

Development of a New Ceramic Substrate with Gas Flow Control Functionality

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ABSTRACT

Emission regulations in many countries and regions around the world are becoming stricter in reaction to the increasing awareness of environment protections, and it has now become necessary to improve the performance of catalytic converters to achieve these goals. A catalytic converter is composed of a catalytically active material coated onto a ceramic honeycomb-structured substrate. Honeycomb substrates play the role of ensuring intimate contact between the exhaust gas and the catalyst within the substrate's flow channels. In recent years, high-load test cycles have been introduced which require increased robustness to maintain low emissions during the wide range of load changes. Therefore, it is extremely important to increase the probability of contact between the exhaust gas and catalyst. To achieve this contact, several measures were considered such as increasing active sites or geometrical surface areas by utilizing substrates with higher cell densities or larger volumes. These measures, however, led to greater consumption of precious metals and decreased vehicle power by increasing pressure losses. Therefore, a new concept substrate, which focuses on gas flow redistribution, has been developed to overcome these negatives. The key points of this development include a compound cell structure design which consists of a higher cell density area in the center portion of the substrate completely surrounded by a lower cell density area and optimization of the cell design for each portion to improve the efficiency of the catalytic converter. As a result, this newly developed honeycomb substrate shifts the trend line relationship of catalytic performance and pressure loss to a higher level. In addition, it reduces precious metal usage, as well as the volume of catalytic converters while maintaining catalytic performance equivalent to that of a conventional honeycomb substrate (400 cell density).

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1. INTRODUCTION

As emission regulations become stricter every year, it has become imperative to improve the performance of catalytic converters used in automobiles powered by internal combustion engines. To achieve high level purification performance, it is important to cause a reaction between the exhaust gas and the catalyst at a high contact rate. The measures that have been tried so far include improvements on the catalyst side, such as using a washcoat to apply a catalyst material to a honeycomb substrate having a uniform cell structure to ensure a sufficient number of active sites of the precious metals in the catalyst or to increase the thermal resistance of the materials⁽¹⁾⁽²⁾⁽³⁾, in addition to improvements on the substrate side, such as increasing the surface area of the honeycomb substrate (by increasing cell density) and its volume. However, increasing the surface area may undesirably increase pressure loss, which can lower the vehicle's output performance. Therefore, an attempt has been made to achieve both a high purification level and lower pressure loss by combining an increase in the surface area with a thinner cell wall.⁽⁴⁾ Reducing the

wall thickness further is difficult, however, because of concern about structural integrity, and it has become difficult to improve performance using only the conventional approach to improving cell shape. Therefore, focus was placed on the flow velocity distribution of the exhaust gas that circulates inside the substrate as a new potential way to ensure a high contact rate. It has been reported that catalyst performance can be efficiently improved by uniformizing flow velocity distribution through an improvement in the diffuser of a catalytic converter.⁽⁵⁾⁽⁶⁾ However, since catalytic converter improvements are highly subject to spatial restrictions, it is presumed that there are limits to achieving both a high purification level and low pressure loss. With the conflicting goals of achieving both a high purification level and low pressure loss, an attempt was made to control the flow velocity distribution by means of a new honeycomb structure (a compound cell structure having an inside area with a higher cell density and an outside area with a lower cell density). The catalyst utilization efficiency was maximized by optimizing the cell specifications of the inside and outside areas, and their effects under

an actual usage environment were compared with conventional substrates, using actual vehicles and engines, and reported in this paper.

2. CONCEPT OF FLOW VELOCITY DISTRIBUTION CONTROL SUBSTRATE

2.1 New Development Concept

The main cause of high exhaust emissions accompanying high load fluctuations, such as those used in the US06 test cycle, is the inability to achieve a sufficient reaction time because of insufficient contact between the gas and the catalyst during high load. Fig. 1 shows the results of a CFD analysis of the flow velocity distribution in the substrate's in-plane direction in the emission discharge area. The figure shows that the flow velocity distribution became skewed in the substrate's in-plane direction and that the exhaust gas flow velocity was especially high in the center area of the substrate but tended to decrease toward the outside area.

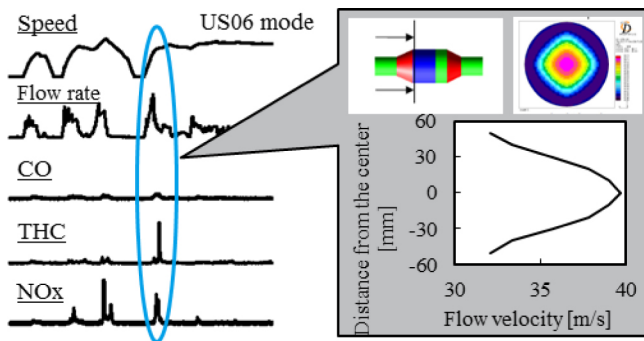


Fig. 1. Flow velocity distribution in the in-plane direction of a uniform substrate

Therefore, to efficiently carry out purification, it is important to ensure that the catalytic reaction progresses over the entire surface of the substrate by reducing the skew in the flow velocity distribution and controlling it to become more uniform. By controlling the flow velocity distribution, it is possible to effectively control the catalytic reaction time (t) and the catalyst deterioration state (A , Ea) as shown in Equation 1, which expresses the catalytic reaction, thereby improving the catalyst utilization efficiency.

$$Q = A \exp\left(-\frac{Ea}{RT}\right) \times C \times t \quad (1)$$

Q : Catalyst purge amount

A : Frequency factor

Ea : Activation energies

C : Density

T : Temperature

t : Reaction Time

2.2 Compound Cell Design

To achieve a uniform flow velocity distribution, it is necessary to control the reaction time, making it uniform over the entire area from the inside to the outside areas of the substrate. Therefore, as shown in Fig. 2, the reaction time in the substrate's in-plane direction was simulated using a parallel circuit model, and the reaction times in the inside and outside areas were computed. The reaction time in each area depends on the exhaust gas flow velocity if the substrate length is constant, and the flow velocity affects the friction-caused resistance that occurs when the gas flows through the substrate.

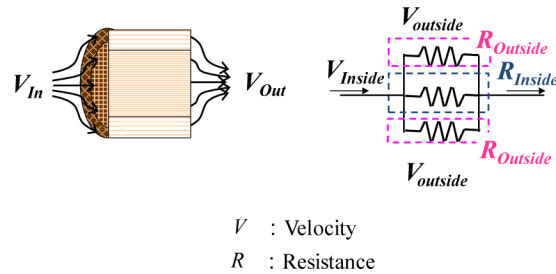


Fig. 2. Concept of flow velocity distribution control

Furthermore, since the substrate parameters that affect the resistance can be determined by the pressure loss (hydraulic diameter)(7) when the gas passes through the cells and cross section S , the flow velocity in each spot can be determined from the overall flow velocity V_{in} , the resistance ratio between the inside and outside cells (hydraulic diameter ratio), and the area ratio between the inside and outside cells. Table 1 shows the parameters used for designing the compound cell structure for controlling the flow velocity distribution.

Table 1. Control parameters for designing the compound cells

	Compared with	
	Hydraulic diameter (D_{inside}) ² /($D_{outside}$) ²	Surface area (S_{inside})/(S_{total})
High		
Low		

2.3 Compound Cell Design Optimization

In order to maximize catalyst utilization efficiency, the analysis procedure shown in Fig. 3 was used to optimize the compound cell design specifications.

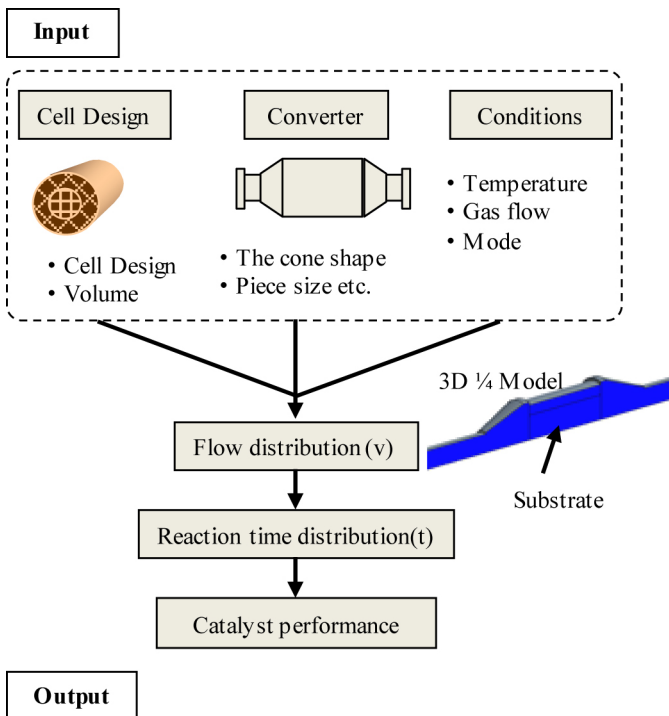


Fig. 3. Compound cell design optimization flow

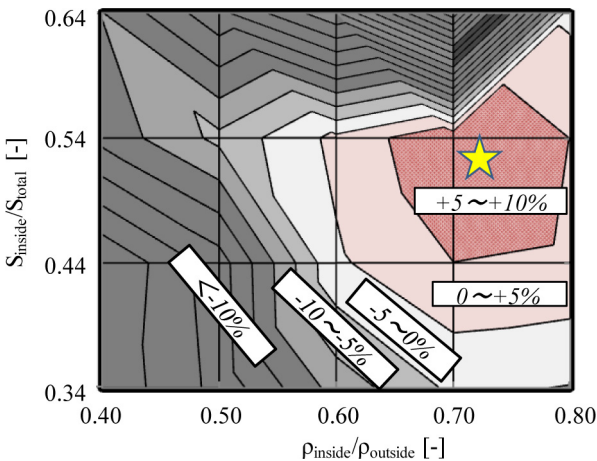


Fig. 4. Purification performance ratio relative to a conventional substrate when the intake air rate is 20 g/s

For comparison, a conventional uniform substrate (4.5 mil/400 cpsi, round shape, with volume of 0.9 liters) and a compound cell substrate (round shape, with volume of 0.7 L) were selected. The cell shape, volume, and operating condition of the substrate were selected as the input items to be used for the analysis. For the catalytic converter shape to be used, the pipe diameters in the front and rear portions were set at 60.5 mm and the lengths of the front and rear cones were set at 55 mm. For the input values, those used in the US06 test cycle were used. Under these conditions, STAR-CCM and a 1/4-size 3D model in a CFD analysis were used to compute the exhaust gas flow velocity distribution, while varying the resistance ratio between the inside and outside cells (hydraulic diameter ratio) and the area ratio between the inside and total areas, which are important parameters when designing the compound cells. Furthermore, by dividing the obtained flow velocity distribution in the substrate's in-plane direction and allocating the input gas volume to the individual areas,

the purification performance of the individual areas was computed (Equation 1), and then combined to compute the overall purification performance. Fig. 4 shows a purification performance ratio between the compound cells and a conventional substrate (4.5 mil/400 cpsi and volume of 0.9 liters) under the conditions of an air intake rate of 20 g/s and a temperature of 400°C, with the resistance ratio between the inside and outside cells shown on the horizontal axis and the area ratio between the inside and total areas shown on the vertical axis.

Fig. 4 shows that there are regions in both the resistance ratio between the inside and outside cells and the area ratio between the inside and outside areas, that provide excellent purification performance, and therefore $\rho_{\text{inside}}/\rho_{\text{outside}} = 0.74$ and $S_{\text{inside}}/S_{\text{total}} = 0.5$ were set for the compound cell design for controlling the flow velocity distribution. Fig. 5 shows the flow velocity distribution using these settings, demonstrating a trend toward a more uniform flow velocity distribution as planned.

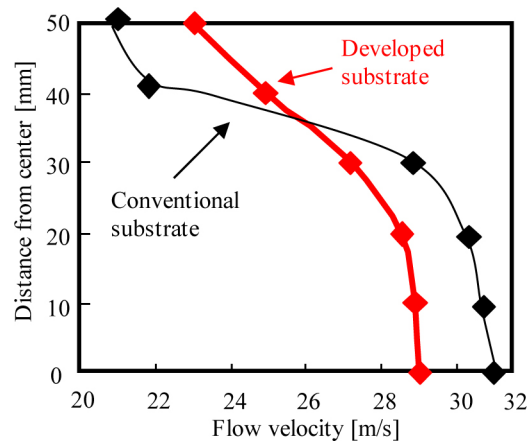


Fig. 5. Flow velocity distribution simulation

In terms of cell wall thickness and cell pitch, a cell shape capable of achieving a geometric surface area (GSA) relative to the conventional substrate (4.5 mil/400 cpsi and volume of 0.9 liters) was selected, taking into account the relationship to pressure loss. For the compound cell design specifications, an inside cell area with 3.5mil/600cpsi, an outside cell area with 4.5 mil/400cpsi, and the area ratio of $S_{\text{inside}}/S_{\text{total}} = 0.5$ were selected.

2.4 Velocity Distribution Uniformity

Uniformity γ can be used as an index expressing the uniformity of velocity distribution and is determined using Equation 2. As the value of γ approaches 1, the velocity distribution becomes more uniform.

$$\gamma = 1 - \sum_{i=1}^N \frac{1}{2} \frac{|V_i - \bar{V}|}{\bar{V} S} S_i \quad (2)$$

V_i : The current velocity of the cell

$\bar{V}$: The average current velocity of substrate

S_i : Cross-sectional area of the cell

S : Cross-sectional area of substrate