

Thermal Analysis of the Exhaust Line Focused on the Cool-Down Process

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ABSTRACT

At the engine restart, when the temperature of the catalytic converter is low, additional fuel consumption would be required to warm up the catalyst for controlling exhaust emission. The aim of this study is to find a thermally optimal way to reduce fuel consumption for the catalyst warm up at the engine restart, by improving the thermal retention of the catalytic converter in the cool down process after the previous trip.

To make analysis of the thermal flow around the catalytic converter, a 2-D thermal flow model was constructed using the thermal network method. This model simulates the following processes: 1) heat conduction between the substrate and the stainless steel case, 2) heat convection between the stainless steel case and the ambient air, 3) heat convection between the substrate and the gas inside the substrate, 4) heat generation due to chemical reactions. The points to be especially noted are: a) in the cool down process, free convection of the gas inside the substrate was based on Darcy's law, b) in the engine operating condition, chemical phenomena and species mass balance in gas phase and catalyst surface was considered. The model was verified by comparing calculated results with experimental measurements.

According to this thermal flow model, in the cool down process, heat from the substrate was mainly conducted through the stainless steel case, and dissipated to the ambient air. The effect of free convection of the gas inside the substrate was predicted to be small. Therefore, an effective way to improve the thermal retention of the catalytic converter was to interrupt the heat conduction between the substrate and the boundary surface to the ambient. In this paper, we propose an optimal way to improve the thermal retention of the catalytic converter while not to deteriorate its cooling performance at high load operation.

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INTRODUCTION

Engine operation with spark timings aggressively retarded from maximum break torque timings for the catalyst activation is an effective means to reduce hydrocarbon emissions at cold start [1]. On the other hand, this operation lowers the engine thermal efficiency, thus deteriorating the vehicle fuel economy [2]. Therefore, reduction of the time required for this operation is desired. A large number of studies have been made on the thermal behavior of the converter. Baba et al. investigated the thermal behavior and the conversion emissions under a warm-up condition using an 1-D model [3], whereas only few studies have so far been made on the cooling characteristics of the converter during parking [4], [5].

The purpose of this study is to improve the fuel consumption at the scene of the engine restart after short parking. We propose an optimal way to improve thermal retention of the catalytic converter using the thermal flow model which can calculate

transient temperature inside the catalytic converter. In addition, we also investigated this effect experimentally by the test vehicle.

MATHEMATICAL MODEL

As shown in [Figure 1](#), the thermal flow of the catalytic converter is described in a 2-D structure. Z-axis is parallel to the gas channels. X-axis is vertical to the gas channels. It is assumed that thermal flow along X-axis is equivalent to Y-axis due to the cylindrical structure. Therefore, we selected a 2-D Cartesian model to reduce the computational complexity. This 2D model was constructed by combination of the energy balance equations, the mass balance equations, and the chemical reaction expressions. The mass balance equations and the chemical reaction expressions were referred by Ramanathan et al. [6]. The energy balance equations were solved using the thermal network method [7].

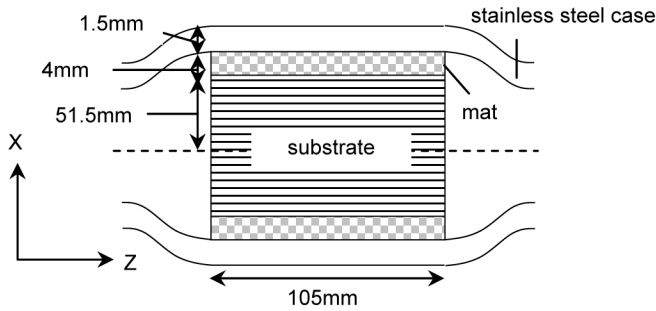


Figure 1. Section of the catalytic converter

Basic Assumption

The basic assumptions for the 2-D thermal flow model are shown below.

1. The substrate temperature inside the same element is constant.
2. The gas stream flow is uniform along the gas channels under the engine operating condition.
3. The gas stream inside the channel is free convection in the cool down process and obeyed Darcy's law [8].
4. The exhaust gas and the air are ideal gases.
5. The phenomena taking place in the channels are one-dimensional and independent of the other channels.
6. Chemical reactions occur on the surface of the catalyst

Energy Balance

As shown in Figure 2, the energy equation for the gas within the substrate in the (i, j) element is given below.

$$\begin{aligned} & (mc)_{gas_i,j} \frac{dT_{gas_i,j}}{dt} \\ & = n_j (Q_{cond_gas_i-1,j} - Q_{cond_gas_i+1,j} \\ & + Q_{flow_i-1,j} - Q_{flow_i+1,j} + Q_{conv_i,j}) \end{aligned} \quad (1)$$

Where i, j are the element number. Since the time derivative related term and the heat conduction term are very small compared with the convection flow term in the engine operating condition, the following equation could be derived.

$$n_j (Q_{flow_i-1,j} - Q_{flow_i+1,j} + Q_{conv_i,j}) = 0 \quad (2)$$

The heat conduction, the heat convection flow, and the heat convection term can be expressed as

$$Q_{cond_i-1,j} = \frac{T_{i-1,j} - T_{i,j}}{R_{i-1,j}} \quad (3)$$

$$Q_{flow_i-1,j} = (\rho c A u)_{i-1,j} (T_{i-1,j} - T_{i,j}) \quad (4)$$

$$Q_{conv_i,j} = \frac{T_{sub_i,j} - T_{gas_i,j}}{R_{i,j}} \quad (5)$$

The thermal resistance R could be defined as follows. For the heat conduction, $R_{i-1,j}$ could be expressed as

$$R_{i-1,j} = \left(\frac{l}{\lambda A} \right)_{i-1,j} \quad (6)$$

For the heat convection, $R_{i,j}$ could be expressed as

$$R_{i,j} = \left(\frac{1}{hA} \right)_{i,j} \quad (7)$$

Since the gas stream flow was assumed to be uniform along the gas channel under the engine operating condition, the velocity in the gas channel was expressed as

$$u = \frac{Q}{\sum n_j A_{channel}} \quad (8)$$

On the other hand, since the gas stream inside the channels was assumed to be free convection in the cool down process and obeyed Darcy's law, the velocity in the gas channel was expressed as

$$u = -\frac{\kappa}{\mu} \frac{\partial P}{\partial z} \quad (9)$$

κ is the permeability and calculated as follow:

$$\kappa = K \frac{\mu}{\rho g} \quad (10)$$

The hydraulic conductivity K should be fundamentally obtained using experiment measurements. But in this paper, the most suitable value was selected from the result of the experiment and the numerical analysis. For fully developed laminar channel flow, the heat transfer coefficient between the exhaust gas and the substrate was determined using the following equations [9].

$$h_{gas} = \frac{Nu \lambda_{gas}}{d} \quad (11)$$

$$Nu = 0.571 \left(Re \frac{d}{z} \right)^{2/3} \quad (12)$$

The energy equation for the substrate in the (i, j) element is given below.

$$\begin{aligned} (mc)_{i,j} \frac{dT_{sub_i,j}}{dt} = & Q_{cond_sub_i-1,j} - Q_{cond_sub_i+1,j} \\ & + Q_{cond_sub_i,j-1} - Q_{cond_sub_i,j+1} \\ & - n_j Q_{conv_i,j} + n_j Q_{reaction_i,j} \end{aligned} \quad (13)$$

In the cool down process, the following equation could be derived.

$$\begin{aligned} (mc)_{i,j} \frac{dT_{sub_i,j}}{dt} = & Q_{cond_sub_i-1,j} - Q_{cond_sub_i+1,j} \\ & + Q_{cond_sub_i,j-1} - Q_{cond_sub_i,j+1} \\ & - n_j Q_{conv_i,j} \end{aligned} \quad (14)$$

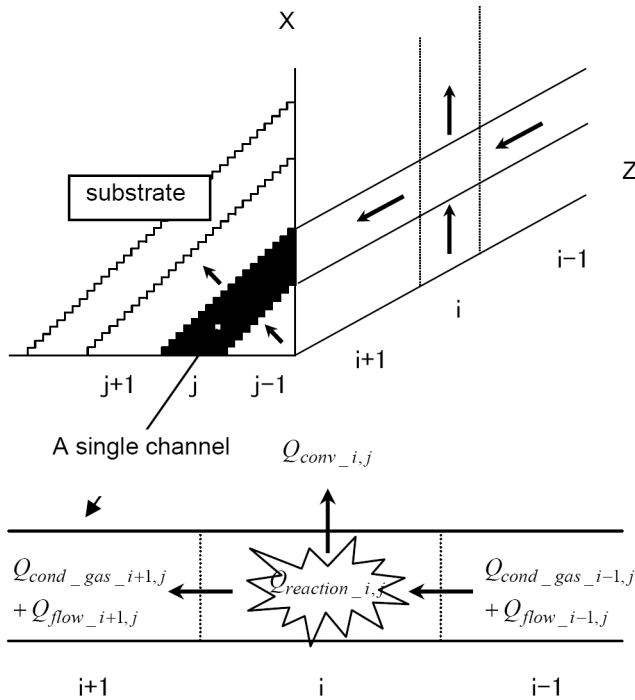


Figure 2. Thermal flow model (substrate)

As shown in Figure 3, the energy equation for the stainless case in the (i, j) element is given below.

$$\begin{aligned} (mc)_{i,j} \frac{dT_{case_i,j}}{dt} = & Q_{cond_case_i-1,j} - Q_{cond_case_i+1,j} \\ & + Q_{cond_case_i,j-1} - Q_{conv_surface_i,j+1} \end{aligned} \quad (15)$$

In the engine operating condition, the heat transfer between the stainless case and the surrounding air is forced convection. The heat transfer coefficient was calculated using the following equation [10].

$$Nu = \frac{h_{air_forced} D}{\lambda} = 0.0296 Re^{4/5} Pr^{1/3} \quad (16)$$

In the cool down process, the heat transfer is free convection. Therefore the heat transfer coefficient was estimated using the following equation.

$$h_{air_free} = 10 \quad (17)$$

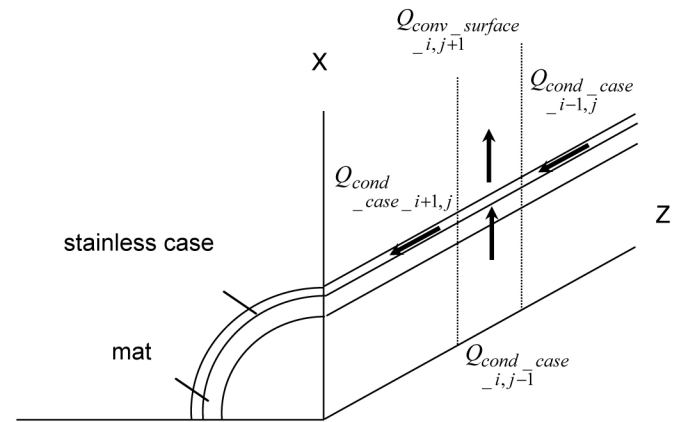


Figure 3. Thermal flow model (stainless case)

MODEL VALIDATION

Experimental Set-Up

At first, temperature distributions of the catalytic converter were measured at the engine test bench to verify the thermal flow model by comparing calculated results with experimental measurements. Figure 4 shows the set-up of the engine test bench. The thermocouple locations are shown in Figure 5. Thermocouples in the substrate were located at three different points along the axial direction in the radial center and along the radial direction in the axial center. Two thermocouples in the mat and four thermocouples at the surface of stainless case were located at the axial center. In addition, two thermocouples were located at the middle of the inlet cone and outlet cone to measure the gas temperature.

In the next step, this model was confirmed using the test vehicle on the chassis dynamometer. Figure 6 shows the setup of the chassis dynamometer. As Figure 7 indicates, one thermocouple in the substrate was located at the radial and axial center. Four thermocouples at the surface of the stainless

case were located at the axial center. Engine specifications, catalytic converter properties and test conditions are shown in Table 1, 2, 3, 4.

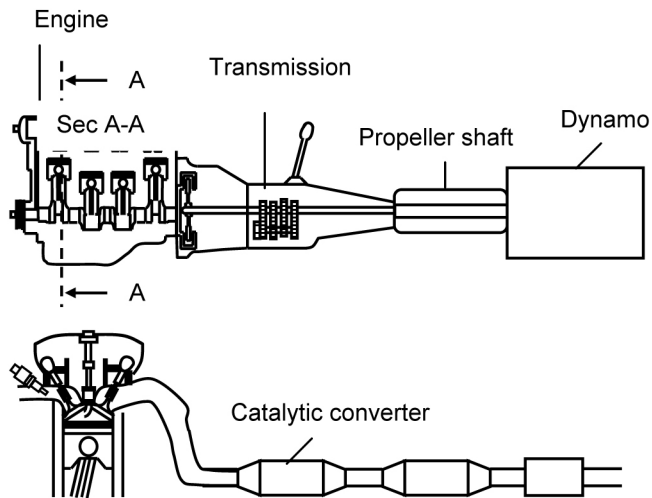


Figure 4. Engine test bench.

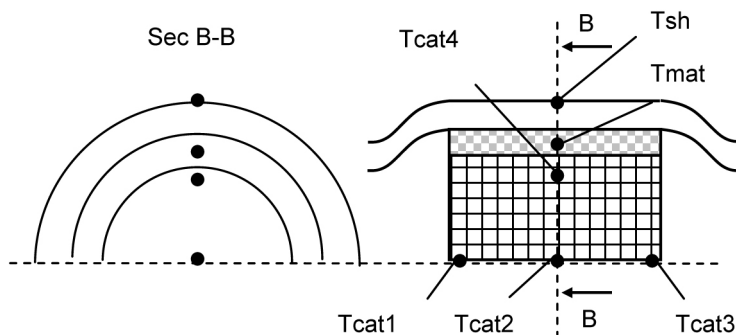


Figure 5. Thermocouple locations along the axial and radial directions of the catalytic converter at the engine test bench

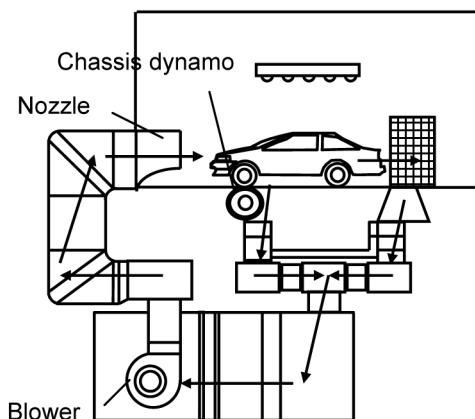


Figure 6. Chassis dynamo-meter

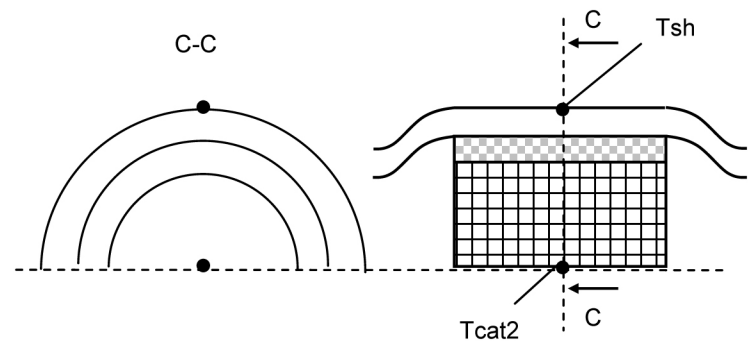


Figure 7. Thermocouple locations along the axial and radial directions of the catalytic converter on the chassis dynamo-meter

Table 1. Engine specifications

Displaced volume	1797 cc
Stroke	88.3 mm
Bore	80.5 mm
Compression ratio	13.0
Number of Cylinders	4

Table 2. Catalytic converter properties

Mass : Substrate	502g
Mass : Mat	41g
Mass : Stainless steel case	730g
Wall thickness : substrate	0.09mm
Thickness : Mat	4mm
Thickness : Stainless case	1.5mm

Table 3. Test conditions in the engine operating condition

Inlet exhaust gas flow rate	15g/s
Inlet exhaust gas temperature	560°C
Initial converter temperature	25°C
Operating time	360 seconds
Ambient temperature	25°C
Wind velocity	Velocity equivalent to vehicle speed

Table 4. Test conditions in the cool down

Initial substrate temperature	650°C
Cool down time	1200 seconds
Ambient temperature	25°C
Wind velocity	0m/s

Engine Test Bench Result

Temperature distributions of the converter were confirmed at the engine test bench to compare with numerical results to validate the thermal flow model.