

Transient Analysis of the Piston Temperature with Consideration of In-cylinder Phenomena Using Engine Measurement and Heat Transfer Simulation Coupled with Three-dimensional Combustion Simulation

Hideaki Mizuno, Koichi Ashida, Atsushi Teraji, Kenshi Ushijima and Shinichi Takemura
NISSAN MOTOR CO., LTD.

Copyright © 2009 SAE International

ABSTRACT

This study examined a method of predicting the piston temperature in reciprocating internal combustion engines with the aim of developing lightweight pistons. Since the piston temperature is strongly affected by the in-cylinder temperature distribution and turbulence, it is necessary to consider the effects of flame propagation, cooling by the intake air, temperature rise due to combustion, in-cylinder flow and the combustion chamber shape. A three-dimensional combustion simulation that can take these effects into consideration was run to calculate the heat transfer coefficient from the piston crown surface and the gas temperature. The results were used as the boundary conditions for an analysis of heat transfer from the piston, and a method was thus developed for analyzing the piston temperature. The hardness method was used to obtain the piston temperature distribution and maximum temperature during engine operation, and a comparison was made with the analytical results to examine the effects of flame propagation.

INTRODUCTION

Along with rising concern about the environment, there are demands for highly efficient internal combustion (IC) engines that can improve fuel economy. One method of obtaining higher efficiency is to reduce the weight of the (IC) engine. In this regard, the weight of the pistons greatly affects weight reductions for other parts. It is important to understand the piston temperature distribution, as material strength depends on temperature. In order to ascertain the piston temperature, it is necessary to develop analytical methods for

investigating the effects of flame propagation due to the in-cylinder flow and the effects of the combustion chamber shape. A variety of analytical methods [1] have been used in efforts to analyze temperature. One of these techniques is the hardness method [2] that measures the softening of materials due to an increase in temperature. Although it is possible to measure the average temperature of the engine with this method, it is difficult to obtain the amplitude of temperature variation and the maximum temperature in a combustion cycle.

As for calculation techniques, a method [3] was reported that can take into account the heat distribution input from combustion gases and transient conditions. The authors have developed a virtual engine [4] capable of reproducing various engine phenomena using a three-dimensional combustion simulation and have researched its application to the development of technologies for obtaining higher efficiency engines.

In this study, a three-dimensional combustion simulation was applied to a piston heat transfer analysis for the purpose of expanding the scope of research done with the virtual engine. This simulation is able to consider the effects on flame propagation of cooling by the intake air, temperature rise due to combustion, in-cylinder flow and the combustion chamber shape. We developed a simple method for predicting the piston crown surface and interior temperatures in order to consider the effects of in-cylinder flow from the intake stroke to the exhaust stroke. This method uses the results of the three-dimensional combustion simulation as the boundary conditions for the heat transfer simulation. In order to validate the calculation results, the detailed temperature distributions of both the piston crown surface and interior

during engine operation were derived from experimental measurements made with the hardness method. Additionally, by comparing the hardness method results and the calculation results, the effects of the in-cylinder flow and flame propagation on the piston temperature distribution were clarified.

CALCULATION MODEL

The detailed temperature distribution of the piston was examined using an analytical model combining the three-dimensional combustion simulation and the heat transfer simulation as shown in Fig. 1. The gas temperature and heat transfer coefficient of the piston crown were calculated from the three-dimensional combustion simulation and given as boundary conditions for the heat transfer simulation.

THREE-DIMENSIONAL COMBUSTION SIMULATION - The piston temperature is affected by the temperature distribution and histories associated with cooling during the intake stroke and temperature increase due to combustion gases. Therefore, to take these effects into account, a three-dimensional combustion simulation capable of considering the in-cylinder flows in the intake, compression, expansion and exhaust strokes and flame propagation was performed. The temperatures shown in Table 1 were applied to each part in the calculations. The gas temperature and the heat transfer coefficient from the intake stroke to the exhaust stroke were calculated by the extended law of the wall [5] developed by Angelberger et al. The heat transfer coefficient h is

given by

$$h = \frac{\Phi}{(T_l - T_w)}$$

where Φ , T_w , and T_l , respectively denote the heat flux of the wall, wall temperature, and the temperature of the cell adjacent to the wall. Angelberger et al. calculated the wall function taking into account the temperature gradient and derived the heat flux of the wall, which they expressed as

$$\Phi = \frac{\rho_w c_p u_\tau T_w}{\theta^+} \ln \left(\frac{T_l}{T_w} \right)$$

where C_p and u_τ respectively represent the specific heat and friction speed, ρ_w is the density of the wall and θ^+ is a dimensionless temperature expressed as

$$\theta^+ = \begin{cases} Pr \eta^+ & \eta^+ < 13.2 \\ 2.075 \ln(\eta^+) + 3.9 & \eta^+ \geq 13.2 \end{cases}$$

$$\eta^+ = \frac{u_\tau}{\nu_1} y$$

where Pr is the Prandtl number and ν_1 the viscous coefficient of the cell adjacent to the wall. Using this model, the heat transfer coefficient of the piston crown surface was calculated and used as the crown surface boundary condition.

CALCULATION OF TRANSIENT HEAT TRANSFER OF THE PISTON - The gas temperature and heat transfer coefficient at the piston crown surface that were calculated in the three-dimensional combustion simulation were mapped two-dimensionally at each crank angle as the boundary conditions for the transient heat transfer model. The heat flux to the piston crown surface is given by

$$\Phi_{t+\Delta t} = h(T_{l,t} - T_{w,t})$$

where $T_{l,t}$ and $T_{w,t}$ respectively denote the temperature of the cell adjacent to the wall and the wall temperature at time t , while $t+\Delta t$ represents the heat flux value for the next calculation cycle at time t . The values of the atmospheric temperature and heat transfer coefficient shown in Table 2 were used as the boundary conditions of other part surfaces. The heat transfer coefficient [6] used by Esfahanian et al., with the lower surface of the top ring piston groove, second ring and oil ring connected to the upper surface, was used for the piston ring heat transfer coefficient, while the piston ring sliding area temperature [7] calculated by Ishijima et al. was

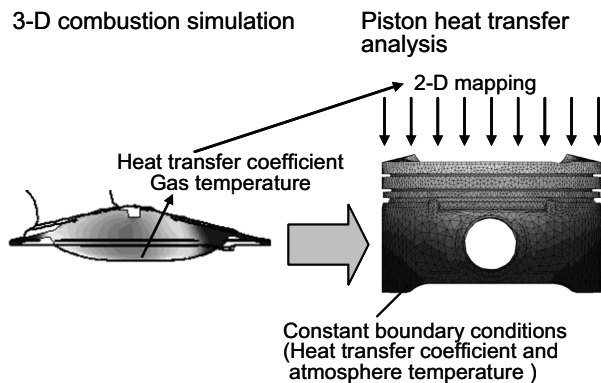


Fig. 1 Schematic of the calculation method

Table 1 Boundary conditions for the three-dimensional combustion simulation

	Temperature, K
Cylinder head	435
Cylinder liner	414
Piston	583
Inlet port	464
Exhaust port	519
Intake manifold	322

Table 2 Boundary conditions
for the piston transient heat transfer calculations

		H, W/m ² K	T, K
Top ring	Upper	885	433
	Lower	1818	433
Second ring	Upper	891	433
	Lower	420	433
Oil ring	Upper	1023	433
	Lower	482	433
Top land		88	400
Skirt		1443	383
Piston pin		1000	383
Other		1928	383

H:Heat transfer coefficient

used for the atmospheric temperature. The values reported by Esfahanian et al. were also used for the top land, skirt and piston connector, similar to the heat transfer coefficient. The value given in the calculations for the heat transfer coefficient of parts other than the piston crown surface, including the rear of the piston skirt and the lower crown area, corresponded to the temperature gradient between the crown surface center and the peripheral parts calculated by the hardness method.

TEST CONDITIONS AND PISTON SHAPE

The specifications of the 4-cylinder gasoline engine and the operating conditions used in this study are shown in Table 3. Considering the importance of performing simulations under conditions where the temperature increases, the operating conditions included wide-open-throttle (WOT) operation at the maximum output speed of 5600 rpm. The intake air temperature was set at 298 K and oil was supplied such that the temperature at the oil gallery inlet was a constant 359 K. For the test fuel, 91 RON regular gasoline was supplied by a multi-point injection (MPI) system, and the spark plug was located approximately in the center of the combustion chamber.

The shape of the piston used in this study is shown in Fig. 2. The geometry of the piston crown surface affects the in-cylinder flow, flame propagation and combustion gas contact area. The piston used in this study was designed to strengthen the in-cylinder flow in order to study the effects of flame propagation on the piston

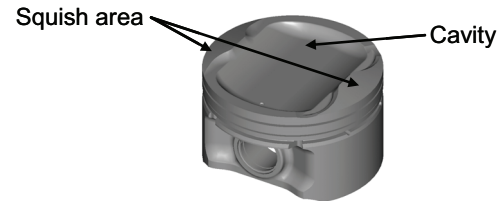


Fig. 2 Piston shape

temperature. A cavity for intensifying tumble flow was provided in the center of the piston crown surface, and squish areas were formed on two peripheral sides to intensify end gas flow.

EXPERIMENTAL TEMPERATURE DISTRIBUTION

To validate the suitability of combining the three-dimensional combustion simulation and the heat transfer simulation, detailed temperature distributions were derived for the piston crown surface and interior under test engine operation by using the hardness method that measures the softening of materials accompanying a rise in temperature. The material used for the piston in this study was aluminum (AC8A-T6), which is generally used in gasoline IC engines and had the specifications shown in Table 4. As the softening of the material is dependent on the type of material, temperature and time, the hardness of a test piece made of AC8A-T6, which had been heated at a constant temperature for 10 hours, was measured, and the relation between temperature and hardness was derived as shown in Fig. 3.

Table 4 Material specifications
of the aluminium piston

Material	AC8A-T6
Thermal conductivity, W / m K	125
Density, kg / m ³	2700
Heat capacity, J / kg K	963

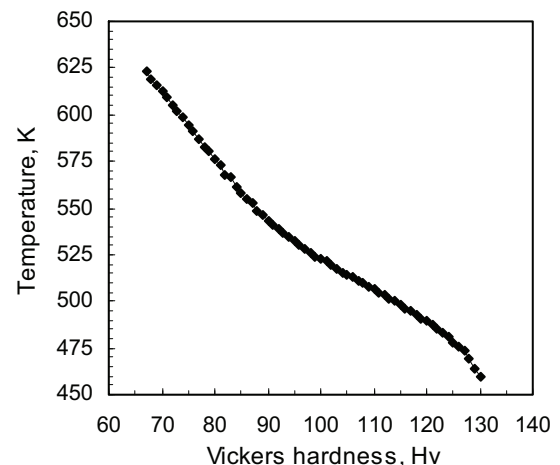


Fig. 3 Effect of temperature on hardness

Table 3 Engine specifications
and operating conditions

Engine type	4-Stroke, 4-Valve, 4-Cylinder
Combustion chamber	Pentroof type
Bore x stroke	84 x 90.1 mm
Compression ratio	10.0 : 1
Engine speed	5600 rpm
Load	WOT
A/F ratio	11.3 : 1
Water and oil temperature	359K