

Concept of “Temperature Swing Heat Insulation” in Combustion Chamber Walls, and Appropriate Thermo-Physical Properties for Heat Insulation Coat

Hidemasa Kosaka, Yoshifumi Wakisaka, Yoshihiro Nomura, Yoshihiro Hotta, Makoto Koike and Kiyomi Nakakita
Toyota Central R&D Labs Inc.

Akio Kawaguchi
Toyota Motor Corp

ABSTRACT

The aim of this work is to investigate the possibility of heat insulation by “Temperature Swing”, that is temperature fluctuation, on combustion chamber walls coated with low-heat-conductivity and low-heat-capacity materials.

Adiabatic engines studied in the 1980s, such as ceramic coated engines, caused constantly high temperature on combustion wall surface during the whole cycle including the intake stroke, even if it employed ceramic thermal barrier coating methods. This resulted in increase in NO_x and Soot, decrease in volumetric efficiency and combustion efficiency, and facilitated the occurrence of engine knock.

On the other hand, “Temperature Swing” coat on the combustion chamber walls leads to a large change in surface temperature. In this case, the surface temperature with this insulation coat follows the transient gas temperature, which decreases heat loss with the prevention of intake air heating, and also which is expected to prevent NO_x and Soot from increasing. In our calculations, the increase of the surface temperature fluctuation, “Temperature Swing” results from the coat of lower heat conductivity and lower heat capacity. Particularly in Gasoline engines, the coat with the appropriate thickness can reduce the heat flux from the wall to the working gas during intake stroke and can avoid engine knock.

Based on our calculations, it is clarified that both the prevention of intake air heating and the low heat rejection were successfully possible with the material of appropriate thermo-physical properties.

In addition to the calculations, a preliminary test-piece experiment was executed. It was demonstrated that the surface temperature of a porous coat, that is a candidate of “Temperature Swing” coat, immediately follows the transient gas temperature, and also the proposed insulation coat can exactly reduce the heat flux in the single-cylinder engine.

CITATION: Kosaka, H., Wakisaka, Y., Nomura, Y., Hotta, Y. et al., "Concept of “Temperature Swing Heat Insulation” in Combustion Chamber Walls, and Appropriate Thermo-Physical Properties for Heat Insulation Coat," *SAE Int. J. Engines* 6(1):2013, doi:10.4271/2013-01-0274.

INTRODUCTION

In the 1980s, a large number of investigations were conducted on various aspects of applying heat insulation to internal combustion engines [1, 2, 3, 4, 5, 6, 7]. The idea was to insulate heat flow from the working gas to the combustion chamber wall, using the materials with low-heat-conductivity and high-heat-capacity. The energy insulated in combustion chamber could be recovered from the exhaust gas, thereby improving overall thermal efficiency and reducing the load of the cooling system [8].

Several drawbacks did exist that were determined through the development processes in the mid-1990s [9]. The first was the issue of elevated combustion chamber temperatures resulting in deterioration of the fuel consumption by slower combustion and undesired high NO_x emission levels, and also particularly in gasoline engines, facilitating the occurrence of engine knock. The second was the decrease in the durability and the reliability of the heat insulation coat over the life.

On the other hand, simulations and experiments on diesel and gasoline engines suggested that the thin, low-heat-conductivity and low-heat-capacity coat was effective on

thermal efficiency [9]. These thin coatings could work as effective thermal barriers during the combustion period with the prevention of intake air heating. However, it was not clarified the relation between the effect of the coat on the thermal efficiency and the thermal properties, and also not investigated the structure of the heat insulation coat in these studies. This paper's focus is to investigate the possibility of "Temperature Swing", which is temperature fluctuation, on combustion chamber walls coated with low-heat-conductivity and low-heat-capacity materials [10], and to generate design guidelines for the desired optimal coat.

CONCEPT OF HEAT INSULATION BY "TEMPERATURE SWING"

The conventional metal surface temperature of combustion chamber walls are shown in Fig. 1 with the working gas temperature. The commonly-used materials for combustion chambers, iron or aluminum, have heat conductivity of 55 to 150W/mK and heat capacity of 2400 to 3400kJ/m³K. The surface temperature of the metal is almost constant during the whole engine cycle ("Normal wall temperature" in Fig.1). Therefore, as shown in Fig. 2, the difference of temperature between the working gas and the wall surface during the combustion period is large, and this is the main cause of heat loss in the combustion chamber.

Traditional adiabatic engines, including the engines with ceramic thermal barrier coatings, cause almost invariably high temperature on the wall surface during the whole cycle including the intake stroke as shown in Fig.3, and result in decrease in the volumetric efficiency, increase in working gas temperature, and facilitate the occurrence of engine knock.

On the other hand, using a "Temperature Swing" coat, which is a low-heat-conductivity and low-heat-capacity material, on the combustion chamber walls, leads to a large change in surface temperature (Fig. 1: Wall temperature of "Temperature Swing" insulation and Fig. 4). As shown in Fig. 1, the surface temperature with the insulation coat follows the transient gas temperature, which decreases heat loss without heating intake air.

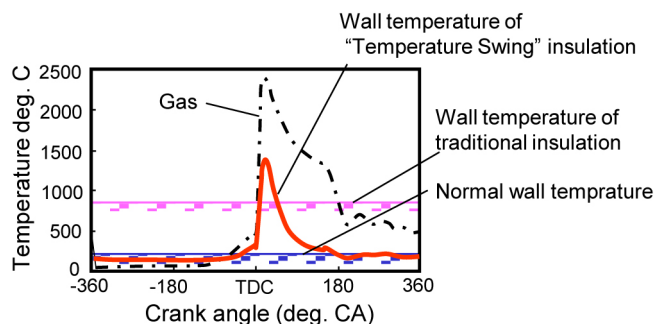


Figure 1. Gas and wall temperature histories

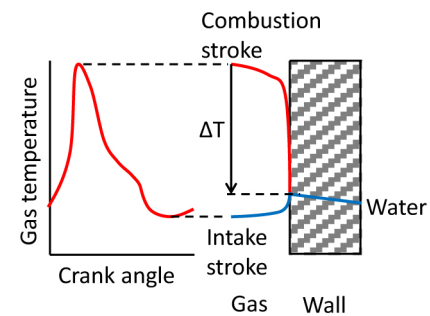


Figure 2. Temperature history of normal wall

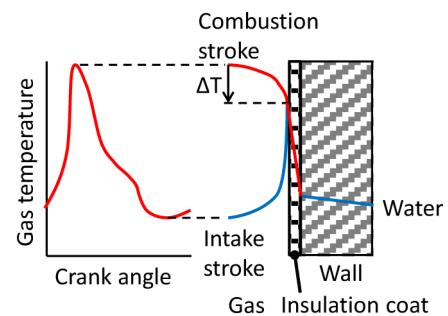


Figure 3. Temperature history of traditional insulation

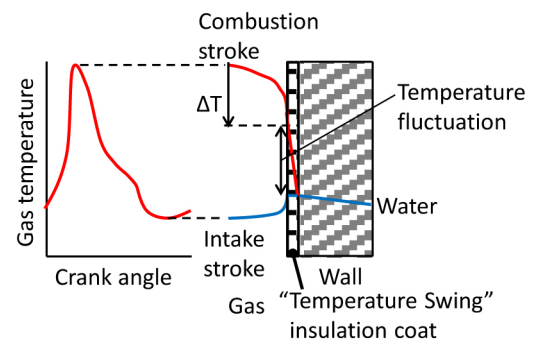


Figure 4. Temperature history of "Temperature Swing" insulation

CALCULATION OF THE SURFACE TEMPERATURE AND THE HEAT TRANSFER RATE IN "TEMPERATURE SWING" COAT

In order to investigate the temperature fluctuation of the heat insulation by "Temperature Swing", a commercial CFD code, STAR-CD, was used [11], and temperature histories on this coated and uncoated walls were compared. Calculation conditions are shown in Table 1, and Fig.5 shows the computational domain that consists of the cylinder, the cylinder head including valves, and intake ports. The solid mesh representing the insulation coat was set on the piston in combustion calculation to evaluate the surface temperature. Figure 5 also shows the boundary condition used in the

calculation, temperature distribution on the piston, the cylinder, the cylinder head, intake ports, and valve surfaces. The above-mentioned CFD was carried out with transient heat conduction to the coat with various material properties and the thickness of 100 μm . The material covered three types with heat conductivity and heat capacity which were smaller by 1/16, 1/32, and 1/64 than those of zirconia, respectively. Figure 6 shows the thermal properties of the investigated insulation materials.

Table 1. Calculation conditions

Engine Type	Naturally-aspirated spark-ignited 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

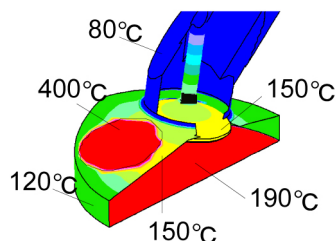


Figure 5. Calculation mesh and wall temperature conditions

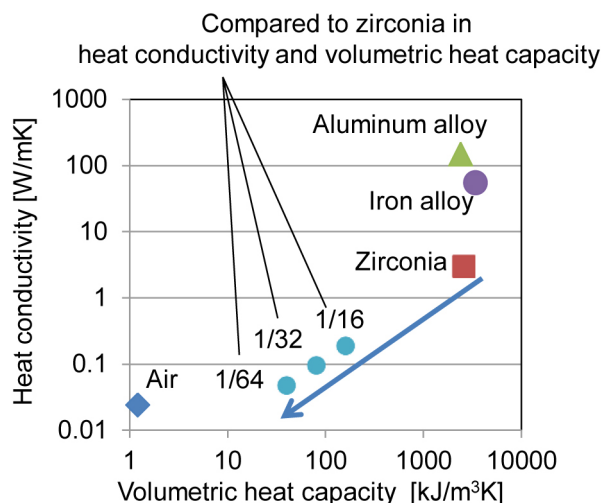
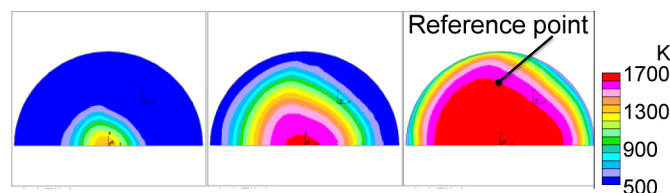


Figure 6. Thermal characteristics of insulation materials

Figure 7 shows the surface temperature of the coat with the 1/64 of zirconia in thermal properties on the piston at TDC, 10 deg. ATDC, 20 deg. ATDC, respectively. The

surface temperature of the conventional metal piston hardly changes during the whole cycle, however, the surface temperature of this insulation coat remarkably changes following flame propagation as shown in Fig.7. The temperature histories at the reference point of the piston surface are shown in Fig.8 as a parameter of thermal properties. The temperature fluctuation range of each insulation coat is defined as the difference between the maximum and the minimum temperatures. According to Fig. 8, it is apparent that the temperature fluctuation is increased as heat conductivity and heat capacity of the coat are lowered.

To provide a rough evaluation of the temperature fluctuation, a simple thermodynamic analysis was conducted. Figure 9 shows the calculation model for the simple analysis that consists the coat and an infinite plate, which was the simplified combustion chamber wall. The wall-averaged heat transfer coefficient and averaged gas temperature calculated from 3D-CFD were given at the surface of the heat insulation coat. The water temperature, 353K, was given at another surface. A one-dimensional calculation of heat conduction in the direction perpendicular to the coat layer of this model was executed under the assumption that the each layer was homogeneous and heat flux flowed in a single direction.



(a) TDC (b) CA=10deg. ATDC (c) CA=20deg. ATDC

Figure 7. Wall temperature distributions of piston surface

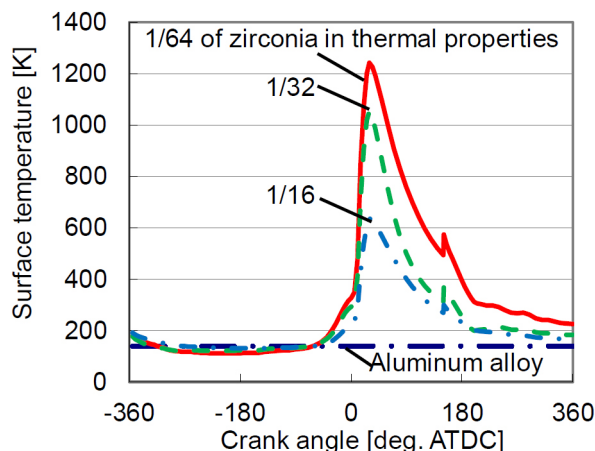


Figure 8. Temperature histories of insulation coat