



Special Feature: Challenges of Internal Combustion Engines for Achieving Low-carbon Society

Research Report

Reduction of Cooling Heat Loss and Improvement of Thermal Efficiency by Application of “TSWIN” to Direct-injection Diesel Engines

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■ABSTRACT■ The reduction of cooling heat loss from the in-cylinder gas to the combustion chamber wall is one of the key technologies for improving the thermal efficiency of internal combustion engines. This paper describes the experimental verifications of “Thermo-Swing Wall Insulation Technology (TSWIN)” and performances that can reduce heat loss to the coolant without any deterioration of engine performances. First, heat flux measurements are applied to the developed insulation coating of “Silica Reinforced Porous Anodized Aluminum (SiRPA)” and show both heat-rejection potential and stable heat insulation performance in an internal combustion engine. Second, SiRPA coating is applied to turbocharged direct-injection diesel engines and achieves cooling heat loss reduction by means of heat rejection and increases not only the exhaust energy but also the piston work, both of which improve the thermal efficiency. Finally, TSWIN shows remarkable improvements of both fuel efficiency and NOx emission in the low temperature engine start condition.

■KEYWORDS■ Diesel Engine, Cooling Heat Loss, Heat Insulation, Heat Flux, Thermal Efficiency, Experimental Verification

1. Introduction

To improve the thermal efficiency of an internal combustion engine, it is essential to reduce all losses including cooling heat loss, exhaust loss, pumping loss and friction loss. Particularly, a reduction in cooling heat loss from the in-cylinder gas to the combustion chamber walls is regarded as an effective means of increasing not only the exhaust energy but also the piston work. This leads to improvement of the thermal efficiency of an internal combustion engine.

Many insulation technologies in the 1980s⁽¹⁻³⁾ led to problems of deterioration of the intake air charging efficiency and an increase in NOx emission because a ceramic wall with low thermal conductivity instead of conventional materials such as aluminium alloy or iron alloy results in the high surface temperature during both the intake and compression strokes and heats up the air in the cylinder.

To overcome these problems, temperature swing insulation, whereby the surface temperature of the combustion chamber wall follows that of the transient gas, was proposed and investigated as a new heat insulation technology.⁽⁴⁻⁹⁾

In our previous study, Kosaka et al.⁽⁷⁾ evaluated the appropriate thermo-physical properties and thickness for “Thermo-Swing Wall Insulation Technology (TSWIN)” in spark-ignition (SI) and compression-ignition (CI) engines to clarify the effect of the insulation coating on the thermal efficiency. The calculations show that the rate of improvement of the thermal efficiency increases as the thermal conductivity and volumetric heat capacity fall.

Nishikawa et al.⁽¹⁰⁾ developed new insulation coatings of “Silica Reinforced Porous Anodized Aluminum (SiRPA)” with low thermal conductivity, low volumetric heat capacity and high temperature durability.

This paper describes the experimental verifications of the TSWIN concept and performances that can reduce heat loss to the coolant without any deterioration of engine performances. First, heat flux measurements are applied to the developed insulation coating of SiRPA and show both heat-rejection potential and stable heat insulation performance in an internal combustion engine. Second, SiRPA is applied to turbocharged direct-injection diesel engines and achieves the cooling heat loss reduction by

means of heat rejection and increases not only the exhaust energy but also the piston work, both of which increase the thermal efficiency. Finally, TSWIN shows remarkable improvements in both fuel efficiency and NOx emission in the low temperature engine start condition.

2. Concept of TSWIN

In general, the cooling heat loss Q' from the in-cylinder gas to the combustion chamber wall of an internal combustion engine is defined by Eq. (1).

$$Q' = A \times h_g \times (T_{gas} - T_{wall}) \tag{1}$$

where A : surface area, h_g : heat transfer coefficient, T_{gas} : in-cylinder gas temperature, T_{wall} : wall temperature.

TSWIN is a cooling heat loss reduction technology that decreases the temperature difference between T_{gas} and T_{wall} by quickly changing the wall temperature following the transient gas temperature. **Figure 1** is a conceptual schematic diagram of the working gas temperature and surface temperatures with different combustion chamber walls corresponding to a metal wall, a traditional heat insulation wall and TSWIN coating.

The surface temperature of the “metal wall” in Fig. 1 remains almost constant during the entire engine cycle. The surface temperature of “thick ceramics” in Fig. 1 features a constant high temperature during the entire cycle including the intake stroke. This fact results in a lower charging efficiency and an increase in the

working gas temperature, which leads to deterioration of the power and an increase in exhaust emissions, as well as the occurrence of engine knock in SI engines. The surface temperature of “Thermo-swing (TSWIN)” in Fig. 1 rises during the combustion period, and then drops during the exhaust and intake strokes. As a result, the cooling heat loss decreases during the combustion period, and the intake air is prevented from being heated.

Figure 2 shows the thermo-physical properties of the metal, heat insulation materials, and air. The ceramics barrier coatings (\square, \blacksquare in Fig. 2) used in traditional insulation has low thermal conductivity compared to metals of aluminium and iron alloy ($\triangle, \blacktriangle$ in Fig. 2). The coating material for TSWIN needs a low thermal conductivity and a low heat capacity relative to traditional insulations. The detailed structure and the thermo-physical properties of TSWIN are described in Secs. 3 and 4.3.

3. Insulation Coating

A large fluctuation in the surface temperature of an insulation coating formed on the combustion chamber wall requires low thermal conductivity λ and low volumetric heat capacity C_v , as described in the previous paper.⁽⁷⁾ Equations (2) and (3) define the correlation between λ and C_v .

$$\lambda = \rho \times C \times K, \tag{2}$$

$$C_v = \rho \times C, \tag{3}$$

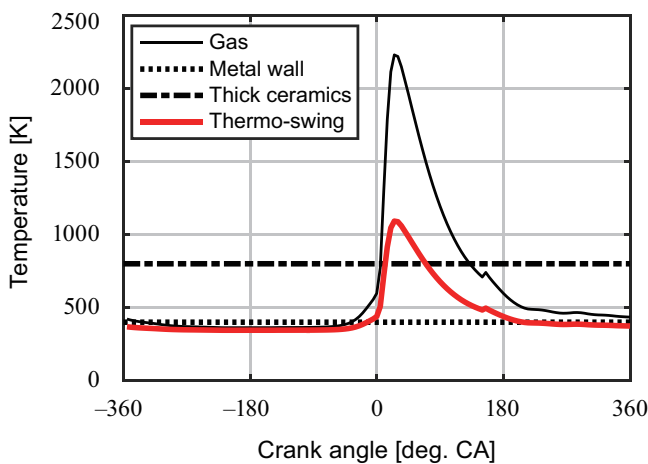


Fig. 1 Transient gas and piston/coating surface temperature showing dependence of coating materials during the entire engine cycle.

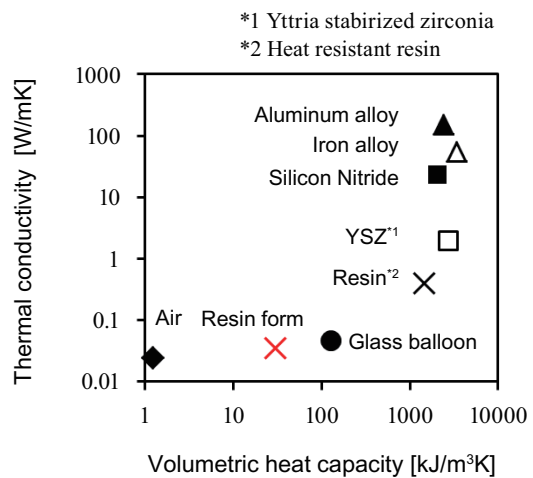


Fig. 2 Thermo-physical properties of metal and insulation materials.

where C is the specific heat capacity and K is the thermal diffusivity.

Since λ and C_v are proportional to ρ , low density is obviously essential to satisfy both the low thermal conductivity and the low volumetric heat capacity. Therefore, the insulation coating must include a large amount of air to reduce its density. In addition, the insulation coating must have high heat resistance since the high-temperature in-cylinder gas and flame make contact with the surface of the insulation coating.

In this study, two types of porous alumina structures with an oxide of the aluminium alloy used as the piston material are investigated, as listed in **Table 1**.

Insulations A and B have a thickness of approximately 100 μm and a high porosity of 50% with two types of pore diameters. One is a minute pore with a diameter of 10–30 nm with a structure consisting of circular cylinders formed perpendicular to the surface. This type of pore is called a “nano-pore.” The other is a relatively large pore with a diameter of about 1–10 μm , which is formed above the crystallized silicon since the anodizing aluminum grows in such a way that it avoids the silicon. This type of pore is called a “micro-pore.”

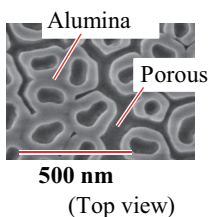
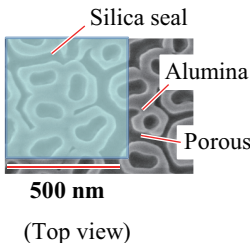
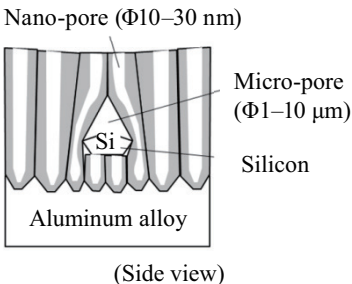
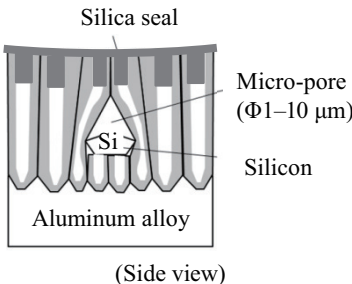
As the nano-pores reach the bottom of the insulation layer, there is a risk of the high-temperature and high-pressure in-cylinder gas passing through the pores during the compression and combustion strokes, which would deteriorate the insulation performance. To prevent this problem, Insulation B has a silica coating over the surface of Insulation A with a thickness of a few microns. This silica-coated porous anodized aluminium (SiRPA) not only seals the in-cylinder gas intrusion but also reinforces the coating.⁽¹⁰⁾

4. Experimental Apparatus

4.1 Heat Flux Measurement with a Single-cylinder Engine

A heat flux sensor with a diameter of 6.2 mm was developed for measuring the cycle-averaged heat flux from the in-cylinder gas to the insulation coating during the overall engine cycle. The insulation coating was formed on the top of the sensor body, and the sensor body was attached to the cylinder head such that the top surface of the sensor faced the combustion chamber.

Table 1 Candidates for TSWIN.

Insulation A	Insulation B
Porous anodized aluminum	Silica reinforced porous anodized aluminum (SiRPA)
 <p>Alumina Porous 500 nm (Top view)</p>	 <p>Silica seal Alumina Porous 500 nm (Top view)</p>
 <p>Nano-pore (Φ10–30 nm) Micro-pore (Φ1–10 μm) Si Silicon Aluminum alloy (Side view)</p>	 <p>Silica seal Micro-pore (Φ1–10 μm) Si Silicon Aluminum alloy (Side view)</p>

Since only the top surface of the sensor body is provided with an insulation coating when measuring the heat flux of the insulation coating, the area of the formed insulation coating is small relative to the overall surface of the combustion chamber, namely, piston, head and cylinder liner. Therefore, there are no differences in the heat release rate patterns of the injected fuel with and without the insulation coatings on the top of the sensor body.

The error incurred as a result of differences between individual heat flux meters was eliminated by comparing the cycle-averaged heat flux before and after the forming of the insulation coating using the same sensor body. Changes in the injected fuel quantity and air flow rate were held to within 0.5% during the data measurement to reduce the error in the data.

The specifications of the single-cylinder research direct-injection diesel engine with a common-rail injection system, as used in this study, are listed in **Table 2**. The cylinder has a bore of 86 mm, a stroke of 96 mm, a displacement of 550 cm³ and a compression ratio of 14.1. The injection system used is a piezo type with a mini sac nozzle. The combustion chamber is a lipless shape with a diameter of 58.7 mm, as shown in **Fig. 3**. The engine operating conditions are listed in **Table 3**. Conditions 1 and 2 correspond to light load and high load conditions, respectively.

4.2 Engine Performance Test with a Four-cylinder Engine

The specifications of a four-cylinder turbocharged diesel engine with a state-of-the-art combustion system and engine calibration are given to meet Euro6 exhaust emission regulations, and to verify the fuel consumption and cooling loss reduction effect in actual operating condition. **Table 4** shows the engine specifications and evaluation conditions. **Figure 4** shows the schematic drawing of the piston cavity shape. Piston cavity shape, injection spray geometry and intake swirl ratio are well designed and calibrated to reduce cooling heat loss by suppressing squish and swirl velocity.⁽¹⁾ Two specifications are selected for the application area of the insulation coating: over the whole top surface of the piston, and excluding the piston cavity, which was left as the original machine metallic surface, as shown in **Fig. 5**.

Table 2 Specifications of single-cylinder research diesel engine.

Bore [mm] × Stroke [mm]	86 × 96
Displacement [cm ³]	550
Compression ratio	14.1
Port swirl ratio	2.3
Fuel injection system	Common Rail
Hole diameter [mm] × Hole number	0.098 × 9
Cone angle [°]	153

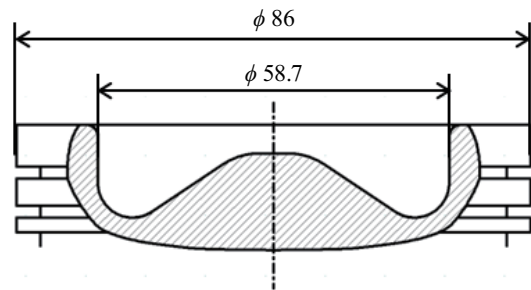


Fig. 3 Schematic of lipless piston cavity for a single-cylinder research engine.

Table 3 Experimental conditions for single-cylinder research engine.

	Condition 1	Condition 2
Engine speed [rpm]	1380	2000
Common rail pressure [MPa]	55	100
Fuel injection quantity [mm ³]	15	40
Charging efficiency [%]	95	130

Table 4 Specifications of four-cylinder turbocharged diesel engine and experimental condition.

Bore [mm] × Stroke [mm]	92 × 103
Displacement [cm ³]	2755
Compression ratio	15.6
Port swirl ratio	2.2
Fuel injection system	Common rail
Engine speed [rpm]	1400
Fuel injection quantity [mm]	10
EGR ratio [%]	40

4.3 Thermo-physical Properties of SiRPA

The thermo-physical properties of SiRPA are listed in **Table 5**. Using Eqs. (2) and (3) in Sec. 3, the thermal conductivity λ and volumetric heat capacity C_v are estimated from the bulk density ρ , specific heat capacity C , and thermal diffusivity K , as measured at 500 K, which is the temperature corresponding to the piston temperature after warming up. The specific heat capacity C is measured by differential scanning calorimetry (DSC). The thermal diffusivity of SiRPA is solved analytically from the measured thermal diffusivity of a double-layer test piece with a SiRPA

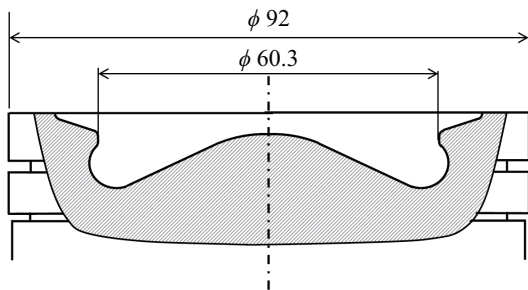


Fig. 4 Schematic of piston cavity for four-cylinder turbocharged diesel engine.

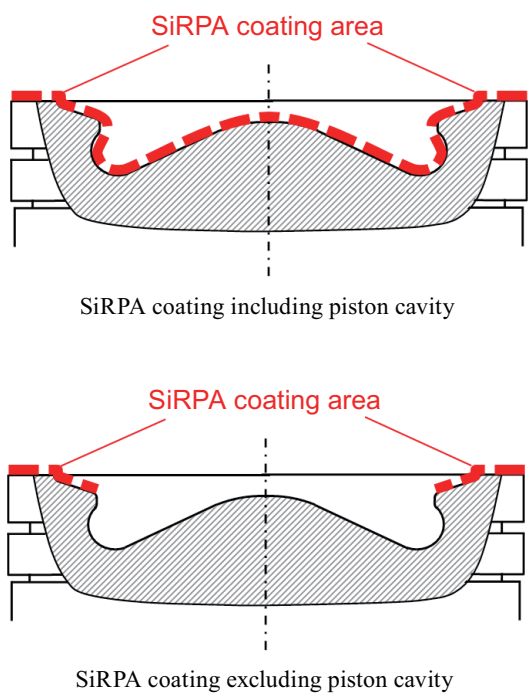


Fig. 5 Two cases of insulation coating application areas.

and aluminum alloy substrate by using a laser-flash methodology.

Figure 6 plots the thermo-physical properties of SiRPA and compares them with those of solid aluminum dioxide. SiRPA has a thermal conductivity of less than 1 W/mK and half the volumetric heat capacity of solid aluminum oxide due to the micro- and nano-pores.

5. Results

5.1 Heat Insulation Performance

The insulation performance of Insulations A and B as shown in Table 1 was evaluated by comparing the cycle-averaged heat flux with and without the insulation coating. Since the sensor body is capable of being attached to and removed from the cylinder head, the cycle-averaged heat flux with different insulation coatings can be compared relatively easily.

Figure 7 compares the cycle-averaged heat flux for Base and Insulations A and B under Condition 1, as listed in Table 3. Both Insulations A and B realize a cooling heat loss reduction. Specifically, the

Table 5 Thermo-physical properties of SiRPA.

Bulk density @500K [g/cm ³]	1.4 ± 0.15
Volumetric specific heat capacity@500K [kJ/m ³ K]	1300 ± 140
Thermal difusivity @500K [mm ² /s]	0.52
Thermal conductivity @500K [W/mK] (Calculated by Eq. (2))	0.67 ± 0.07

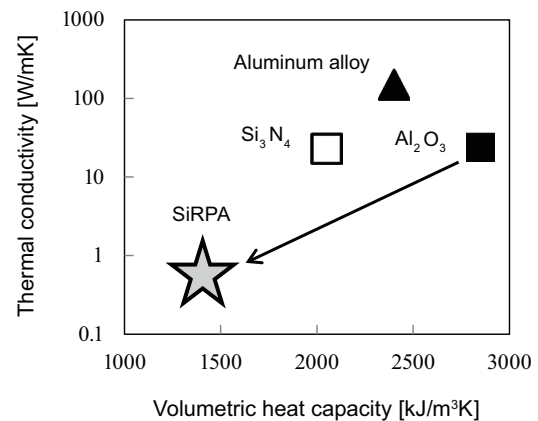


Fig. 6 Comparison of thermo-physical properties between SiRPA, ceramics and aluminum alloy.

cycle-averaged heat flux for Insulation B is lower than that for Insulation A, which means that there is an improvement in the insulation performance. **Figure 8** compares the insulation mechanisms of Insulations A and B. The silica coating over the surface of the porous anodized aluminum stops the in-cylinder gas from going inside through the nano-pores in Insulation A. As a result, a quantity of closed pores, which do not communicate with the outside gas, increase and improve the insulation performance relative to that of Insulation A. To ensure the stability of the insulation performance, the

cycle-averaged heat flux for Insulation B was compared before and after operating under Condition 2. The difference in the cycle-averaged heat flux before and after operating under Condition 2 was only 1%. In addition, the reliability of Insulation B was also confirmed from SEM images captured before and after engine operation.⁽¹⁰⁾

Given these insulation performance and reliability results, Insulation B is formed over the piston of a diesel engine and employed in the engine performance test. As shown in Sec. 3, Insulation B is named SiRPA.

5.2 Heat Balance Analysis

The heat balance was evaluated to verify the reduction effect of fuel consumption and cooling heat loss by using a four-cylinder turbocharged diesel engine in the operation condition shown in Table 4.

Figure 9 shows the cylinder pressure and rate of heat release for SiRPA coating cases when including the piston cavity and excluding the piston cavity. The heat release rate of the SiRPA coating excluding the piston cavity shows a slight increase after the top dead center compared to that of the baseline case, which is considered as an apparent increase in the heat release rate caused by heat loss reduction. Any significant delay in the combustion rate is not observed. **Figure 10** shows the improvement in fuel consumption of both heat insulating coating cases compared to the baseline engine without SiRPA coating. The fuel consumption improvement effect when the SiRPA was coated on the piston top surface excluding the piston cavity was much higher than the SiRPA coated including the piston cavity. In addition, since the increase of exhaust temperature was approximately 2°C for both

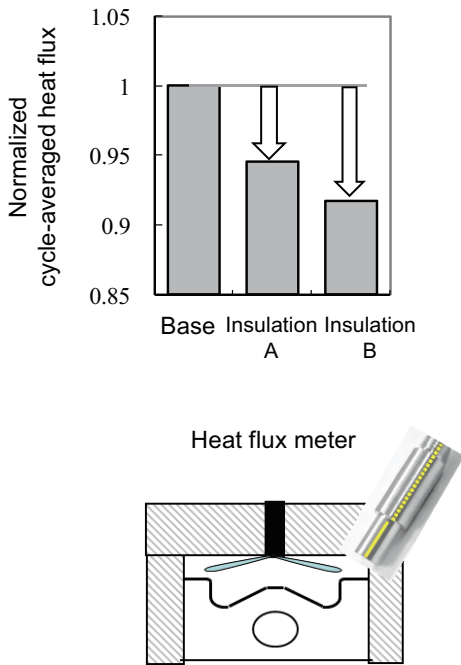


Fig. 7 Cycle-averaged heat flux and measuring location.

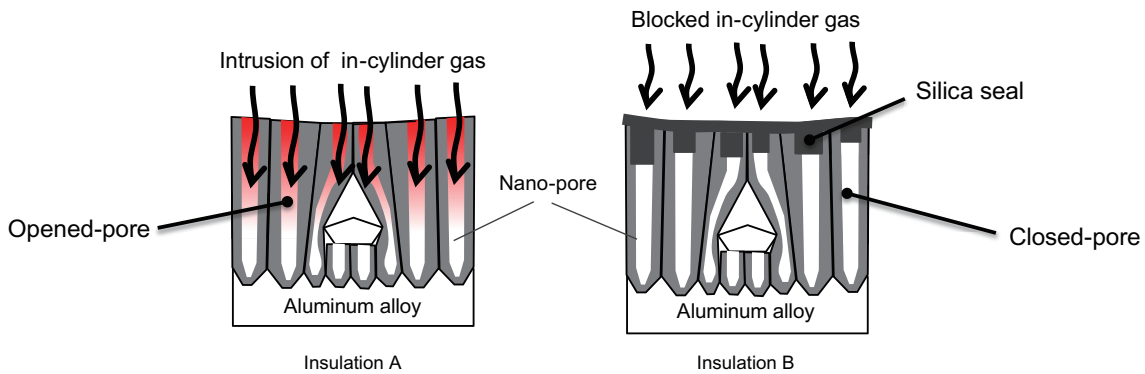


Fig. 8 Insulation mechanisms of A and B.

specifications, as shown in **Fig. 11**, this result cannot be explained simply by the insulating area ratio. Other factors revealed during the studies are presented in the following section.

This section focuses on the difference in the surface roughness between SiRPA and the machined metal wall. The surface roughness of the machined metal wall is less than Ra 1 μm . On the other hand, that of SiRPA is approximately Ra 3–5 μm , which is caused by the non-uniform anodized coating surface height generated in the micro-pore formation process. **Figure 12** shows the ISFC deterioration caused by a surface roughness change from Ra 1 μm to Ra 5 μm by increasing the EGR rate. From this graph, the ISFC deterioration due to the surface roughness should be significant with the higher EGR rate condition.

We assumed that the surface roughness influences

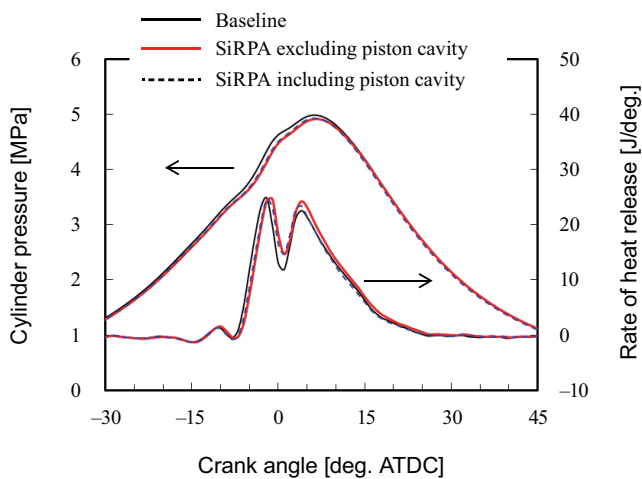


Fig. 9 Cylinder pressure and ROHR comparison with SiRPA coating on piston surface including cavity and excluding cavity.

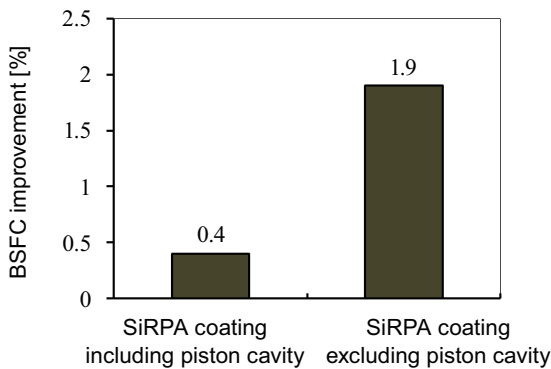


Fig. 10 BSFC improvement comparison with SiRPA coating on piston surface including cavity and excluding cavity.

combustion development mainly during the spray impingement in the piston cavity. Therefore, the spray and combustion phenomenon were optically investigated with a Rapid Compression Machine (RCM).⁽¹²⁾ The experimental conditions are already listed in **Table 6**. The surface roughness of the spray impinging wall was set to Ra 1.4 and 6 microns to clarify the effect of surface roughness.

Figure 13 shows direct observation photographs. In the case of surface roughness of Ra 1.4 micron, the impinged spray and flame move rapidly along the impinging wall surface and diffuses toward a wide area. On the contrary, in the case of Ra 6 microns, the fuel and flame move relatively slower along the wall. In the picture at 2.61 ms after start of injection the luminous flame still exists near the impinging surface. To more precisely investigate the above-mentioned

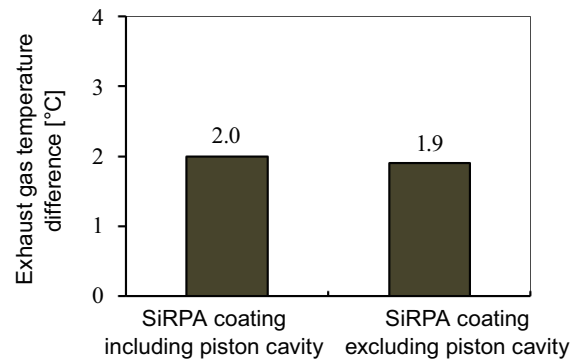


Fig. 11 Exhaust temperature difference comparison with SiRPA coating on piston surface including cavity and excluding cavity.

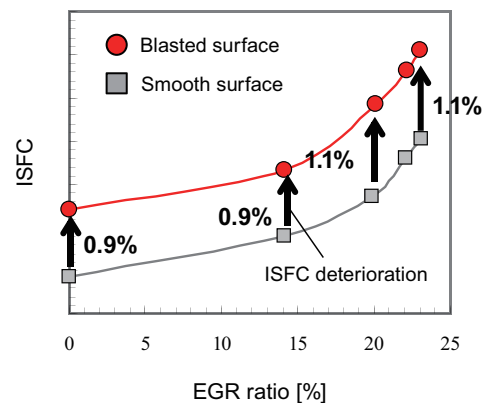


Fig. 12 ISFC deterioration by increase in metal piston surface roughness with various EGR rate.

phenomena, a CFD simulation was conducted. The simulation was performed using “Star-CD(R)” with Bai’s spray wall impingement model in conjunction with the standard wall function for a smooth surface or specification of Nikuradse’s sand-grain roughness height for a rough surface.⁽¹³⁾ To make the difference clearer, the roughness height was set as 100 microns, although it is higher than the actual SiRPA roughness. Engine operating speed and mean effective pressure were 2000 rpm and 1.64 MPa, respectively.

Figure 14 shows the distribution of the equivalence ratio and the gas temperature on the vertical cross section of the nozzle hole axis. In the case of a smooth surface, momentum reduction of the impinged spray

and the mixture on the combustion chamber wall is relatively small. After the impingement, the mixture direction changes along the cavity wall toward the protrusion of the piston cavity bottom and diffuses upwards. On the other hand, in the case of a rough surface, the mixture motion becomes slow, due to the reduced wall jet flow velocity, and the residence time in the cavity becomes long. Corresponding to this, a mass of high temperature gas stays for longer time in the cavity, and is considered to cause increased cooling heat loss.

Figure 15 shows the schematic drawing of mixture formation on the SiRPA coating piston. In case of SiRPA coating excluding the piston cavity, the surface roughness in the cavity is kept smooth, so the mixture formation progress rapidly. On the SiRPA coated part, the direction of spray and reverse squish flow are the same, so the influence of the surface roughness becomes smaller. As the result of these analyses, SiRPA coating excluding the piston cavity is considered as an effective

Table 6 Experimental condition for spray flame observation.

Injection pressure [MPa]	80
Fuel injection quantity [mm ³]	12
Nozzle diameter [mm]	0.12
Nozzle hole number	6
Ambient pressure [MPa]	4
Ambient temperature [K]	900
Swirl ratio	2

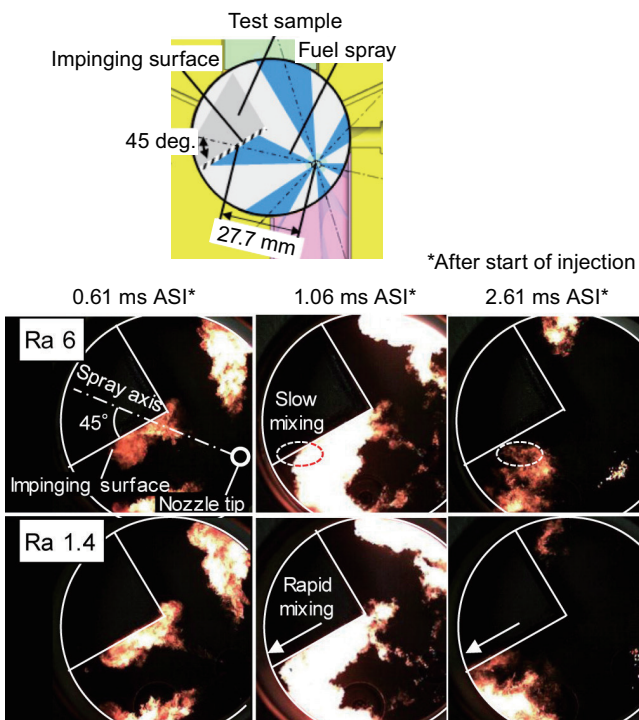


Fig. 13 Effect of surface roughness on flame mixing speed.

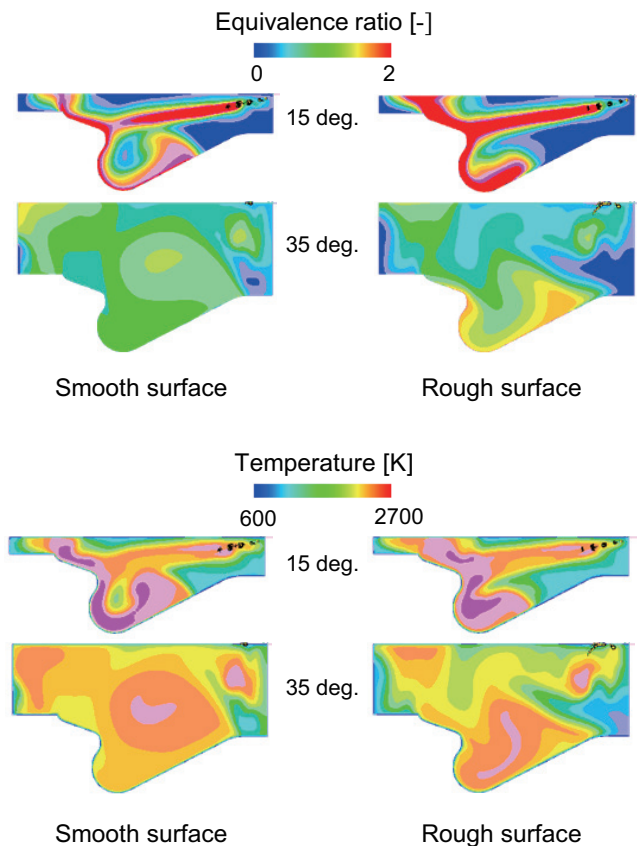


Fig. 14 Equivalence ratio and temperature distribution by CFD simulation (2000 rpm, Pme: 1.64 MPa).

methodology to utilize the insulation coat with the current surface roughness for a direct-injection diesel engine piston application. **Figure 16** shows the heat balance comparison between the baseline and SiRPA coating excluding the piston cavity in the operating condition of Table 4. The cooling heat loss is reduced, and both piston work and the exhaust energy increases.

5.3 Effects on Cold Start

Considering the future emission and fuel consumption regulations, performance after cold starting at low temperature of -7°C was examined. Specifications of the tested engine are the same as in Table 4, and the area of SiRPA coating excluding the piston cavity shown in Fig. 5 (left). The engine was soaked at -7°C , and the water and oil temperatures were the same at the engine starting time.

There was little difference between including and excluding the SiRPA coating regarding the time to

reach stable combustion after starting. However, under the idling condition after the cold starting shown in **Fig. 17**, the SiRPA coating excluding the cavity showed 10% lower NOx emission at the peak level, and 5.1% lower fuel consumption at 60 seconds after starting than that of baseline.

The main reason for this improvement is considered as cooling heat loss reduction, because there was no major difference in unburned fuel loss, except just after starting. With the reduced heat loss, the thermal energy requirement to maintain the engine speed became smaller. As the result, the burning fuel amount and the NOx emission are considered to be reduced.

As the result of these studies, TSWIN, which was the first in the world to be developed, has been adopted in the 2.8L ESTEC 1GD diesel engine.⁽¹¹⁾ No remarkable damage was detected on the insulation coating throughout every durability test before the start of production. In this application, it was confirmed that TSWIN can be used together with low heat rejection combustion systems such as a low swirl, low squish apparatus, and each gain in thermal efficiency can be added. For further improvement of heat insulation performance, enlarging the insulation area is important. Nevertheless, partly coated SiRPA is concluded to be an effective methodology to utilize as an insulation

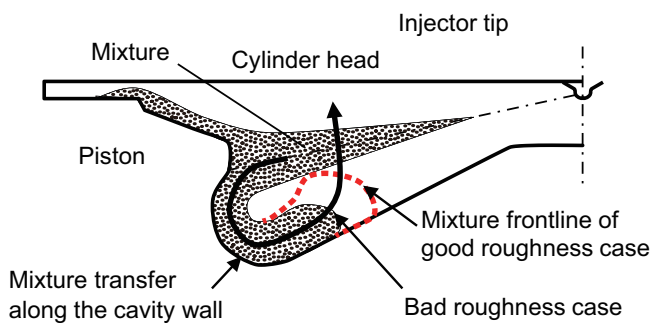


Fig. 15 Schematic drawing of mixture formation phenomena.

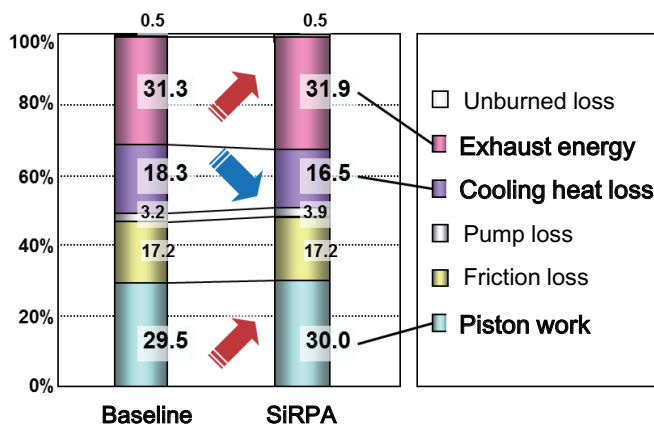


Fig. 16 Heat balance comparison between baseline and SiRPA coating excluding the piston cavity.

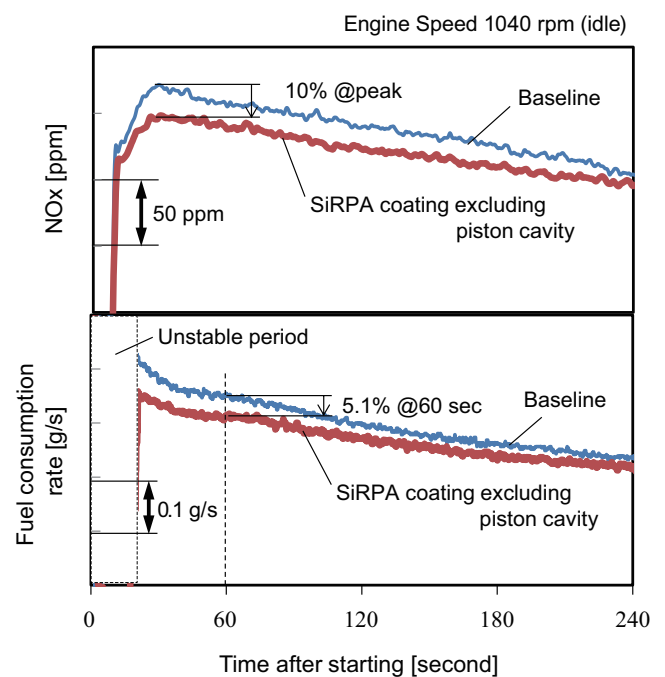


Fig. 17 NOx and fuel consumption comparison after -7°C cold starting.

coating with the current surface roughness for a direct-injection diesel engine piston application.

The thermal efficiency improvement range of TSWIN can be enhanced with the realization of new insulation materials with lower heat conductivity and lower volumetric heat capacity,⁽⁷⁾ and it is expected to be applied for a wide variation of internal combustion engines.

6. Conclusions

In this study, insulation materials which both reduce cooling heat loss without air heating and raise thermal efficiency were investigated to realize the experimental verification of the TSWIN concept.

In addition, the proposed insulation material was formed on the piston surface of a turbocharged diesel engine, and the cooling heat loss reduction and the rate of improvement of thermal efficiency were evaluated. As a result, the following conclusions can be drawn.

- (i) Silica reinforced porous anodized aluminum (SiRPA) has been developed and the performance is evaluated in a four-cylinder direct-injection turbocharged diesel engine. The reduction of cooling heat loss and increase in both brake work and exhaust loss are observed. As a result, improvement of fuel consumption (about 2% at a light load, as an example) is verified experimentally.
- (ii) SiRPA coating on the piston top surface excluding the piston cavity shows superior performance of a cold start at -7°C . NOx reduction is 10%, and fuel consumption improvement is 5.1%.
- (iii) By applying the porous anodized aluminum formed on the surface of the aluminum alloy piston, the sealing of the nano-pore is effective to obtain excellent insulation performance and reliability. This is because the sealing suppresses the invasion of high-pressure combustion gas into the insulation layer.
- (iv) SiRPA coating on the piston top surface excluding the piston cavity shows better fuel consumption than that including the piston cavity. The importance of surface roughness of the fuel spray impinging area on the combustion chamber wall was confirmed, and it was found that keeping a smooth surface by omitting the insulation coating on the piston cavity was the cause of the improvement.

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Constructive discussions about analysis of insulation coating with Mr. H. Kadoura and Dr. H. Hojyo of Toyota Central R&D Labs., Inc. have been helpful to us.

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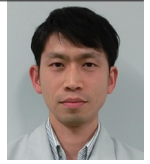
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