



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

Research Report

### Concept of Thermo-swing Heat Insulation on Combustion Chamber Walls and Required Thermo-physical Properties for Heat Insulation Coating

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**■ABSTRACT■** This study focuses on the investigation of heat insulation by a thermo-swing coating with large temperature fluctuations on the combustion chamber wall. A large temperature change of the coating surface following the gas phase temperature is realized during the entire engine cycle due to lower thermal conductivity and volumetric heat capacity. As a result, the coating leads to a lower temperature difference between the gas phase and the surface, reducing heat loss. A 1D thermodynamic calculation is used to determine the dependence of the transient surface temperature on the thermophysical properties and thickness. The surface temperature fluctuation increases significantly as the thermal conductivity and the volumetric heat capacity decrease. In addition, a 1D cycle simulation is conducted to evaluate the thermal efficiency with a thermo-swing coating. Boundary conditions are derived from the 1D thermodynamic calculation and 3D-CFD. For SI engines, a coating with appropriate properties and thickness can reduce heat loss without intake air heating or engine knock. For CI engines, the indicated thermal efficiency can be improved approximately two-fold as compared to SI engines because of the larger temperature fluctuation amplitude and the presence of a turbocharger as an energy recovery device. In addition, heat insulation of thermo-swing coating is experimentally demonstrated with a single cylinder diesel engine. The prototype thermo-swing coating containing glass balloons embedded in a ceramic-containing binder on the cylinder head demonstrates the potential to reduce heat loss.

**■KEYWORDS■** Heat Insulation Engine, Coating, Heat Flux, Thermal Efficiency, Simulation

#### 1. Introduction

The importance of reducing heat loss to combustion chamber walls for internal combustion engines has been recognized from the early stage of their development. During past decades, a variety of analytical and experimental studies were devoted to reducing heat loss.<sup>(1-7)</sup> The idea was to reject heat flux from the working gas to the combustion chamber wall coated with a ceramic. Increased internal energy in the combustion chamber can be used as piston work. Moreover, the increased exhaust gas temperature is recovered with a turbocharger, thereby improving the overall thermal efficiency and reducing the load of the cooling system.<sup>(8)</sup> Several drawbacks, however, did exist that were recognized through the development stage in the mid-1990s.<sup>(9)</sup> One of the largest issues was the elevated temperature of combustion chamber walls resulting in deterioration of the volumetric efficiency by intake air

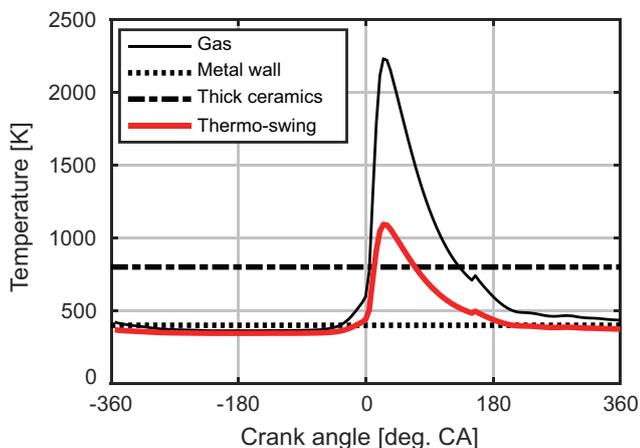
heating, increased NO<sub>x</sub> emission, and engine knock. Another issue was the decrease in the durability and the reliability of the ceramic coating over the engine's lifetime. Recent numerical and experimental studies suggested that a thin ceramic coating is effective for improving thermal efficiency.<sup>(5)</sup> Only a few studies have explored the required thermophysical properties and practical structures for the ideal heat insulation. This paper focuses on the analytical investigation of the possibility of thermo-swing<sup>(10)</sup> with a larger surface temperature fluctuation on the combustion chamber walls coated with low-thermal-conductivity and low-heat-capacity materials. Furthermore, the reduction of heat loss is experimentally demonstrated with a single-cylinder engine.

#### 2. Concept of Thermo-swing Heat Insulation

The behavior of thermo-swing coating is illustrated

by comparing temperature profiles during the entire engine cycle. The surface temperatures of a metal wall as a conventional material, a thick ceramic coating as a traditional heat insulation material, and the proposed thermo-swing coating are compared with the gas temperature in **Fig. 1**.

Commonly used materials for combustion chambers, such as iron or aluminum alloy, have thermal conductivities in the range of 55 to 150 W/mK and the volumetric heat capacities in the range of 2400 to 3400 kJ/m<sup>3</sup>K. The surface temperature of the metal is approximately constant during the entire cycle due to the larger heat capacity (Fig. 1, dotted line). Therefore, the temperature difference between the working gas and the surface during the combustion period is relatively large, which causes larger heat loss (**Fig. 2(a)**). Traditional heat rejection engines cause invariably higher surface temperatures during the entire cycle (Fig. 1, chain line; and Fig. 2(b)). The resulting volumetric efficiency decreases with increasing gas temperature. The occurrence of engine knock is also increased. In contrast, a large temperature change following transient gas phase temperature is realized for the thermo-swing coating (Fig. 1, red solid line). Figure 2(c) shows that the coating achieves a lower surface temperature during the intake stroke and a higher temperature during the combustion stroke due to the lower volumetric heat capacity, which enables the reduction in heat loss without intake air heating.

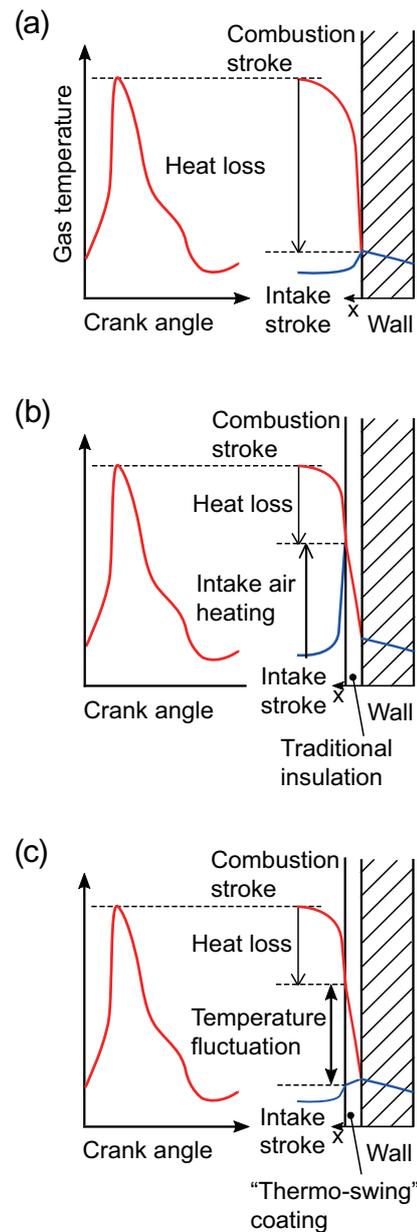


**Fig. 1** Transient gas and piston/coating surface temperature in dependence of coating materials during the entire engine cycle.

### 3. Analytical Evaluation of Thermo-swing Coating

#### 3.1 SI Engines

The surface temperature of the combustion chamber wall is significantly related to thermal efficiency. Thus, the dependence of the transient profile of surface temperature on the thermophysical properties of the coating materials is calculated using STAR-CD, a commercial CFD program.<sup>(11)</sup> Calculations are



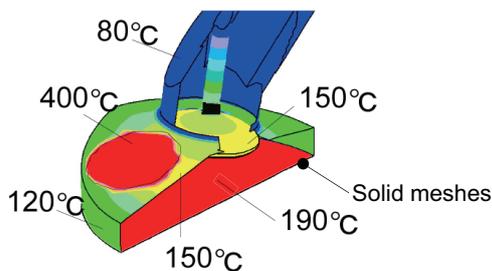
**Fig. 2** Schematic views of the in-cylinder transient gas temperature profiles and wall-normal profiles. (a) Metal wall (b) thick ceramics coating as a traditional insulation (c) "Thermo-swing" coating.

performed under wide open throttle (WOT) conditions for a naturally aspirated spark ignition (SI) engine, as shown in **Table 1**. **Figure 3** shows the computational domain, which consists of a cylinder, a cylinder head, intake valves, and an intake port. The solid meshes representing the surface layer of the reference material and three types of thermo-swing coating are applied to the piston top to evaluate the surface temperature. For the reference material, the thermal conductivity and volumetric heat capacity are set to the values of aluminum alloy. For the thermo-swing coating, both values are set to be smaller by 1/16 (Case A), 1/32 (Case B), and 1/64 (Case C), compared to the values for zirconia, as shown in **Fig. 4**. Surface boundary temperatures are derived from the experimental data, as shown Fig. 3. Combustion simulation is conducted with coupled fluid/solid heat conduction during the entire engine cycle. The details of the models used for 3D-CFD were described previously.<sup>(11)</sup>

**Figure 5** shows the resulting surface temperature distributions for the solid meshes on the piston for Case C. Clearly, the surface temperature greatly

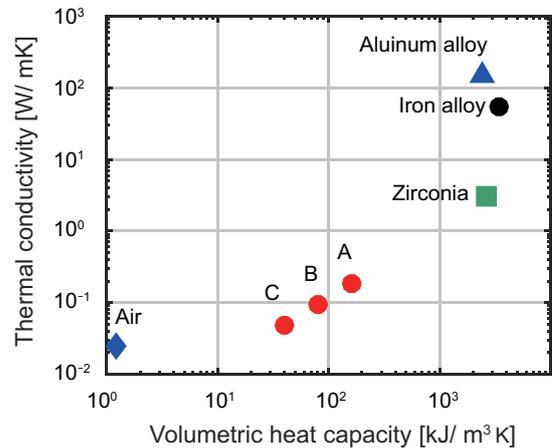
**Table 1** Calculation conditions.

Engine Type	Naturally-aspirated spark ignition engine
Stroke	86 mm
Bore	86 mm
Compression ratio	10.5: 1
Engine speed	2000 rpm
Load	WOT (Wide Open Throttle)
Fuel	Gasoline
Equivalence ratio	1.0
10-90 % combustion period	24 deg. CA

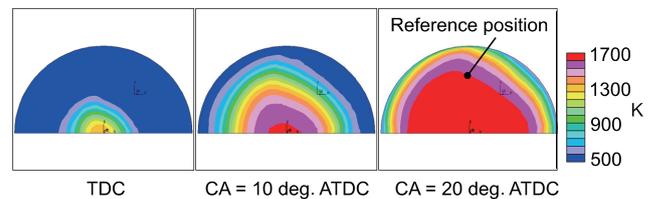


**Fig. 3** Computational domain and wall surface temperatures as boundary conditions for 3D-CFD.

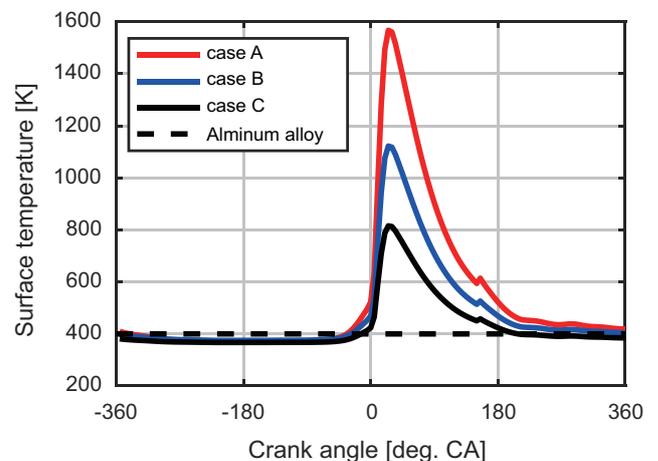
increases near TDC with flame propagation initiated from the center of the combustion chamber. For varying thermophysical properties, the temporal profiles of surface temperature at the reference position are shown in **Fig. 6**. For the reference material, the surface



**Fig. 4** Thermophysical properties of considered materials.



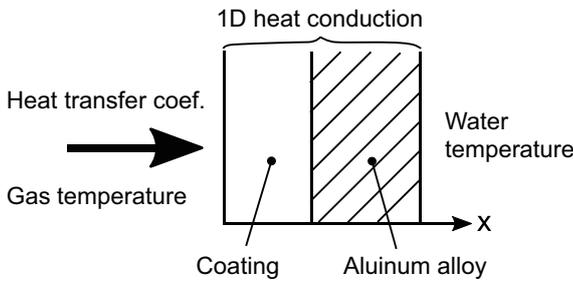
**Fig. 5** Surface temperature distributions with thermophysical properties of Case C derived from 3D-CFD.



**Fig. 6** Calculated surface temperature profiles in dependence of coating materials during the entire engine cycle.

temperature is almost constant during the entire cycle, whereas the temperature profile for Case C exhibits remarkably large fluctuation during the combustion stroke. It is apparent that the temperature fluctuation amplitude increases with lower thermal conductivity and volumetric heat capacity.

The thermophysical properties of the coating and its thickness are important factors with respect to temperature fluctuation amplitude and resulting thermal efficiency. For the parametric study, a 1D thermodynamic calculation is used to estimate the dependence of the transient surface temperature on the thermophysical properties and thickness. **Figure 7** outlines the calculation model, which consists of the coating and the combustion chamber wall as an infinite plate. As the boundary conditions at the thermal load side, the transient heat transfer coefficient and gas phase temperature are derived from the spatially averaged values in the above-mentioned 3D-CFD. The influence of wall temperature on combustion due to the coating is ignored. For the cooling side, a constant temperature is assumed for the cooling water. The thermophysical properties are set to the values shown in **Table 2**, as compared with other materials in **Fig. 8** (Cases 1 and 2). For zirconia and Case 1 with varying thickness, temporal averaged heat fluxes from the wall

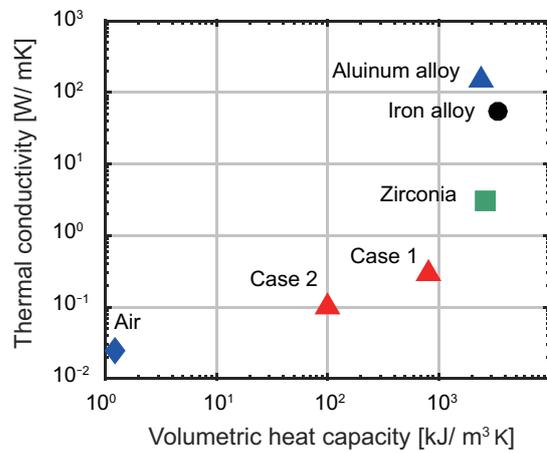


**Fig. 7** 1D thermodynamic model for surface temperature estimation in dependence of coating materials and thickness.

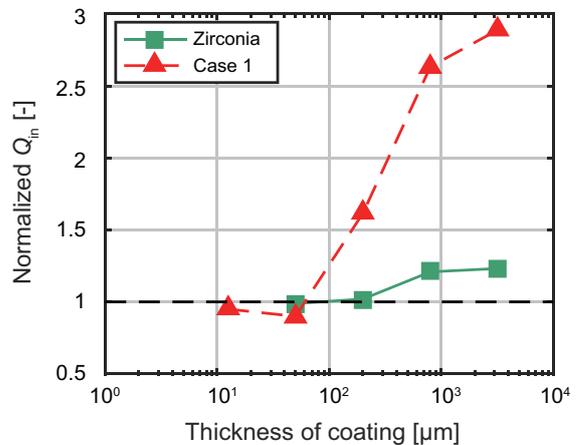
**Table 2** Thermophysical properties of considered materials in 1D thermodynamic calculation.

	Case 1	Case 2
Thermal conductivity [W/mK]	0.3	0.1
Volumetric heat capacity [J/m <sup>3</sup> K]	800	100

to the working gas during the intake stroke  $Q_{in}$  are shown in **Fig. 9** to evaluate the possibility of intake air heating. The values are normalized by  $Q_{in}$  for the conventional metal wall. For the zirconia coating,  $Q_{in}$  with a thickness of up to 100  $\mu\text{m}$  is constant at 1.0. For increasing thicknesses over 100  $\mu\text{m}$ ,  $Q_{in}$  starts to increase up to 1.3, which indicates that the thick coating of zirconia causes intake air heating. The behavior follows previous experiments. For Case 1,  $Q_{in}$  is found to be smaller than 1.0, in the range of 10  $\mu\text{m}$  to 100  $\mu\text{m}$ . This observation indicates that the working gas could be cooled by the coating during the intake stroke, which helps significantly to suppress engine knock.



**Fig. 8** Thermophysical properties of considered materials in 3D-CFD.



**Fig. 9** Temporal averaged heat flux from the wall to the working gas during intake stroke,  $Q_{in}$ . The values are normalized by  $Q_{in}$  without coating.

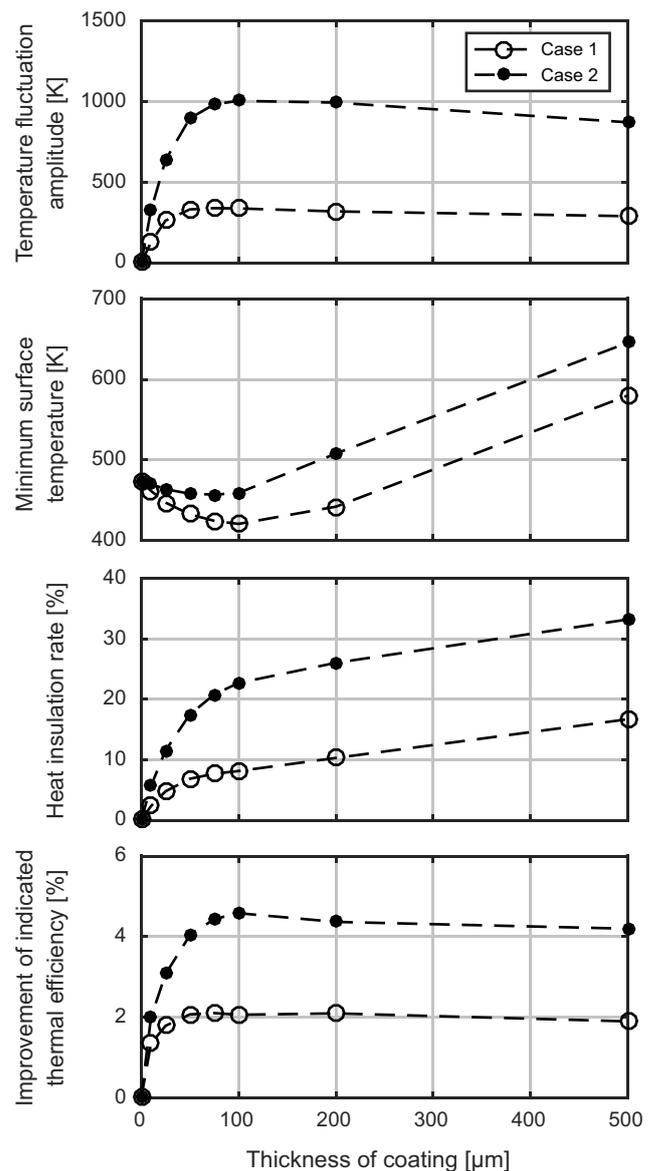
To evaluate the influence of the coating on the thermal efficiency, a cycle simulation is performed with the thermophysical properties of Cases 1 and 2 and coatings of different thicknesses. The configuration is similar to that described in Table 1. The ignition timing is set to the knock limit or Minimum Advance for Best Torque (MBT) in consideration of the knock occurrence. The heat release rate is defined using the Wiebe function. Engine knock is evaluated with the Livengood-Wu function, and the ignition delay is estimated by detailed reaction calculation. The boundary conditions for the surface temperature are given by the above-mentioned 1D thermodynamic calculation. The coating is considered to be applied to the piston top and the cylinder head surface including valves because it was found to be difficult to keep any coatings on the cylinder liner due to sliding with the piston rings. The details of the model used are described in a previous paper.<sup>(12)</sup>

The resulting surface temperature fluctuation amplitude, the minimum temperature during the entire cycle, the heat rejection rate, and the thermal efficiency improvement rate are summarized in **Fig. 10**. The higher minimum temperature compared to the value without the coating indicates intake air heating. The heat insulation rate is the normalized difference of heat loss between the cases with/without the coating.

Figure 10 shows that the peak gain of thermal efficiency is realized with the thickness of 100  $\mu\text{m}$  for both cases. For thicknesses greater than 100  $\mu\text{m}$ , the minimum temperature during the entire cycle is higher than that without coating, causing intake air heating. As a result, the thermal efficiency with the coating decreases due to an increase in pumping work. This observation indicates that the thick coating, even with low thermal conductivity and low volumetric heat capacity, causes the previously reported drawback.

### 3.2 CI Engines

For expanding the analytical evaluation to compression ignition (CI) engines, the previously described procedure is applied to a turbocharged diesel engine with the coating of Cases 1 and 2, as shown in Table 2. 3D-CFD<sup>(13)</sup> is performed with the operating condition, as shown in **Table 3**, which provides the transient heat transfer coefficient and in-cylinder gas temperature. A 1D thermodynamic calculation is



**Fig. 10** Effect of the coating thickness and thermal properties on thermal characteristics for the SI Engine.

**Table 3** Calculation conditions.

Engine Type	Turbo-charged diesel engine
Stroke	96 mm
Bore	86 mm
Compression ratio	13.8: 1
Engine speed	2100 rpm
Nozzle specification	$\phi 0.11 \times 10$
Amount of fuel	60 mm <sup>3</sup> /st

carried out to determine the dependence of the surface temperature profiles on the thermophysical properties and thickness. Finally, a 1D cycle simulation<sup>(14)</sup> is performed to evaluate the improvement of thermal efficiency.

For CI engines, the instantaneous heat transfer coefficient obtained from 3D-CFD has the local distribution shown in Fig. 11. The local heat transfer coefficient is larger at the sidewall of the piston cavity with flame impingement. Further analysis considering such a local effect should be performed to evaluate the influence on pollutants and thermal fatigue of the coating. It is assumed, however, that the evaluation of the total thermal efficiency is feasible with the spatially averaged heat transfer coefficient and gas phase temperature in this study.

Figure 12 shows the resulting temperature fluctuation amplitude, the minimum temperatures of the coating surface, the heat insulation rate, and the improvement rate of the indicated thermal efficiency obtained from the cycle simulation. For Case 1, the thickness of 100  $\mu\text{m}$  achieves the maximum improvement of thermal efficiency, generating the largest temperature fluctuation amplitude.

The benefit of the thermo-swing coating is obviously larger for CI engines (Fig. 12), as compared to SI engines (Fig. 10). For CI engines, a larger heat transfer coefficient causes a larger temperature fluctuation due to the higher cylinder pressure and faster flow motion. In addition, the in-cylinder gas temperature is generally lower than that for SI engines due to the lean equivalence ratio, generating a lower temperature difference between the gas phase and the wall surface originally. Even with a similar fluctuation amplitude of the surface temperature, as shown in

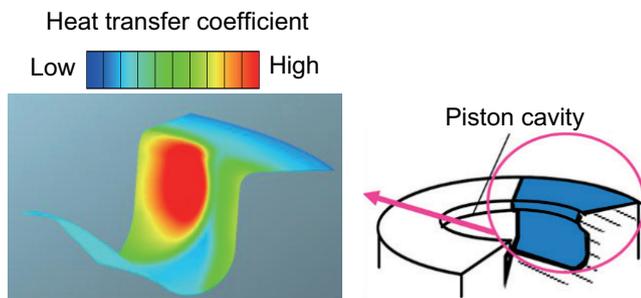


Fig. 11 Heat transfer coefficient distributions of the piston surface derived from 3D-CFD (CA = 10 deg. ATDC).

Figs. 10 and 12, the reduction ratio for the temperature difference is larger, which causes a larger improvement in thermal efficiency. The energy recovered as a result of the increase in exhaust gas energy by a turbocharger is also considered. For Case 1, with a thickness of 100  $\mu\text{m}$ , the thermal efficiency is improved by 3.8%, where the temperature fluctuation amplitude is approximately 500 K. For the experimental analysis shown in the next section, our primary goal is the evaluation of the coating with the thermophysical properties of Case 1.

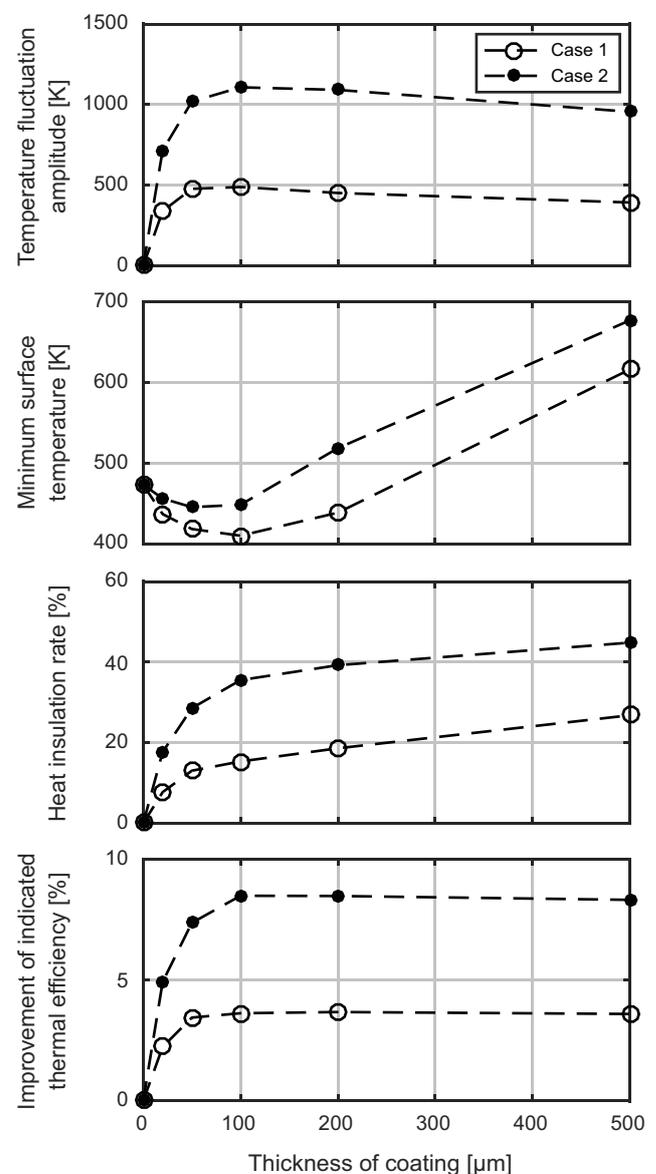


Fig. 12 Effect of the coating thickness and thermal properties on thermal characteristics for the CI Engine.

## 4. Experimental Evaluation

### 4.1 Proposed Structure for Thermo-swing Coating

In this section, we present a prototype thermo-swing coating to demonstrate the potential of heat loss reduction on a laboratory scale. Such low-thermal-conductivity and low-volumetric-heat-capacity materials, for example, porous media and bubble materials, already exist. These materials, however, have an open porous structure, which allows gas to penetrate the coating, thereby increasing the heat loss. The proposed structure consists of enclosed balloons fixed with a low-heat-conductivity binder, as shown in Fig. 13. The thermophysical properties are evaluated with a 2D heat conduction model. The combined layer with glass balloons (diameter: 18  $\mu\text{m}$ ; shell thickness: 1  $\mu\text{m}$ ) embedded in a ceramic-containing binder realizes a porosity of 70%. As a result, the estimated thermophysical properties achieve the value for Case 1.

### 4.2 Heat Flux Measurement with the Single-cylinder Engine

The behavior of the thermo-swing coating is studied in greater detail using a single-cylinder engine. The engine is equipped with a single 550-cc cylinder and a direct injection system for diesel combustion. Table 4 shows the operating conditions. The engine was described in detail in a previous study.<sup>(15)</sup> The heat

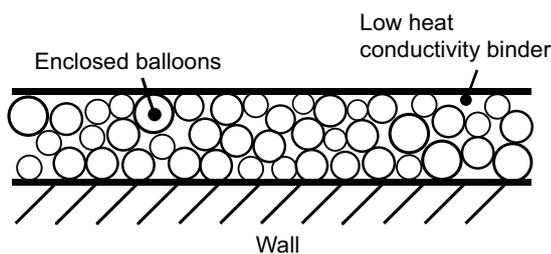


Fig. 13 Proposed structure of “Thermo-swing” coating.

Table 4 Engine operating conditions.

Engine speed	2000 rpm
Common Rail Pressure	100 MPa
Amount of fuel	40 mm <sup>3</sup> /st.
Charging efficiency	130 %

flux is measured by an originally developed heat flux sensor attached to the cylinder head. The prototype coating is formed on the top of the sensor head. For the measured transient heat flux with/without coating, the values normalized by the peak heat flux without coating are shown in Fig. 14. During the intake stroke, the thermo-swing coating realizes a larger heat flux, which indicates that the intake air is cooled by the coating. Even in CI engines, intake air cooling greatly improves volumetric efficiency. In addition, during the combustion stroke, the heat flux with the coating decreases significantly. Figure 15 shows the cycle averaged heat flux normalized by the value without coating. The heat flux with thermo-swing coating is

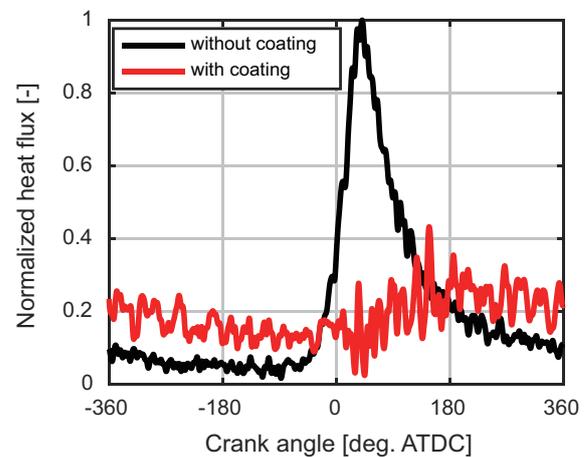


Fig. 14 Measured instantaneous heat flux on the cylinder head of a single cylinder engine.

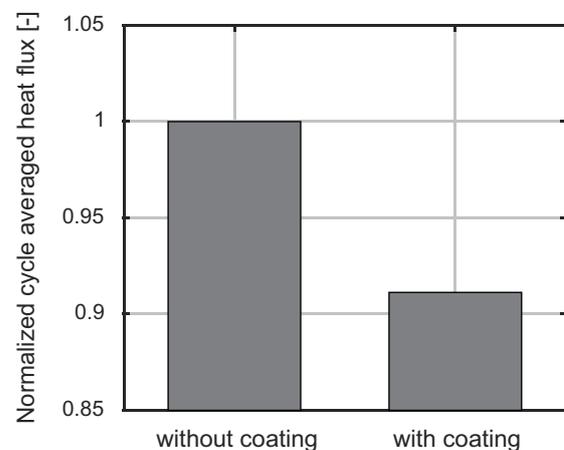


Fig. 15 Cycle averaged heat flux on the cylinder head normalized by the value without coating.

approximately 10% lower than that of the metal wall. This observation indicates that the proposed structure can reduce the heat flux during the combustion stroke without intake air heating. For further study, the influence of the coating on the piston cavity and the thermal resistance should be considered.

## 5. Conclusion

This study presented analytical and experimental investigations of the thermo-swing coating. Calculations were conducted to estimate the dependence of the surface temperature fluctuation amplitude on the thermophysical properties and coating thickness. In addition, the prototype thermo-swing coating was experimentally investigated with a single cylinder diesel engine. The major conclusions are as follows:

- A large temperature change of the thermo-swing coating following the transient gas phase temperature was realized due to decreased thermal conductivity and volumetric heat capacity. A 1D thermodynamic calculation was used to determine the dependence of the surface temperature fluctuation on the thermophysical properties.
- For the evaluation of thermal efficiency, a 1D cycle simulation was conducted. The result revealed that both the prevention of intake air heating and heat loss reduction are possible under appropriate thermophysical properties. For CI engines, the benefit of the thermo-swing coating is larger than that for SI engines.
- A prototype thermo-swing coating was experimentally evaluated with a developed heat flux sensor attached to a single cylinder diesel engine. The combined layer with glass balloons embedded in a ceramic-containing binder can reduce the heat flux during the combustion stroke.

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Figs. 3, 5, 8, 11 and Tables 1 and 3

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