

Development of Temperature Estimation Method of Whole Engine Considering Heat Balance under Vehicle Running Conditions

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ABSTRACT

For detailed temperature estimates in the engine of a running motorcycle, newly researches were conducted on the method for calculation of temperature distribution using a three-dimensional (3D) thermal conductivity simulation after calculating the total balance of heat generation and heat dissipation of the engine using a one-dimensional (1D) thermal simulation. This project is targeted at air-cooled engines in which the cooling conditions vary significantly depending on the external shapes of the engines and the airflow around them. The heat balance is calculated using the 1D thermal simulation taking into account all the routes and processes for dissipation to the atmosphere of the heat that is generated by the combustion in the engine. The 1D engine cycle simulation is applied to calculate the heat transmission to the engine from the combustion. For the calculation of heat transfer within the engine, the engine components are converted to a one-dimensional model. The empirical equation established from the measurements and the one-dimensional computational fluid dynamics (1D-CFD) are combined to calculate the heat transfer to the engine oil. The 3D-CFD is applied to calculate the heat transfer to the atmosphere. For the final estimation of engine temperature distribution, the 3D thermal conductivity simulation is applied using the fluid temperatures and heat transfer coefficients inside and outside the engine as the boundary conditions. Thus, it is confirmed that the newly-developed temperature estimation method permits accurate estimation of the engine temperature distribution in complete motorcycles under running conditions. Also proven is that the engine temperature can be accurately estimated even in another motorcycle equipped with a different engine.

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INTRODUCTION

The growing demands for fuel economy in recent years call for development of light and compact engines having a high thermal efficiency. While the thermal efficiency of engines is improving due to various innovations, approximately 30% of the fuel's energy is released to the atmosphere, which is referred to as "cooling loss".

The heat in an engine is released to the atmosphere via the engine components, coolant and engine oil. When the cooling is inadequate, the engine temperature rises excessively. As a result, lowering of the volumetric efficiency, knocking and lowering of material strength may occur, which causes loss of engine performance and/or durability. For air-cooled engines in particular, lightness/compactness and the retention of heat dissipation capacity are two contradicting demands. It is therefore necessary to pay attention to the balance between the heat entering the engine and that leaving the engine in order to design an engine while ensuring performance, durability and compactness. Furthermore, in motorcycles equipped with air-cooled engines, the cooling conditions vary significantly depending on the external shapes of the engines

and the airflow around them. It is therefore necessary to analyze the engine temperatures of a complete motorcycle under running conditions.

In the meantime, the so-called "digital development", in which no prototype engine is produced in the early stages of development, is becoming the mainstream of recent engine development in an effort to reduce the development period. It is necessary to accurately estimate the temperature distribution in the engine in the early stages of development in order to accurately simulate the intake air temperature, which affects volumetric efficiency and knocking, as well as the durability of engine parts.

There are many examples of past research on engine cooling and temperature estimation(1), (2), (3), (4), (5). The conventional ways include the following.

1. A method that assesses heat dissipation from the engine outer surface to the atmosphere and from the water jacket to the coolant by the heat transfer coefficient using the 3D-CFD

2. A method that estimates temperature distribution using a thermal conductivity simulation with measured temperatures and heat fluxes of a part of the engine as the boundary conditions
3. A method that estimates coolant temperature when operating in test mode using a 1D thermal fluid simulation

As such a method is unable to directly estimate the temperature or requires measured temperatures and/or heat flux data from various parts of the engine, it cannot be used to get an accurate temperature estimate in the design stage. Although the heat balance of coolant is taken into account, the estimate cannot be extended to the temperature distribution in the various parts of the engine.

Accordingly in this project we developed a method for estimating, in an early stage of design, engine temperature distribution in an air-cooled engine under the running conditions of a complete motorcycle. A feature of this method is that it takes into account a total heat balance of the engine. Especially detailed heat transfer processes are taken into account for the cylinder and the cylinder head, which are

subjected to high temperatures. The accuracy of this method for temperature estimation has been validated, and we will describe the details hereafter.

TEST MOTORCYCLES

Table 1 shows the engine specifications of the two motorcycles used in this project. An air-cooled, 300 cm³ engine with its single cylinder canted forward 15 degrees was used for the development and validation of the temperature estimation method (Vehicle A in Table 1). The test motorcycle is equipped with an oil cooler. The air guide plates, or "shroud," direct air flow to the spark plug for cooling.

A motorcycle equipped with an air-cooled, 110 cm³ engine with its single cylinder canted forward 80 degrees was used for the additional validation of the temperature estimation method in this project (Vehicle B in Table 1). This motorcycle is not equipped with an oil cooler. This motorcycle was selected as having significant differences in engine displacement, power output, engine configuration and airflow around the engine compared to Vehicle A.

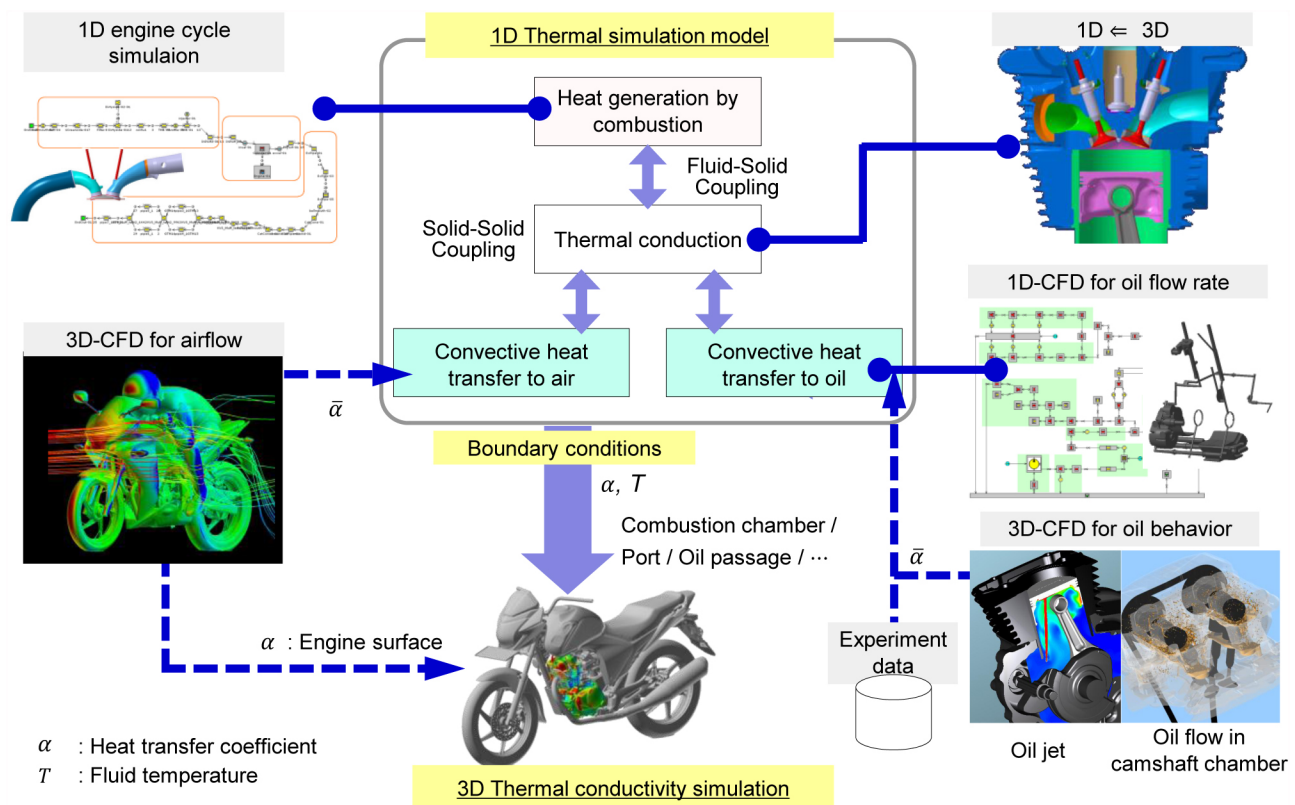


Figure 1. Overview of the developed temperature estimation method

Table 1. Engine specifications of test motorcycles

	Vehicle A	Vehicle B
Engine type	4 stroke engine	4 stroke engine
Number of cylinders	1	1
Engine configuration	15 degrees inclined from vertical	80 degrees inclined from vertical
Cooling system	Air cooled	Air cooled
Bore [mm]	79	50
Stroke [mm]	59.5	55.6
Displacement [cm ³]	291.6	109.1
Compression ratio [-]	9	9
Max brake power [kW]	17.9 (7500 r/min)	6.2 (7500 r/min)
Max brake torque [Nm]	25.2 (6000 r/min)	8.6 (5500 r/min)
Max vehicle speed [km/h]	128	89

OVERVIEW OF TEMPERATURE ESTIMATION METHOD

Figure 1 shows an overview of the temperature estimation method developed in this project. To calculate the heat balance in an air-cooled engine, it is necessary to take into account all the routes from the heat source up to the heat dissipation such as the heat input from the combustion to the engine, the heat transfer within the engine, the heat transfer from engine inner surface to the engine oil, the heat dissipation from the oil cooler to the atmosphere, and the heat dissipation from the cooling fins to the atmosphere. A 1D thermal simulation model is used for the comprehensive calculation with all the above factors coupled. The formulas coupled in the model are as per the following.

- The 1D engine cycle simulation is used to calculate the processes through which the combustion heat is transferred to the structural engine components via the combustion chamber walls.
- The three-dimensional shapes of the cylinder head and the cylinder are converted to the 1D thermal simulation model to calculate the heat transfer within the engine.
- The 1D-CFD for oil flow rate is used to calculate the the heat transfer from the internal walls of the engine to the engine oil. It should be noted that the empirical equation of the heat transfer coefficient determined from measurements is applied to the part where the engine oil flows along wall such as in the camshaft chamber in the cylinder head. The 3D-CFD for oil behavior and the empirical equation of the heat transfer coefficient are applied to calculate the heat dissipation processes in which the heat in the piston is transferred to the engine oil sprayed from the oil jet.
- Another 3D-CFD for airflow is used to calculate the heat transfer processes, in which the heat is dissipated to the atmosphere when the complete motorcycle is running.

The heat balance in the engine is determined by coupling the above formulas. Using the accordingly determined temperatures and heat transfer coefficients of the working gas and the engine oil as the boundary conditions, the temperature distribution in the various parts of engine is determined by the 3D thermal conductivity simulation.

DETAILS OF TEMPERATURE ESTIMATION METHOD

Calculation of Heat Input to Engine

One of the key techniques in temperature estimation is the calculation of heat input from the combustion gas to the structural engine components. 1D engine cycle simulation is a technique commonly applied to engine development(6), (Z), and recently allows a very accurate calculation of in-cylinder pressures. Figure 2 shows an outline of the 1D engine cycle simulation model. Here, the three-dimensional shape in the intake and exhaust systems of the engine is converted to a 1D model. The gas flow in the engine is determined by calculation after discretization of the equations of mass conservation, Navier-Stokes, energy conservation, etc. In addition, the power output, torque, etc. at the subjected engine speed and load conditions are calculated from the thermodynamics calculation of the engine.

Figure 3 shows a comparison of the calculated and the measured engine power output, torque and in-cylinder pressure. As Figure 3(a) shows, the calculated steady-state power output and torque when the throttle is fully opened are in good agreement with the measurement across all engine speeds. As Figure 3(b) shows, the calculated in-cylinder pressures within a cycle of the engine at 8000 r/min are also in good agreement with the measurement. We have thus concluded that the 1D engine cycle simulation is sufficiently accurate to be applied to the calculation of heat inputs to the structural components of an engine.

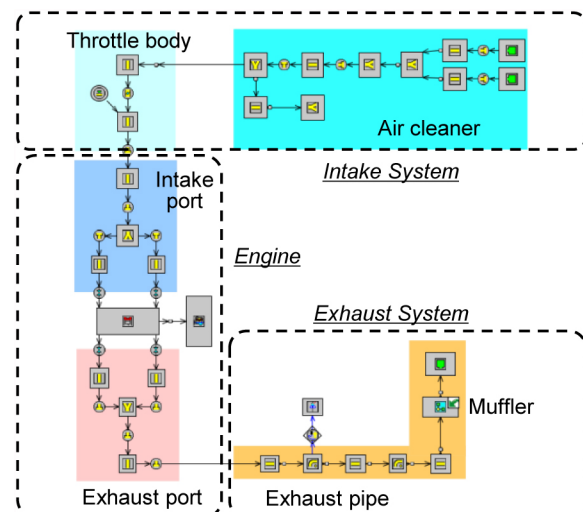
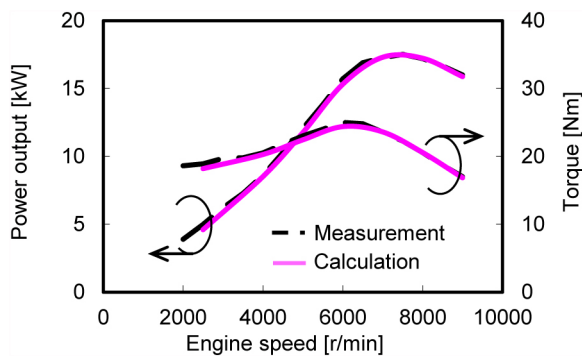
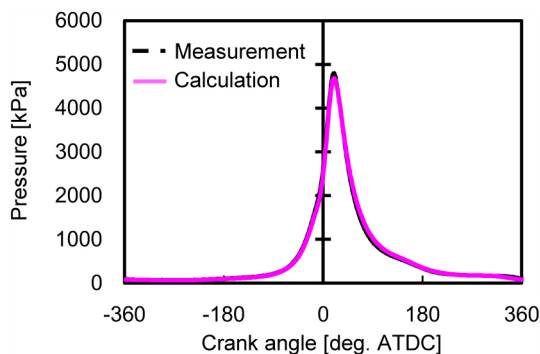


Figure 2. Outline of 1D engine cycle simulation model



(a). Power output and torque



(b). Pressure in cylinder

Figure 3. Comparison of power output, torque and pressure in cylinder

Calculation of Heat Transfer in Engine Components

The heat in the engine components (e.g., cylinder head, cylinder) is transferred via three-dimensional routes. To convert such a route to the 1D thermal simulation model, we tried discretization to a number of zones as Figure 4 shows. The cylinder body and the sleeve are discretized in the direction of the cylinder axis as well. Depending on the piston position, the heat transfers are calculated in both cases from combustion gas to the sleeve directly and to the sleeve via the piston and the piston rings. The thermal conductivity of each component, such as the cylinder head, cylinder, and valves, are also defined in the model. Moreover, the heat transfer coefficients are defined on each boundary surface where the different materials are in contact. In places where a part such as the valve guide and valve seat is interference-fit, an infinitely large heat transfer coefficient (i.e., a thermal contact resistance of 0) is set.

Heat Transfer Coefficient between Cylinder Body and Sleeve

The predominant cylinder construction in small displacement, air-cooled engines is a cast-iron sleeve molded in the aluminum body. It is known that in this type of cylinder, a small clearance occurs between the cylinder body and the sleeve when the engine is operating under high temperature conditions due to the difference in the thermal linear expansion coefficients of aluminum and cast iron. The decrease of contact surface between the two parts due to the clearance interferes

with the heat transfer from inside the cylinder to the cooling fins. To incorporate the said conditions into the 1D thermal simulation model, we created test equipment to measure the heat transfer coefficient between the cylinder body and the sleeve. As the test equipment in Figure 5 shows, a temperature gradient was created in the cylinder by heating the cylinder bore surface uniformly with high-temperature fluid (oil) and cooling the outside with low-temperature fluid (water). All the cooling fins were removed from the cylinder body for uniform cooling of the external wall of cylinder.

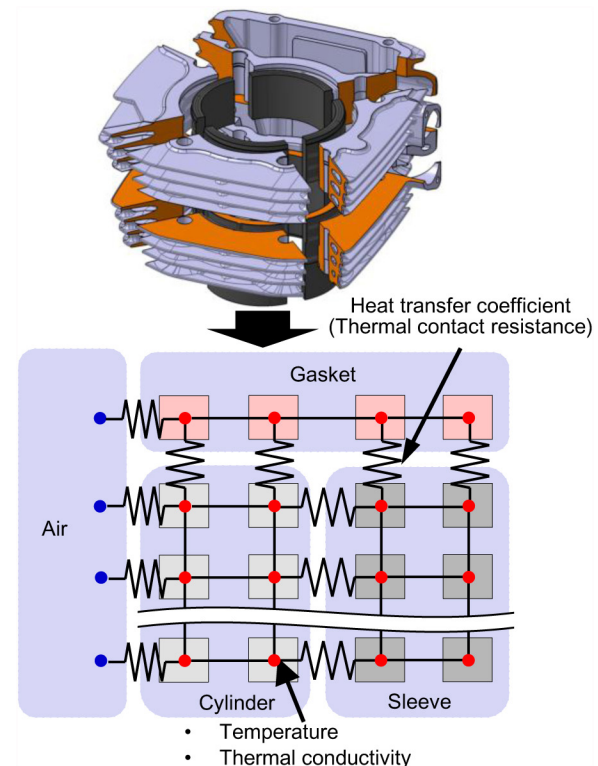


Figure 4. Outline of heat transfer model in 1D thermal simulation

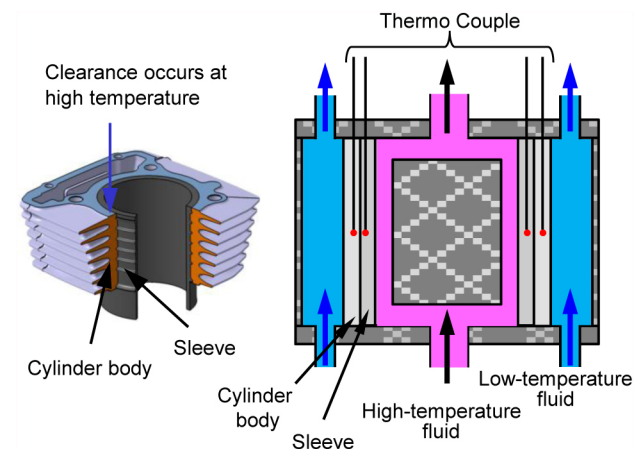


Figure 5. Test equipment for measurement of heat transfer coefficient between cylinder body and sleeve

In these tests, a uniform temperature in the axial direction of the cylinder was created by increasing the flow rates of the high-temperature and the low-temperature fluids as much as

possible. Under these conditions, the temperature gradient exists only in the radial direction of the cylinder as Equation (1) shows.

$$\frac{\partial^2 T}{\partial r^2} + \frac{1}{r} \frac{\partial T}{\partial r} = 0 \quad (1)$$

Where T is the temperature in the cylinder, and r is the distance in the radial direction of cylinder. Under the above assumption, the temperature distribution in the radial direction of the cylinder can be represented by the Equation (2).

$$T(r) = C_1 \ln r + C_2 \quad (2)$$

where C_1 and C_2 are constants.

Also, the heat flux, q , in the radial direction can be represented by Equation (3).

$$q(r) = -k \cdot \frac{\partial T}{\partial r} = -\frac{C_1 \cdot k}{r} \quad (3)$$

where k is the thermal conductivity of the cylinder.

The heat transfer coefficient between the cylinder body and the sleeve can be determined by dividing the heat flux on the boundary surface by the temperature difference. However, as the cylinder body and the sleeve of an actual engine are thin, it is difficult to measure the temperature distribution. We therefore decided to calculate the temperature distribution in the cylinder body and sleeve using the heat transfer coefficient between the high-temperature fluid and the sleeve, and between the low-temperature fluid and the cylinder body.

Accordingly, these heat transfer coefficients were acquired through a separate experiment using a dummy cylinder. Here, we presumed that the heat transfer coefficient between the fluid and the solid does not depend on the solid material.

Under the above-mentioned conditions, the heat transfer coefficient between the cylinder body and the sleeve is determined by the following steps.

1. As Figure 6 (a) shows, using the dummy cylinder made of a single material having a known thermal conductivity, the temperature distribution in the radial direction in the dummy cylinder, and the fluid temperatures on the heating side and the cooling side were measured.
2. Using the outcomes from Step 1, the temperature and the heat flux of the dummy cylinder were determined from Equations (2) and (3).
3. Using the outcomes from Step 2, the heat transfer coefficients α_{Hot} and α_{Cool} between the high-temperature

fluid and the wall, and between the low-temperature fluid and the wall, respectively, were calculated using Equations (4) and (5).

$$\alpha_{\text{Hot}} = \frac{q(r_{\text{Hot}})}{T_{\text{Hot}} - T(r_{\text{Hot}})} \quad (4)$$

$$\alpha_{\text{Cool}} = \frac{q(r_{\text{Cool}})}{T(r_{\text{Cool}}) - T_{\text{Cool}}} \quad (5)$$

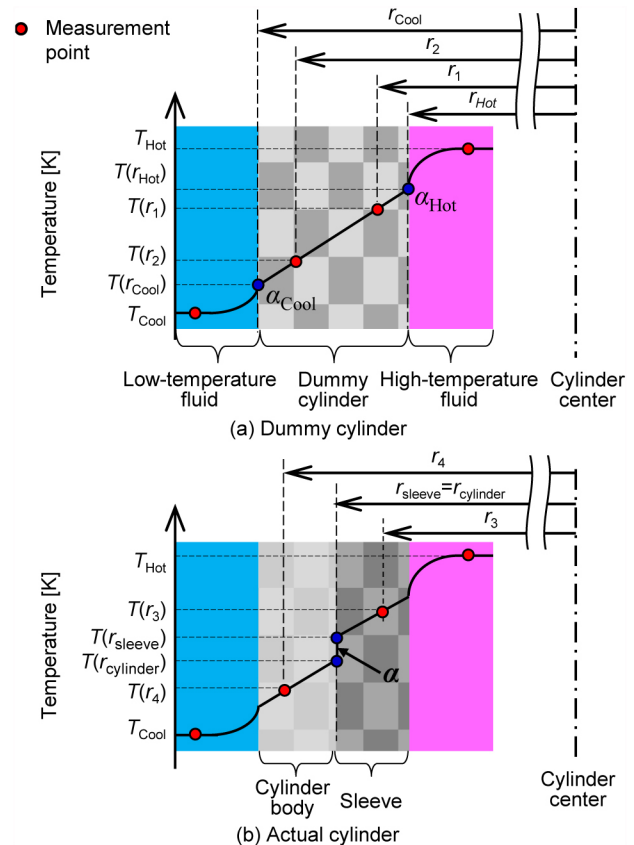


Figure 6. Calculation technique of heat transfer coefficient between cylinder body and sleeve

4. As Figure 6(b) shows, using the actual cylinder body and the sleeve, the temperatures of the sleeve, cylinder body, the high-temperature fluid, and the low-temperature fluid were measured.
5. Using the temperature measured in Step 4 and the heat transfer coefficients determined in Step 3, the radial distributions of the temperature and the heat flux in the cylinder body and the sleeve were determined, and lastly the heat transfer coefficient between the cylinder body and the sleeve was calculated.

$$\alpha = \frac{q}{T(r_{\text{Sleeve}}) - T(r_{\text{Cylinder}})}$$