

Reduction of Heat Loss and Improvement of Thermal Efficiency by Application of “Temperature Swing” Insulation to Direct-Injection Diesel Engines

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ABSTRACT

The reduction of the 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 an experimental verification of the “temperature swing” insulation concept, whereby the surface temperature of the combustion chamber wall follows that of the transient gas. First, we focus on the development of “temperature swing” insulation materials and structures with the thermo-physical properties of low thermal conductivity and low volumetric heat capacity. Heat flux measurements for the developed insulation coating show that a new insulation material formed from silica-reinforced porous anodized aluminum (SiRPA) offers both heat-rejecting properties and reliability in an internal combustion engine. Furthermore, a laser-induced phosphorescence technique was used to verify the temporal changes in the surface temperature of the developed insulation coating. This was found to quickly rise during the combustion stroke and then drop during the expansion stroke. Second, a SiRPA coating was formed over the entire surface of the diesel piston cavity, and the thermal efficiency and the heat-loss reduction were investigated for a single-cylinder direct-injection (DI) diesel engine with a bore of 86 mm and a stroke of 96 mm. An energy balance analysis showed that the SiRPA coating achieves heat loss reduction by means of heat rejection and an increase in not only the exhaust energy but also the piston work, which increases the thermal efficiency.

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1. INTRODUCTION

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

Many studies [1,2,3] in the 1980s succeeded in reducing heat loss by reducing the temperature difference between the in-cylinder gas and the combustion chamber wall by raising the surface temperature of the combustion chamber wall, which was fabricated from a ceramic material with a low thermal conductivity and a high temperature durability, instead of a metal such as an aluminum or iron alloy.

However, these insulation technologies led to problems with a deterioration in the intake air charging efficiency and an increase in NOx emissions because the high surface temperature, during both the

intake and compression strokes, heats the air being drawn into the cylinder. In addition, soot emissions increase because the raised in-cylinder gas temperature shortens the ignition delay and increases the viscosity of the in-cylinder gas, and then adversely affects the formation of the fuel-air mixture in a diesel engine.

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 that would not lead to heating of the air being drawn into the cylinder [4,5,6,7,8,9,10].

Assanis et al., [4] observed the temporal changes in the surface temperature for a range of ceramic insulation coatings, such as partially stabilized zirconium (PSZ) and silicon nitride, by means of heat conduction calculation in the ceramic insulation coating on the metal combustion chamber wall. Wong et al., [5] also calculated the effect of the coating thickness on the temperature swing of PSZ, and noted that a thin coating of about 100 microns with a low thermal conductivity and low heat capacity is appropriate for improving the thermal efficiency.

In our previous study [7], we evaluated the appropriate thermophysical properties and thickness for temperature swing insulation in spark-ignition (SI) and compression-ignition (CI) engines to clarify the effect of the insulation coating on the thermal efficiency. As a result of this calculation, we showed that, as the thermal conductivity and volumetric heat capacity fall, the rate of improvement of the thermal efficiency increases. Furthermore, we proposed the use of a stacked structure consisting of empty particles fixed with a low thermal conductivity binder as a temperature swing insulation coating. We demonstrated that the surface temperature of the proposed insulation coating falls quickly compared to that of the metal wall, when the high temperature surface of the insulation coating is cooled by an air jet at room temperature.

These studies determined the temporal change in the surface temperature of the insulation coating and the possibility of improving the thermal efficiency by using different insulation coatings. However, there have been few experimental studies addressing the development of a temperature swing coating and the experimental verification of the temperature swing concept in an internal combustion engine.

This paper presents an experimental verification of the “temperature swing” insulation technology, which reduces the heat loss without intake air heating and raises the thermal efficiency, by quickly changing the surface temperature of the insulation coating during the entire cycle applied to a direct-injection (DI) diesel engine. First, the insulation materials were investigated in terms of the requirement for them to have both thermo-physical properties and a high level of temperature durability. Second, the heat insulation performance of the proposed insulation coating was evaluated by heat flux measurement and surface temperature measurement for a single-cylinder diesel engine. Third, the proposed insulation material was formed over the entire piston surface of a DI diesel engine, and the heat loss reduction and improvement in the thermal efficiency were evaluated by means of an energy balance analysis. Furthermore, the effects of the injection timing and EGR rate on the heat loss reduction by heat rejection were investigated and discussed.

2. CONCEPT OF TEMPERATURE SWING INSULATION

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

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

Where, A : surface area, h_g : heat transfer coefficient, T_{gas} : incylinder gas temperature, T_{wall} : wall temperature

“Temperature swing” insulation is a 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 schematic diagram of the surface temperatures attained with different combustion chamber walls and working gas temperatures. Three surface temperatures are shown, corresponding to a metal wall, a traditional heat insulation wall, and the temperature swing insulation wall. Figure 2 shows the thermo-physical properties of metal, heat insulation material, and air.

The surface temperatures for the metals commonly used for combustion chambers, namely, aluminum or iron alloy (Δ , $\blacktriangle$ in Figure 2), remain almost constant during the entire engine cycle (“metal wall temperature” in Figure 1). Traditional adiabatic engines, including those with ceramic thermal-barrier coatings ($\square$, $\blacksquare$ in Figure 2), feature a constant high temperature on the wall surface 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 a deterioration in the power and an increase in exhaust emissions, as well as the occurrence of engine knock in SI engines.

On the other hand, a “temperature swing” insulation coating, which has a low thermal conductivity and a low heat capacity relative to a traditional thermal barrier coatings, exhibits a fast and large change in the surface temperature (wall temperature of temperature swing insulation in Figure 1, and Figure 3). Since the surface temperature with the “temperature swing” coating rises during the combustion period, and then drops during the exhaust and intake strokes, the heat loss decreases during the combustion period, and the intake air is prevented from being heated.

The improvement in the thermal efficiency by application of the “temperature swing” insulation was calculated by a cycle simulation with a boundary condition of the temporal change in the surface temperature [7]. The temperature fluctuation was evaluated by the application of a one-dimensional heat conduction calculation in the direction perpendicular to the insulation coating layer on the chamber wall [7]. Table 1 lists the assumed conditions for a turbocharged diesel engine. Figure 4 shows the evaluated thermo-physical properties for two insulation coatings.

Figure 5 indicates the temperature fluctuation range and indicated specific fuel consumption (ISFC) improvement rate with different thicknesses of insulation coating. The peak gain in the ISFC improvement rate occurs at a thickness of around 100 μm for the two insulation cases. This is because a thickness in excess of 100 μm leads to intake air heating even in a low heat capacity material, thus causing the thermal efficiency to decrease due to an increase in the pumping work. In addition, as both the thermal conductivity and volumetric heat capacity fall, the improvement rate of the thermal efficiency diminishes due to a decrease in temperature fluctuation.

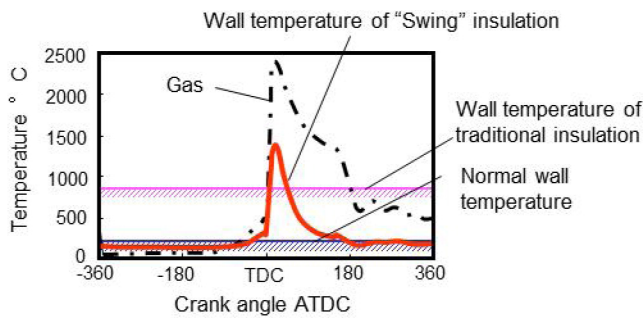


Figure 1. Wall temperatures with different heat insulations

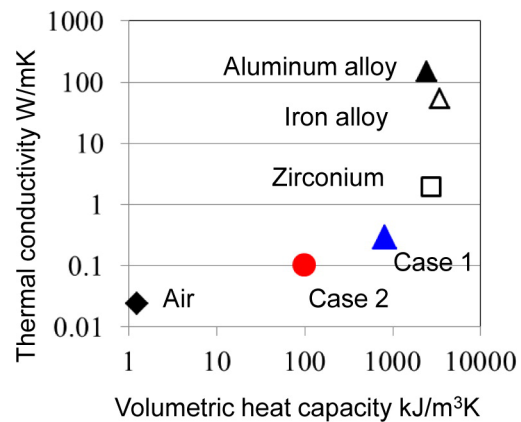


Figure 4. Thermo-physical properties of evaluated insulation coats

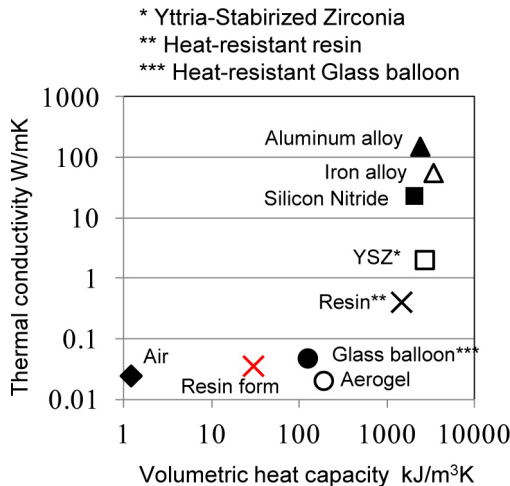


Figure 2. Thermo-physical properties of metal and insulation materials

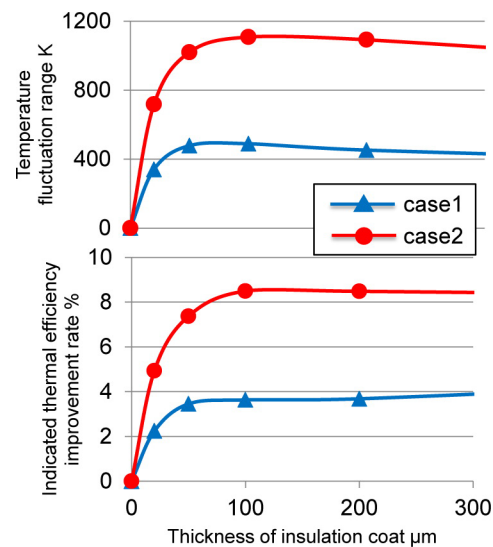


Figure 5. Comparison of ISFC improvement rate by "Temperature Swing" (Calculation) [7]

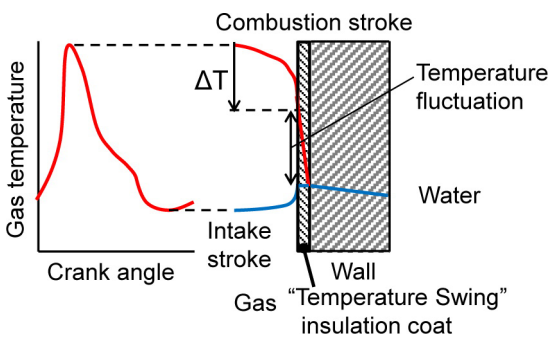


Figure 3. Temperature history of swing insulation

Table 1. Calculation conditions of diesel engine

Engine Type	Turbocharged DI diesel engine
Bore x Stroke	86mm x 96mm
Compression ratio	13.8
Engine Speed	2100 rpm
Amount of Fuel	60 mm ³ /st

3. PROPOSED INSULATION MATERIALS

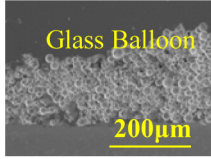
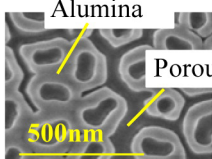
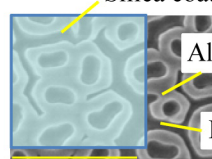
A large fluctuation in the surface temperature of an insulation coating formed on the combustion chamber wall requires a low thermal conductivity λ and low volumetric heat capacity C_v , as shown in Figures 4 and 5. Equations (2) and (3) define the correlation between λ and C_v .

$$\lambda = \rho \times C \times K \quad (2)$$

$$C_v = \rho \times C \quad (3)$$

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

Table 2. Candidates for insulation materials of this paper

Insulation A	Insulation B	Insulation C
Glass Balloon + Ceramics Bond	Porous Anodized aluminum	Porous Anodized aluminum with silica coat
 Side view	 Top view	 Top view

Since λ and C_v are proportional to ρ , a low density is obviously essential to satisfying both the low thermal conductivity and low volumetric heat capacity. Therefore, the material or structure of the insulation coating must include a large amount of air to reduce its density. In addition, the insulation material must have a high heat resistance since the high-temperature in-cylinder gas and flame are in direct contact with the surface of the insulation coating. In this study, we developed three types of material with structures including a large amount of air as candidate temperature swing insulation coatings, as listed in Table 2.

Insulation A has a stacked structure of empty particles, made of heat-resistant glass, fixed with a ceramic bonding material. Since the empty particles have an average diameter of 18 μm and a shell thickness of approximately 1 μm , the empty parcel itself has a high porosity of 70%, therefore forming an insulation coating with a low density. The empty particles and ceramic bonding material are mixed and sprayed onto a substrate of aluminum alloy. This is then baked to harden the insulation coating at a temperature of 200°C.

As a second candidate for the temperature swing coating, we focused on a porous alumina structure, with an oxide of aluminum alloy used as the piston material. Insulation B is our developed porous alumina, which is formed by anodizing aluminum alloy. In general, anodized aluminum is frequently adopted as an anti-wear coating for piston ring grooves. However, our developed insulation coating is significantly different from an anti-wear coating in terms of its porosity and thickness. An anti-wear coating is hard with a low porosity and a thickness of less than 30 μm . On the other hand, Insulation B has a high porosity of 50% and a thickness of approximately 100 μm .

Next, Figure 6 is a schematic of the structure of Insulation B. Insulation B has numerous pores of two sizes. 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.” According to Nishikawa et al. [10], micro-pores and nano-pores have a porosity of 40% and 10%, respectively, which produces a low density relative to that of dense aluminum oxide.

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, perhydropolysilazane (hereinafter, polysilazane), which is converted to silica upon reacting with water vapor in the air, was coated over the surface of porous anodized aluminum with a thickness of a few microns. This silica-coated porous anodized aluminum is proposed as a third temperature swing candidate, as listed in Table 2. Here, the third candidate is called “Insulation C.”

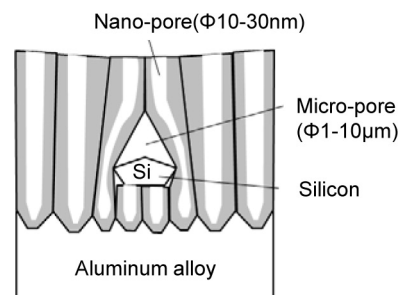


Figure 6. Detailed structure of porous anodized aluminum [10]

4. EXPERIMENTAL APPARATUS

4.1. Engine Specifications

The specifications of the single-cylinder research DI diesel engine, with a common-rail injection system, as used in this study, are listed in Table 3. The cylinder has a bore of 86 mm, a stroke of 96 mm, a displacement of 550 cm^3 and a compression ratio of 14.1.

The nozzle specifications are also listed in Table 3. The nozzle used was a mini sac type with a nozzle diameter of 0.098 mm and a cone angle of 153°. The combustion chamber was a lipless type with a diameter of 58.7 mm, as shown in Figure 7.

Figure 8 shows the experimental apparatus for the single-cylinder engine. Lysholm compressors, driven by an external motor, realize the arbitrary charging efficiency (called η_c). An arbitrary EGR rate was also controlled by an externally driven motor. The intake temperature was adjusted to 75°C by a heat exchanger located in the intake pipe. The exhaust pressure was kept at atmospheric pressure. The temperature of the cooling water and lubricating oil at the inlet of