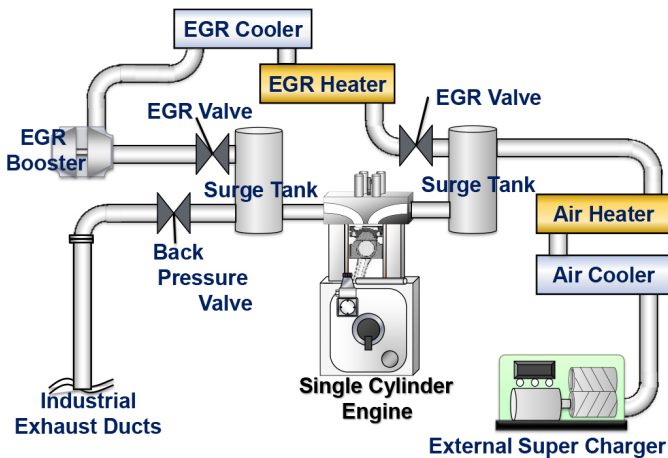


Figure 3. Experimental Engine System Layout

Top View Visualization System

Top view visualization system which observed in-cylinder combustion phenomena with a high speed digital camera was utilized to investigate the detailed flame structure for revealing the influence of local flame temperature and instantaneous flame movement on heat loss to the wall.

As shown in Fig. 4, the top view visualization system utilized a sapphire window in the cylinder head, located where one of the exhaust valves previously existed, by modifying exhaust port from Siamese style to straight type. The observable field of view covers the combustion chamber wall circumference where one of the spray flames impinges. Compared with bottom view technique, top-view visualization allows use of actual engine materials and combustion chamber shape, except for the single exhaust valve configuration. Thus, the effect of wall material and/or combustion chamber wall shape can be examined. For safety and convenience of optical adjustment, the optical passage above the window was fitted with a 45 degree inclined flat mirror to the direction of a high speed digital camera. The reflectivity of the mirror was nearly flat over the whole visible light wavelength range. The high-speed digital camera used in this study was a FASTCAM SA-Z (PHOTRON Ltd.) equipped with a 200mm macro lens. For the magnified observation very close to the cavity wall, four inline teleconverters (three 2xs and one 1.4x) were inserted between the lens and camera body. The camera was utilized for capturing the images of 6.7mm square with 1024 pixel square resolution at 14,400 fps (0.5 degrees crank angle per frame at 1200 rpm.)

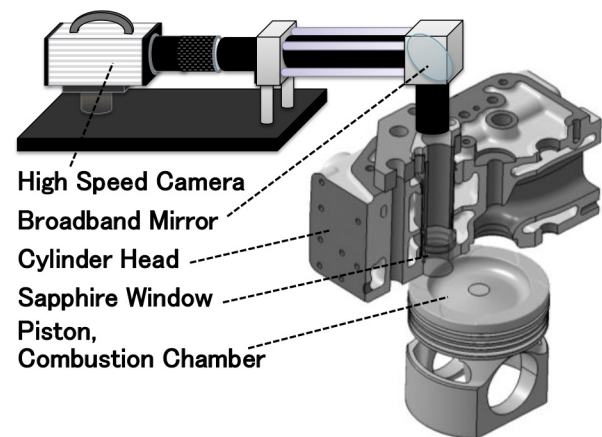


Figure 4. Top-View Combustion Visualization System

Since the top view combustion observation is based on the flame luminosity itself (no other reference light sources), it is difficult to identify the position of the flame impinged wall by flame quenching at very close to the wall even after flame impingement occurs. So, squish area of all the pistons utilized in the top view combustion observation was painted with heat-resistant silver and then radially and tangentially marking-off by 1mm space (see Fig. 5.) The combustion chamber utilized in the test was a shallow-dish toroidal type (that is the edge of squish area is the side wall of the cavity),