

A Numerical Simulation Study on Improving the Thermal Efficiency of a Spark Ignited Engine --- Part 2: Predicting Instantaneous Combustion Chamber Wall Temperatures, Heat Losses and Knock ---

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ABSTRACT

The objective of this work is to develop a numerical simulation model of spark ignited (SI) engine combustion and thereby to investigate the possibility of reducing heat losses and improving thermal efficiency by applying a low thermal conductivity and specific heat material, so-called heat insulation coating, to the combustion chamber wall surface. A reduction in heat loss is very important for improving SI engine thermal efficiency. However, reducing heat losses tends to increase combustion chamber wall temperatures, resulting in the onset of knock in SI engines. Thus, the numerical model made it possible to investigate the interaction of the heat losses and knock occurrence and to optimize spark ignition timing to achieve higher efficiency. Part 2 of this work deals with the investigations on the effects of heat insulation coatings applied to the combustion chamber wall surfaces on heat losses, knock occurrence and thermal efficiency.

To reduce engine heat losses and improve the thermal efficiency, the heat insulation coating was applied to the combustion chamber wall surfaces. Specifically, wall surface temperatures, heat losses and thermal efficiency corresponding to the thickness of the material and the compression ratios were investigated by using the numerical model described in Part 1. In case of the combustion chamber wall surface entirely coated with the material at low load, applying the heat insulation material can make the MBT (Minimum advance for best torque) earlier, resulting in highly-increased thermal efficiency. The results imply that low thermal conductivity and low specific heat materials should be coated at proper locations with an optimized thickness to improve overall thermal efficiency.

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INTRODUCTION

Reducing heat losses is a very important factor to improve thermal efficiency in internal combustion engines. The instantaneous heat flux through the combustion chamber wall is determined by coupling equations (1) and (2), which describe the unsteady thermal conductivity inside the wall and the heat transfer at the wall surfaces, respectively.

$$\rho c \frac{\partial T}{\partial t} = \frac{\partial}{\partial x} \left(k \frac{\partial T}{\partial x} \right) + \frac{\partial}{\partial y} \left(k \frac{\partial T}{\partial y} \right) + \frac{\partial}{\partial z} \left(k \frac{\partial T}{\partial z} \right) + \dot{s} \quad (1)$$

$$q_B = h \Delta T = h(T_f - T_B) \quad (2)$$

where,

ρ : Density
 c : Specific heat

t : Time
 k : Thermal conductivity
 $\dot{S}$: Source term
 q_B : Boundary heat flux
 h : Heat transfer coefficient
 T_f : Surrounding-fluid temperature
 T_B : Boundary temperature
 x, y, z : Position

One of the conventional methods for reducing heat losses is utilizing a low thermal conductivity material for cylinder head, liner or piston head. For example, Kawamura et al. used a ceramic material to construct a heat-insulated engine with no cooling system and demonstrated its reliability [1]. However, this method had adverse effects on the exhaust gas characteristics because intake heating and higher in-cylinder temperature promoted NOx formation. It also reduced the ignition delay for the diesel spray, causing increased soot formation. An alternative approach that may alleviate these problems has recently been proposed. It is based on coating

the combustion chamber walls with a material having a low specific heat capacity and thermal conductivity known as heat insulation coating.

Because the material of heat insulation coating has a low thermal conductivity, the heat flux through the combustion chamber wall should be low. Furthermore, it should enable the wall surface temperature to change quickly with that of the in-cylinder gas, thereby minimizing ΔT . Thus, heat insulation coating could therefore reduce thermal losses without affecting intake heating. However, while increased wall surface temperatures can help to reduce heat losses, they tend to have unfavorable effects on the onset of knock in spark ignited engines [2,3,4]. It is therefore necessary to consider how any treatment aimed at reducing heat losses in SI engines affects the onset of knock. In general, lower wall surface temperatures are associated with higher heat losses but suppress knock. This is favorable during operation at high loads or high engine speeds. On the other hand, higher wall surface temperatures can reduce heat losses but the resulting intake heating may induce knock. Therefore, such conditions are desirable during low load operations or cold starts. A slightly different case arises when the wall temperature fluctuates during an engine cycle. Such fluctuations are referred to as the wall temperature swing; when the swing is large, heat losses are reduced because ΔT is low. In addition, knock can be avoided because the effect of intake heating is limited. A schematic illustrating the effect of the combustion chamber wall surface temperature on knock and heat loss is shown in Figure 1.

There have been a number of studies on these phenomena. For examples, Fujimoto et al. developed a non-dimensional combustion model coupled with a heat conduction analysis model in the combustion chamber, and used it to determine how compression ratios and cooling losses affect the calculated thermal efficiency [5]. Kosaka et al. performed numerical simulations to investigate the effects of coating the walls of the combustion chambers in diesel and gasoline engines with low thermal conductivity and low heat capacity materials. Their results demonstrated that it is possible to simultaneously prevent the heating of the intake air and reduce thermal losses [6].

Part 1 of this work described the development of a numerical simulation model consisting of a non-dimensional two-zone combustion model, an autoignition model in the unburned gas and an unsteady one-dimensional heat transfer model in the combustion chamber wall [7]. The accuracy of the numerical model was then validated. Here, the authors report an investigation by predicting how applying heat insulation coatings to the walls of the combustion chamber affects the wall temperature swings, heat losses, knock occurrence and thermal efficiency.

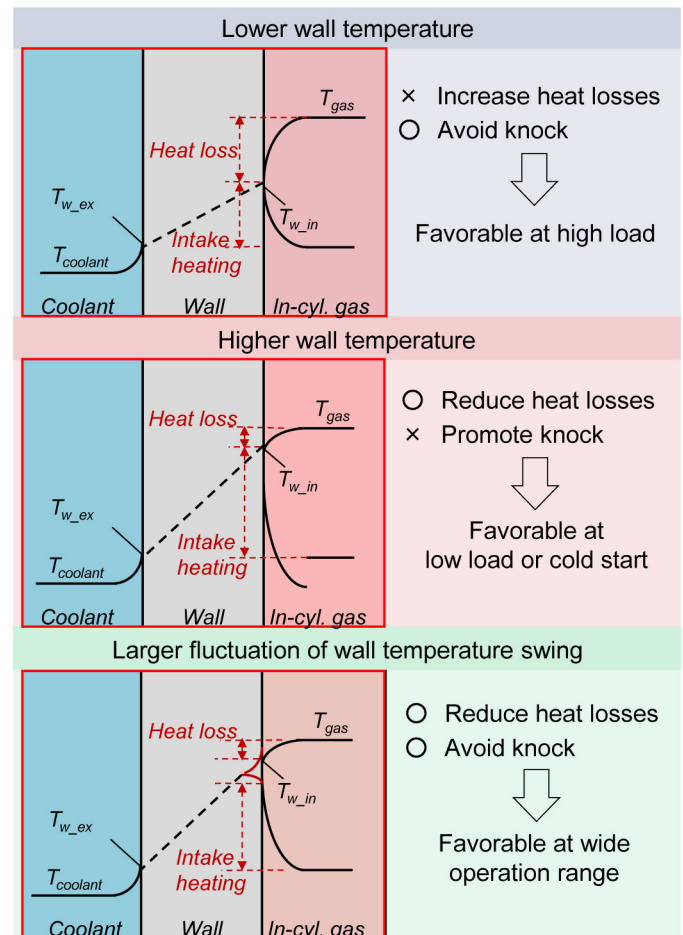


Figure 1. The effect of the combustion chamber wall surface temperature and its swing on heat losses and knock

THE NUMERICAL MODEL

GT-POWER was used to develop the numerical model of a spark ignited engine combustion. A non-dimensional two-zone SI combustion model was combined with an autoignition model in the unburned gas, an instantaneous heat transfer model in the combustion chamber wall, and a spark ignition timing optimization scheme in order to predict how changes in the surface temperature of the combustion chamber walls affects heat losses and the incidence of knock. The development and validation of the numerical model are described in Part 1 of the present study, so here we will only outline it in the form of the schematics shown in Figure 2.

In this work, it was assumed that the combustion chamber walls were coated with a material of low thermal conductivity and low specific heat. The heat insulation coatings were modeled by modifying the properties of the control volumes (CVs) corresponding to the coating thickness.

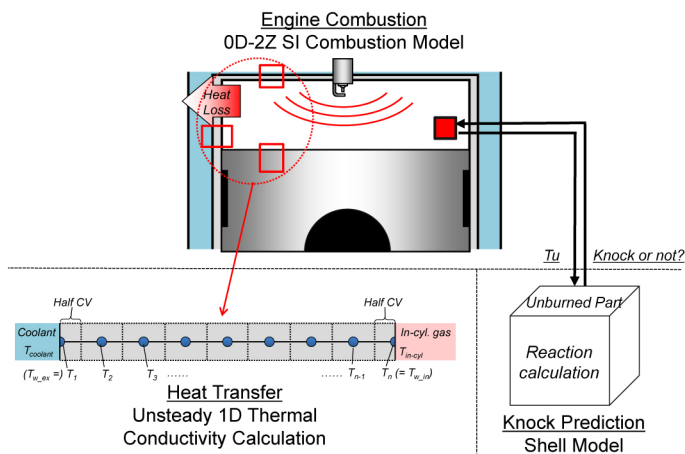


Figure 2. Schematics illustrating the components of developed numerical model

CALCULATION RESULTS AND DISCUSSION

Calculation Procedures and Conditions

Iterative engine cycle simulations were performed using the numerical model whose design and validation were discussed in Part 1 of this work. The iterative calculations were allowed to proceed until the cycle average wall surface temperature converged. If knock occurred during an iterative calculation, the spark ignition timing is automatically retarded by the optimization scheme mentioned in Part 1.

Table 1. Calculated engine operating conditions

Engine speed rpm	1200
IMEP kPa	Equivalent 200, 700
Equivalence ratio	1.0
EGR ratio %	0
Ignition timing deg.ATDC	Optimized

The engine operating conditions assumed in the calculations are shown in Table 1. An engine speed of 1200 rpm was selected to represent typical engine operating conditions. Calculations were performed using two IMEP values: 200 kPa, to represent the low loads typically encountered during the cruising mode operation; and 700 kPa to represent high load conditions and then to investigate the knock occurrence and its avoidance under these conditions. The coolant water and lubricant oil temperatures were set at 80 and 100 deg.C, respectively. The thermal properties of the combustion chamber materials are shown in Table 2. The cylinder head and inner wall were assumed to be made of iron while the piston head wall to be made of aluminum. The heat insulation coating was assumed to have ideal thermal properties [6] as shown in Table 3 in order to evaluate the effectiveness of heat insulation coatings in a best-case scenario. The thickness was increased from 0.05 to 1.01 mm, so the discretized CV length was set at 0.02 mm. In order to maintain constant intake

conditions, the throttle angles were fixed at the values used in conventional operation (i.e. those used in the absence of coating).

Table 2. Properties of the combustion chamber materials

Component	Cyl. head & liner	Piston head
Material	Iron	Aluminum
Wall thickness mm	6	10
Thermal conductivity W/mK	80	240
Density kg/m ³	7870	2702
Specific heat J/kgK	500	940

Table 3. Thermal properties of the heat insulation coating

Thermal conductivity W/mK	0.1
Density kg/m ³	222
Specific heat J/kgK	450
Volumetric specific heat J/kgK	100
Coat thickness mm	0.05 ~ 1.01

The Effect of Heat Insulation Coatings Applied to the Entire Combustion Chamber Wall Surface

First, iterative calculations were conducted on the assumption that the heat insulation coating would be applied uniformly over the entire surfaces of the combustion chamber walls. Traces of the wall surface temperature for the cylinder head and cylinder liner are shown in Figure 3, with the results obtained in the absence of heat insulation coating being indicated by the '0 mm' values. The heat insulation coating causes the wall temperature swing to become more pronounced, and the wall temperature increases with the thickness of the coating. The ranges of fluctuations of the cylinder head and piston head are much greater than those for the cylinder liner because the mean gas temperature, which is used to calculate the heat transfer in the cylinder head and piston head wall surfaces, is much higher than the unburned gas temperature at both loads. In the wall temperature traces, there are small increases near the crank angle of 360 deg.ATDC. This is caused by increase of mass flow rate during the intake and exhaust valve's overlap. In addition, the cylinder liner wall surface temperature trace increases slightly just before 180 deg.ATDC. This is due to changes in the boundary condition ongoing from the unburned gas temperature to the mean gas temperature at EVO by the software's restriction. The increase at EVO is larger at high load because the gas temperature and heat transfer coefficient under these conditions are greater than those encountered under low load conditions. As the thickness of the coating increases, the wall temperature starts to peak at later crank angles, and normal flame propagation does not occur if the coating thickness is greater than 0.17 mm at high load. This is due to knock and the retardation of the spark ignition timing, as discussed in detail below. The maximum,