NIPPON STEEL TECHNICAL REPORT No. 70 JULY 1996

UDC66.097.5:621.43.068

Development of High Performance Metal Catalyst Support for Cleaning Automobile Exhaust Gases

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Abstract:

Nippon Steel is pushing ahead with the development of high-performance metal supports to meet increasingly stringent future automobile exhaust gas regulations. The following characteristics are required of catalytic converters: (1) high cleaning performance inherent in catalysts; (2) low pressure loss to deliver desired horsepower; and (3) compact size to ensure siting freedom. Metal supports are advantageous over ceramic supports in all of these three characteristics. Aiming at further functional improvements, Nippon Steel is working to reduce the thickness of honeycomb foils, optimize metal support design, and develop an integral mounting method, among other things. The integral mounting method will contribute to lowering total catalytic converter cost by adopting a fabrication process that utilizes the flexibility of metals and making metal supports equal to ceramic supports in terms of price competitiveness. An electrically heated metal catalyst (EHC) system is being completed as a future technology.

1. Introduction

Environmental conservation have been one of the most important keywords for technology development in recent years and will continue to be so in the future. Centering on exhaust gas cleaning technology, the automobile industry has long took the initiative in this field. Automotive exhaust gas cleaning systems depend to a large extent on exhaust system catalyst technology as well as electronic control technology, such as for the air-fuel mix. Particularly, catalysts were made indispensable for controlling automobile emissions by the 1970 Clean Air Amendments (popularly known as the Muskie Act) of the United States. In 1974, catalytic converters were installed on 1975-model cars for the first time in Japan [1-3]. Initial catalytic converters used pellet catalysts or pellets of activated alumina coated with such noble metals as platinum and palladium. As a result of the progress of honeycomb substrate manufacturing technology, monolith catalysts or assemblies of minute tubes are now adopted on almost all automobiles because they offer low pressure loss and are light in

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weight[1]. Supports used as monolith catalysts are mostly cordierite ceramic supports now. In recent years, increasing attention has been paid to metal supports composed of heat-resistant stainless steel foils to achieve still lower pressure loss and higher performance[1].

Nippon Steel started developing metal supports in 1986 and launched its metal support production business in 1991. Before commencing its metal support business, the stable manufacture of a durable support structure was Nippon Steel's primary target, and developing suitable materials, structures, and processes was the major theme. Since the metal support business was launched, the emphasis has shifted to developing technology for reducing metal support product costs (a low-cost nonbrazing process has already been completed) and developing new metal support products of added functionality to meet even stricter exhaust gas emission standards expected to be introduced in the future.

In response to regulations in the United States and Europe, Nippon Steel is developing a method of integrally mounting metal foils and electrically heated catalysts (EHCs) with excellent initial cleaning performance. This article introduces the design concepts and technological outlines of these high performance catalyst supports.

2. Description of Metal Supports

Nippon Steel's metal supports are described briefly here. The metal support consists of a honeycomb core comprising flat and corrugated ferritic stainless steel foils, each measuring 20 or so micrometers in thickness and alternately formed into a spiral. The honeycomb core thus formed is then inserted into a jacket. A highly heat-resistant nickel-base filler metal is used to braze the flat and corrugated foils and the honeycomb core and jacket. **Photo 1** shows a completed metal support. The metal support is then coated with the catalyst and welded with the cones, flanges and other parts to form a catalytic converter.

3. Development of High Performance Metal Support

3.1 Description of high performance metal support

As an automotive component, the functions required of the catalytic converter are high cleaning performance and low pressure loss, if excluding the mandatory durability. Low pressure loss is not directly related to exhaust gas cleaning performance, but is indispensable for horsepower and fuel economy improvements, and, therefore, is as important as the high exhaust gas cleaning performance for the automobile.

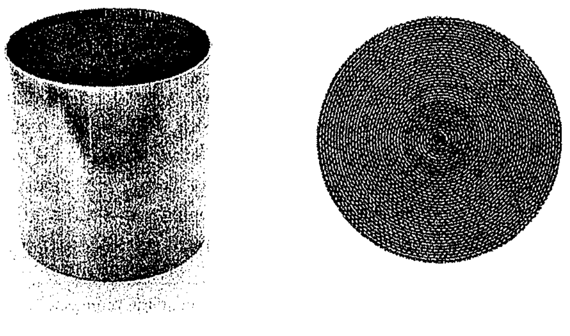


Photo 1 General view of metal support

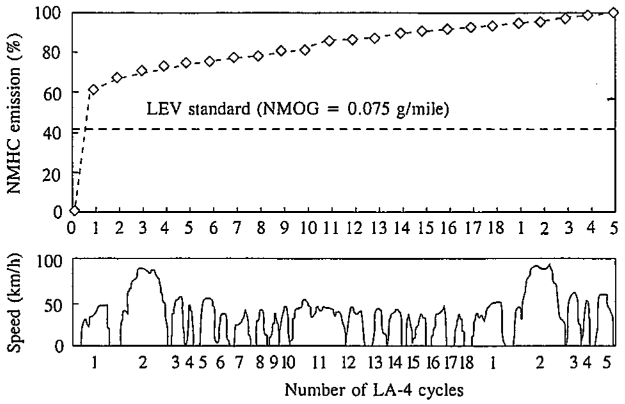


Fig. 1 HC emission rate in LA-4 mode[4]

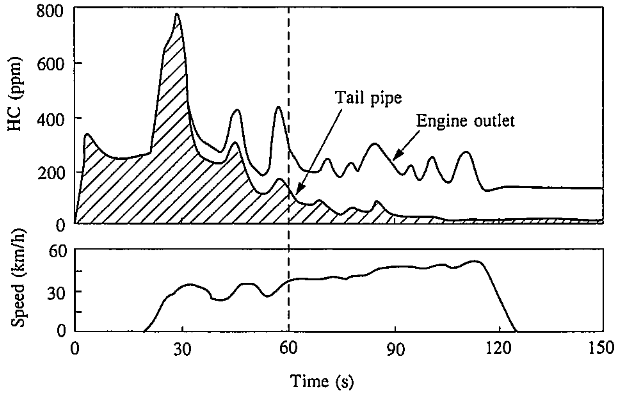


Fig. 2 HC emission and conversion behavior at engine start[4]

The temperature at which an automotive emission control catalyst becomes active is said to be about 600 K. At lower temperatures, the catalyst does not properly function, resulting in exhaust gas, containing hydrocarbons (HC), carbon monoxide (CO) and nitrogen oxides (NO$_x$), being released into the atmosphere. **Fig. 1** shows the cumulative ratio of HC emissions per cycle to the total HC emissions in the LA-4 mode, one of the exhaust gas test modes. The catalyst is tested in its cold or cold-start condition. Immediately after the cold start of the engine, the catalyst is not fully warmed up. It is evident that 60% or more of the total HC emissions are discharged in the first cycle[4]. **Fig. 2** shows a more detailed analysis of the first cycle. A large amount of HC is emitted for about one minute after the start of the engine[4]. The engine is stopped for 10 minutes when it returns from cycle 18 to cycle 1 during the test. During this time interval, there is the possibility of the catalyst cooling below its active temperature.

To obtain high cleaning performance, therefore, it is important to heat the catalyst to the active temperature region soon after the start of the engine. This will minimize catalyst cooling and maintain the catalyst at the active temperature when the engine is stopped, and also shorten the time during which the catalyst is inactive.

During the warm-up of the metal support, the thermal energy of the exhaust gas is the only source of heat unless a special heating method such as electrical heating is employed. It is readily understood that reducing the heat capacity of the honeycomb core is advantageous for the early activation of the catalyst. The smaller heat capacity is not conducive for retaining the activated catalyst's temperature after the engine has stopped. Such a mounting method is required that allows for thermal insulation to prevent thermal dissipation. The above discussion shows that the exhaust gas cleaning performance of the metal support must be improved simultaneously by enhancing the characteristics of the honeycomb core and establishing a method of mounting the honeycomb core that has a thermal insulation effect.

As shown in **Fig. 3** and **Table 1**, the state of California in the United States enacted the low-emission vehicle (LEV) standards to reduce HC emissions to 1/150 of the unregulated levels[5]. In Europe, similar regulations will be adopted around the year 2000. These stringent standards require especially high initial exhaust gas cleaning performance. A catalyst light-off method that depends only on the thermal energy of the exhaust gas is sometimes unable to canter the problem of unconverted gas emissions immediately after a cold start. In such a case, the technology of externally heating the catalyst such as electrical heating becomes indispensable.

3.2 Increase in functionality of honeycomb core

3.2.1 Light-off performance

As described above, the catalyst during a cold start is heated by the thermal energy of the exhaust gas. The lower the heat capacity of the support, the faster the catalyst will be activated. **Table 2** compares the properties of a general metal support with a conventional ceramic support. Assuming the same wall area, the heat capacity of the support per unit wall area (kJ/K·m^2) is theoretically calculated as specific heat (kJ/kg·K) × density (kg/m^3) × {1 - void fraction (%)/100}/geometrical surface area per unit reactor volume (m^2/m^3). The calculated value is 0.09 for the metal support and about two-thirds lower compared with the 0.25 for the ceramic support. When coated with approximately 20 micrometers of washcoat, the metal support can fully retain its advantage. Nippon Steel is developing foil supports to reinforce the advantage of metal supports.

Fig. 4 shows the CO conversion efficiency measurements from a cold start to an idling condition of catalytic converters with metal supports composed of foils 20, 30, and 50 μm in thickness. Sharp improvements in the CO conversion efficiency are noted with the foil supports of the 20- and 30-μm thicknesses. This means that lowering foil thickness is effective in improving the cold-start exhaust gas cleaning performance of the metal-supported catalytic converters during the initial operation of the engine.

When foil thickness is reduced, however, foil stiffness diminishes by such a degree that the foils are deformed as they are twisted into the honeycomb core. Honeycomb cores are difficult to fabricate stably from foils less than 50 μm in thickness.

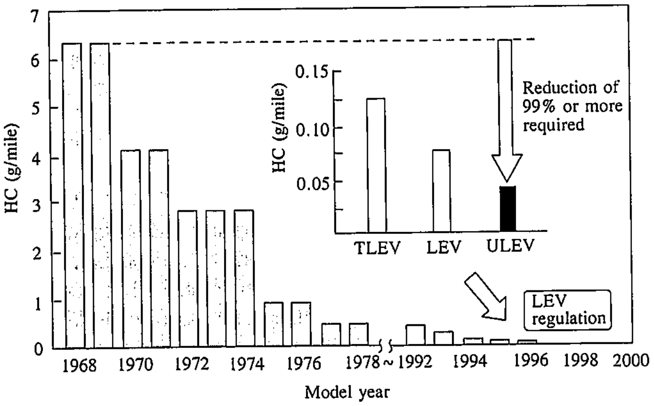


Fig. 3 Changes in emission regulations in California, United States

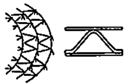
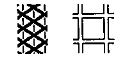
Table 1 NMOG standards and proportions of low-emission vehicles in California

Year	Existing vehicles		TLEV	LEV	ULEV	ZEV*	NMOG standard average
	0.039	0.25	0.125	0.075	0.04	0	(g/mile)
1994	10%	80%	10%				0.250
1995		85%	15%				0.231
1996		80%	20%				0.225
1997		73%		25%	2%	(2%)	0.202
1998		48%		48%	2%	(2%)	0.157
1999		23%		73%	2%	(2%)	0.113
2000				96%	2%	(2%)	0.073
2001				90%	5%	(5%)	0.070
2002				85%	10%	(5%)	0.068
2003				75%	15%	(10%)	0.062

*Specified (as of April 1996, ZEV standards will be postponed to 2003)

Source: California Air Resources Board (CARB)

Table 2 Comparison of properties of metal support and ceramic support at cell density of 400 cells/in^2 (excerpted from references[6-8] with some modifications)

	Metal support	Ceramic support
Material	Ferritic stainless steel (Fe-20Cr-5Al)	Cordierite ($2MgO{\text -}2Al_2O_3{\text -}5SiO_2$)
Specific heat (kJ/kg·K)	0.5	1.0
Density (kg/m^3)	7.2×10^3	$2.5{\text -}2.7 \times 10^3$
Thermal conductivity (W/m·K)	23.3	1.0
Coefficient of thermal expansion (K^{-1})	15×10^{-6}	0.6×10^{-6}
Standard wall thickness (m)	50×10^{-6}	150×10^{-6}
Void fraction (%)	91	73
Cell shape		
Geometrical surface area per unit reactor volume (m^2/m^3) (without washcoat)	3,600	2,800

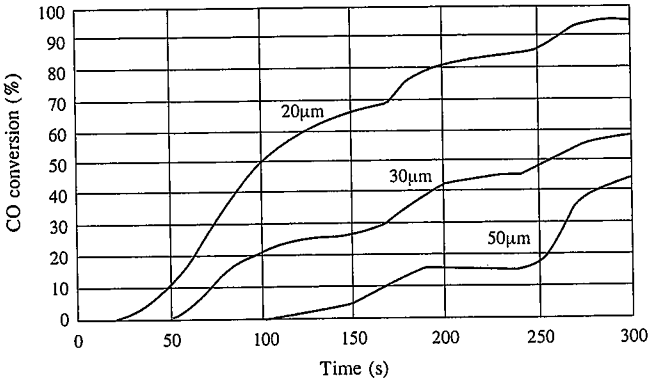


Fig. 4 Change in CO conversion under idling conditions after cold start

Nippon Steel is striving to develop the technology to fabricate metal supports from such thin foils.

The design of a metal support with high light-off behavior calls for factors, other than the heat capacity of foils, to be taken into account. For example, Oh and Cavendish[9] described the light-off behavior of a honeycomb core exposed to an exhaust gas stream, using the following three equations, and simulated the exhaust gas cleaning performance of the honeycomb core.

1)Basic equation based on the heat balance of the honeycomb core:

$$(1-\varepsilon)\rho_s\frac{\partial(C_{ps}T_s)}{\partial t}$$
$$=\lambda_s(1-\varepsilon)\frac{\partial^2 T_s}{\partial x^2}+hS(T_g-T_s)+a(x)\sum_{i=1}^{n}(-\Delta H)_i\bar{R}_i(\bar{c}_s,T_s) \quad\cdots\cdots(1)$$

2)Basic equation based on the heat balance of the exhaust gas:

$$\varepsilon\rho_g C_{pg}\frac{\partial T_g}{\partial t}=-\nu\rho_g C_{pg}\frac{\partial T_g}{\partial x}+hS(T_s-T_g) \quad\cdots\cdots(2)$$

3)Basic equation based on the mass transfer of the exhaust gas:

$$\varepsilon\frac{\partial c_{g,i}}{\partial t}=-\nu\frac{\partial c_{g,i}}{\partial x}-k_{m,i}S(c_{g,i}-c_{s,i}) \quad\cdots\cdots(3)$$

where ε = void fraction of the honeycomb core; ρ_s = solid density; ρ_g = gas density; C_{ps} = specific heat capacity of the solid; C_{pg} = specific heat of the gas; t = time; T_s = solid temperature; T_g = gas temperature; λ_s = thermal conductivity of the honeycomb core; ν = flow velocity of the gas; x = coordinate along the flow direction; h = heat transfer coefficient; S = geometrical surface area per unit reactor volume; a(x) = catalytic surface area per unit reactor volume (a measure of catalytic activity); $(-\Delta H)_i$ = heat of combustion of species i in the exhaust gas; $\bar{R}_i(\bar{c}_s, T_s)$ = reaction rate for species i at T_s where $\bar{c}_s$ is the gas coposition;$c_{g,i}$ = concentration of species i in the bulk gas; $c_{s,i}$ = concentration of species i on the solid surface; and $k_{m,i}$ = mass transfer coefficient of species i in the exhaust gas.

Figs. 5 and 6 show the CO conversion efficiencies simulated by the above basic equations when the inlet gas temperature is 600 and 700 K, respectively. When the inlet gas temperature is high, it is natural that the light-off performance of the catalyst should be high. Note that when the inlet gas temperature is 600 K, the light-off time of the catalyst decreases with decreasing cell density and that when the inlet gas temperature is 700 K, this behavior is totally reversed. This difference in light-off behavior may be explained as follows. When the inlet gas temperature is low, the heating rate is controlled by the heat capacity of the honeycomb core (first term on the left side of Eq. (1)), and the light-off performance of the catalyst improves with decreasing honeycomb core cell density. When the inlet gas temperature is raised, the light-off behavior of the catalyst is controlled by the heat transfer between the honeycomb core and the exhaust gas (second term on the right side of Eq. (1) and second term on the right side of Eq. (2)). Rapid catalyst light-off is favored by cell density with large geometrical surface area per unit reactor volume[9].

The inlet gas temperature varies with the engine type and control method or with the location of the catalytic converter. The amount of cell density must be optimized to suit the environment where the catalytic converter is to be mounted. When the catalytic converter is located directly below the exhaust manifold where the exhaust gas temperature is especially high, for example, the light-off performance of the catalyst may be effectively enhanced by reducing the heat capacity of the honeycomb core with the use of thinner foils, increasing the cell density, and raising the heat exchange area between the exhaust gas and the cell walls.

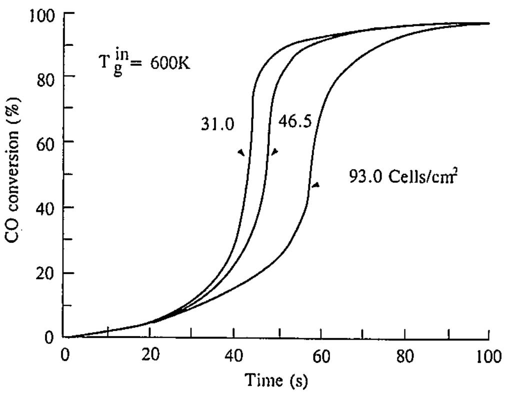


Fig. 5 Change in CO conversion from cold start when inlet gas temperature is 600 K[9]

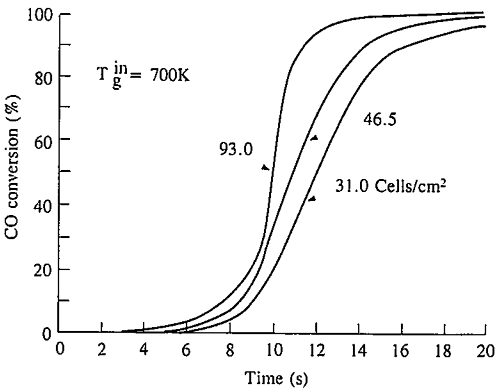


Fig. 6 Change in CO conversion from cold start when inlet gas temperature is 700 K[9]

From a design freedom viewpoint, Nippon Steel has the technology to change the cell density from 50 cells/in² (7.87 cells/cm²) to 600 cells/in² (93 cells/cm²), and can design honeycomb cores under optimum conditions for specific locations.

3.2.2 Low pressure loss

When the catalytic converter is used to clean exhaust gas, pressure loss in the exhaust gas invariably increases as it passes through the large-surface-area honeycomb structure. If the pressure loss is reduced while maintaining the desired exhaust gas cleaning capacity, fuel consumption can be reduced, leading to improved performance overall.

When ceramic and metal supports with a cell density of 400 cells/in² (62 cells/cm²) are compared in pressure loss, the void fraction is 73% for the ceramic support with a wall thickness of 150 μm and 91% for the metal support with a wall thickness of 50 μm. See **Table** 2. Since the metal support's void fraction is greater, it is considered to have a smaller pressure loss[7,8].

The gas pressure loss across channels with the length far greater than the cross-sectional area, as observed with catalytic supports, is mostly accounted for by the frictional loss between the gas stream and the channel wall surface. The frictional pressure loss can be described by Darcy's equation(10). From the equation, it is derived that the pressure loss changes not only with the void fraction of the honeycomb core but also with the geometric surface area per unit reactor volume and the cell length. If the catalytic support is designed according to the desired void fraction alone, its pressure loss properties may be degraded.

As shown in **Fig.** 7, the pressure loss of the exhaust gas stream through the individual cells of the honeycomb core arises from sudden decreases and increases in channel cross-sectional area at the cell inlet and outlet, respectively, and from the friction between the exhaust gas stream and the cell wall. When the flow in each channel is laminar (the Reynolds number Re is less than 2,300), the frictional pressure loss per cell is given by:

$$\Delta p = \frac{32 \mu L \nu_{cell}}{d_e^2} \quad \cdots\cdots(4)$$

or

$$\Delta p = \frac{64}{Re} \frac{L}{d_e} \frac{1}{2} \rho_g \nu_{cell}^2 \quad \cdots\cdots(5)$$

where μ = viscosity coefficient; L = channel length; ν_{cell} = gas velocity in the cell; and d_e = equivalent diameter.

The factor 64/Re on the right side of Eq. (5) is Darcy's frictional factor in circular pipe. This value is about 57/Re for typical square cells in ceramic supports and about 52/Re for cells of right-angled isosceles triangle-shaped section in metal supports. When compared in terms of cell shape, the metal supports have a pressure loss about 9% smaller than that of the ceramic supports.

Using $d_e = 4s_c/\ell = 4\varepsilon/S$ and $\nu_{cell} = \nu_a/\varepsilon$, the pressure loss equation for cells of right-angled isosceles triangle-shaped section may be rewritten as follows:

$$\Delta p = \frac{32 \mu L \nu (\nu_a/\varepsilon)}{(4\varepsilon/S)^2} = \frac{1.625 \mu L \nu_a S^2}{\varepsilon^3} \quad \cdots\cdots(6)$$

where s_c = cross-sectional area of the cell; ℓ = circumferential length of the cell; S = geometrical surface area per unit reactor volume of the honeycomb core; ε = void fraction of the honeycomb core; and ν_a = gas velocity outside of the cell (or gas velocity just before entry into the cell). When the gas velocity is equal, the frictional pressure loss is directly proportional to the cell length L and the square of the geometrical surface area per unit reactor volume S and inversely proportional to the cube of the void fraction ε. A larger void fraction (ε^3) reduces frictional pressure loss, but frictional pressure loss increases if the geometric surface area per unit volume S or the channel length L affects it greater than the void fraction.

To describe the frictional pressure loss equation more accurately, Hawthorn derived the following equation by considering the surplus pressure loss in the development stage of a boundary layer near the cell inlet(11):

$$\Delta p = \frac{64}{Re} \frac{L}{d_e} \frac{1}{2} \rho_g \nu_{cell}^2 \left(1 + 0.0445 Re \frac{d_e}{L}\right)^{0.5} \quad \cdots\cdots(7)$$

The pressure loss for turbulent flow (Re > 2,300) in a smooth-surfaced pipe can be obtained by the following empirical formula of Blasius(10):

$$\Delta p = \frac{0.3146}{Re^{0.25}} \frac{L}{d_e} \frac{1}{2} \rho_g \nu_{cell}^2 \quad \cdots\cdots(8)$$

The pressure loss for a sudden decrease in the cross-sectional area at the entrance of a pipe line and for a sudden increase in the cross-sectional area at the exit of a pipe line can be calculated by the frictional pressure loss equation to which the following is added(12):

$$\left\{(1-\varepsilon)^2 + \left(\frac{1}{C_c} - 1\right)^2\right\} \frac{1}{2} \rho_g \nu (\nu_a/\varepsilon)^2 \quad \cdots\cdots(9)$$
$$: C_c = 0.582 + \frac{0.0418}{1.1 - \varepsilon^{0.5}}$$

With a general catalytic support size (cell diameter of about 1 mm and support length of about 100 mm), however, the pressure loss due to friction in each cell is far greater than the pressure loss at the entrance or exit. It is safe to assume that the pressure loss across the catalytic support occurs due to pipe friction.

Fig. 8 shows the pressure loss across honeycomb cores measured using room-temperature air. The solid line indicates the calculated values by Eq. (7) or a pressure loss equation in the laminar flow region. The broken lines indicate the calculated values by Eq. (8) or a pressure loss equation in the turbulent flow region. The filled squares (■) indicate the measured values. When

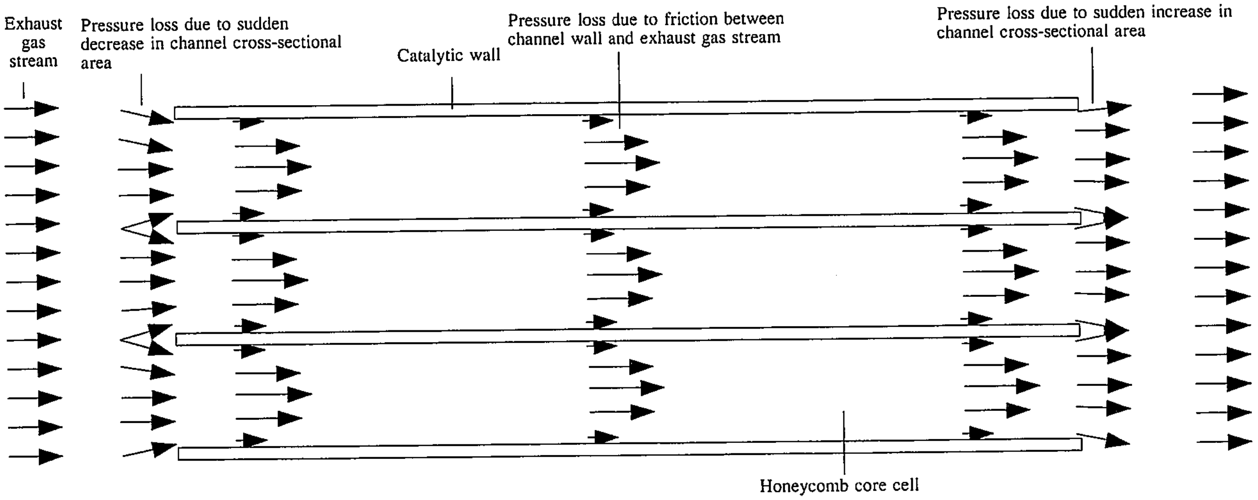


Fig. 7 Schematic illustration of pressure loss in honeycomb core cells mechanism

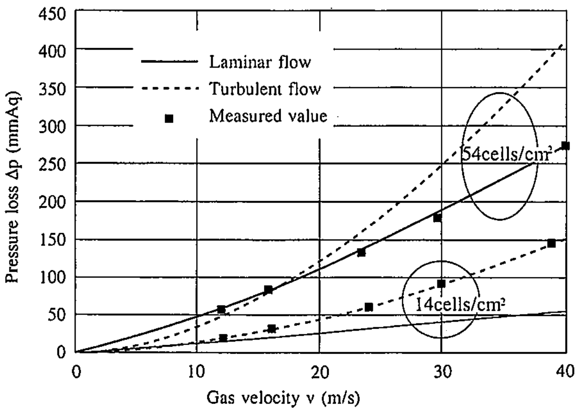


Fig. 8 Pressure loss across honeycomb core

the cell density is low (14 cells/cm²), the exhaust gas stream is high in the Reynold's number and falls in the turbulent flow region. When the cell density is high (54 cells/cm²), the exhaust gas stream falls in the laminar region. The calculated values approximately agree with the measured values. This means that the pressure loss characteristics of catalytic supports can be derived by the above-mentioned equations.

According to the above discussion, the pressure loss across the metal support can be reduced by decreasing the void fraction of the metal support. To reduce the pressure loss due to friction in the cells, it is important to: 1) decrease the cell density to decrease the geometric surface area per unit reactor volume of the honeycomb core; 2) increase the cross-sectional area of the honeycomb core to lower the velocity of the exhaust gas through the cells; and 3) decrease the length of the honeycomb core. A reduction in the specific surface area cuts the exhaust gas cleaning performance of the catalytic support, and a rise in the cross sectional area of the honeycomb core increases the space required for installing the catalytic converter. These conditions need not be met at the same time. As described with respect to the conditions to obtain high light-off behavior in the previous section, it is necessary to design the cell density and size by considering the environment where the catalytic converter is to be installed or according to whether the property to be emphasized on the automobile that the catalytic converter is to be installed is high exhaust gas cleaning performance or low pressure loss.

It is said to be very difficult to design ceramic supports with a desired cell density or size. Nippon Steel's metal support manufacturing technology is at such a level that the cell density and size of metal supports can be designed as required for specific catalytic converter applications.

3.3 Functionality of integral mounting method

As already described, the catalytic support is cooled by a mechanism different from that of heating, or is cooled by heat radiating from the jacket. The conventional metal support that has a honeycomb core in direct contact with the jacket is clearly disadvantageous with respect to cooling because heat readily conducts from the honeycomb core to the jacket. To thermally insulate between the honeycomb core and the jacket, Nippon Steel developed the integral mounting technology of fabricating the catalytic converter integral with the exhaust pipe using a heat-insulating seal, thereby preventing the catalyst to cool when the engine is shut down. **Fig.** 9 schematically illustrates the integral mounting method. This method is confirmed to provide sufficient structural durability.

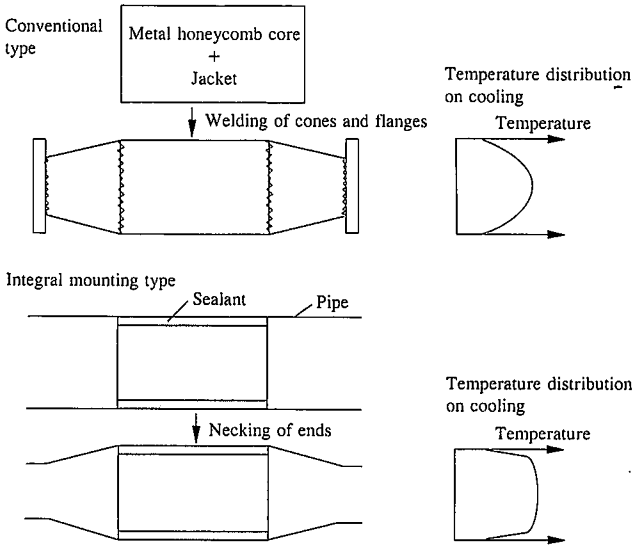


Fig. 9 Schematic illustration of integral mounting method

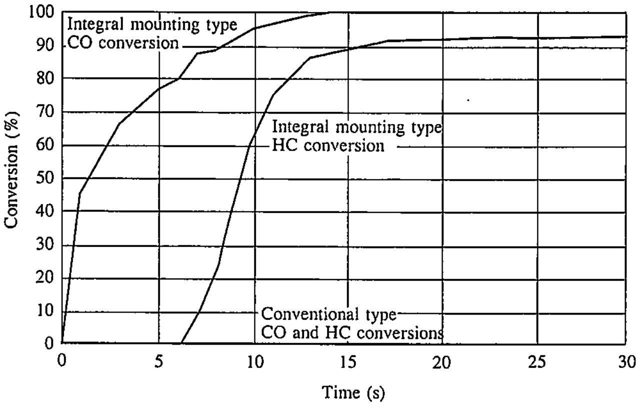


Fig. 10 Changes in CO and HC conversions during idling after cooling from 1,173 K for 13 minutes

An integral mounted metal support and a conventional metal support without seal were heated to 1,173 K, cooled in air for 13 minutes, and investigated for CO and HC conversion efficiencies in the idling condition. The results are compared in **Fig.** 10. The conventional non-heat-insulated metal support converts practically no HC and CO immediately after a cold start. The integral mounted metal catalyst begins to convert CO immediately after starting the engine and converts HC a few seconds later. The heat insulation is effective in preventing the cooling of the metal support when the engine is stopped.

Based on its heat retention capability, the integral mounting design improves the exhaust gas cleaning performance of the catalytic converter. The cost of the metal-supported catalytic converter can also be cut down substantially by a fabrication process that takes advantage of metal's flexibility. Coupled with the foil downgauging and pressure loss reduction techniques, the integral mounting method can retain a performance advantage over the ceramic-supported catalytic converter.

Sections 3.2 and 3.3 covered the functional improvement of the metal honeycomb core and the development of the integral mounting method. The development of technology to capitalize on the potential of the metal support is Nippon Steel's most pressing issue.

3.4 Electrically-heated catalytic support

As noted in Section 3.1, there are moves to adopt very stringent automotive exhaust gas control standards in California and Europe. Such policies make it imperative to substantially improve the cold-start cleaning performance of catalytic converters by adding functions lacking in conventional catalytic supports. To obtain cold-start exhaust gas cleaning performance immediately after the start of an engine, a method known as electrically heated catalytic support (EHC) is proposed. This involves electrically heating the foils comprising the catalytic support and warming the catalyst[13,14].

It is known that HC emissions can be reduced by electrically heating the entire catalytic support with about 4 kW of electric power[5]. The maximum amount of power that can be reasonably supplied from an ordinary battery is about 1.5 kW. An EHC requiring 4 kW of power is not practical for any vehicle configuration[5]. EHCs with high cold-start conversion efficiencies using low power are the focus of research in this area[15,16].

Considering that two EHCs are required for a V engine, Yoshizaki et al.[5] proposed a "surface layer-heated EHC" that assures a high cold-start conversion efficiency with a low-power input of less than 1 kW. This concept is described below.

Minute scattered regions on the exhaust gas upstream end of the EHC are first heated in a concentrated manner. **Photo 2** shows an example of the concentrated heating pattern. Since the portions to be electrically heated are small in area, the catalyst reaches the light-off temperature in a few seconds after the application of the small power, oxidizes CO or HC, and generates a large amount of reaction heat. The reaction heat is described by the third item on the right side of Eq. (1) in Section 2.2.1. This reaction heat warms sequentially adjacent regions and activates the catalyst there. The net result is high exhaust gas cleaning performance with provided by low electric power soon after the engine start.

Nippon Steel is working jointly with Toyota Motor Corp. on the development of the process for manufacturing a low-power EHC based on the above-mentioned concept. With the surface layer-heated EHC under development, the honeycomb core is resistively heated by applying voltage between the electrode positioned at the center of the support and the jacket.

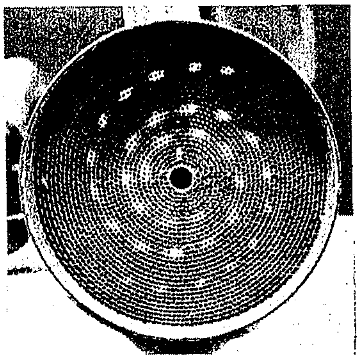


Photo 2 General view and heat generation pattern of EHC

The support is electrically insulated in the radial direction by coating the foils with an insulating material. The foils are made of the stainless steel YUS 205M1, an Fe-20Cr-5Al alloy developed by Nippon Steel that contains trace amounts of lanthanum and cerium, among other elements. When the foils made of the alloy are heated in air, a strong alumina film of high adhesion is formed on the foil surface to facilitate the application of the electrically insulated coating[17]. The support is joined by a special method to break the electric insulation in some sections. Electric current flows short circuits these joints, generating heat at the joints. To deliver equivalent exhaust gas cleaning performance, the electric power required for the newly developed surface layer-heated support is reduced to one-fifth of that required for a totally-heated metal honeycomb core.

The EHC features a conductive path, therefore its durability is difficult to achieve using the structural fabrication process[6] utilized to make conventional metal supports. Now that the method of mechanically holding the honeycomb core is established, the EHC can acquire the same reliability of a heat-resistant structure as required for general metal supports.

Based on the aforementioned basic technology, the developmental work is continuing for mass production in the near future.

4. Conclusions

Catalytic converters must meet the following requirements:

(1) high exhaust gas cleaning performance to satisfy the essential purpose of the catalyst;

(2) low pressure loss to deliver the necessary horsepower of the automobile; and

(3) small size, allowing mounting in any location.

Metal supports have long been known to be advantageous over ceramic supports for these characteristics. In its research, Nippon Steel has been reducing the heat capacity and pressure loss of the honeycomb core, improving the light-off behavior, and assuring the desired conversion performance by using thinner foils. It is also striving to improve the properties of the metal support by optimizing the design of the metal support (concerning shape, size and cell density); and to maintain the high conversion performance of the metal support by improving the heat insulation capacity with the use of an integral mounted metal support. These efforts are bearing exceptional results. High cost has been one disadvantage of metal supports. The total cost of catalytic converters is being reduced by adopting the process whereby component parts are assembled into one piece by taking advantage of the flexibility of the metal support. Metal-supported catalytic converters are now as price competitive as ceramic-supported catalytic converters.

Nippon Steel took the initiative in developing the EHC or electrically heated catalytic support in response to increasingly demanding future exhaust gas control standards. A "surface layer-heated EHC" is being perfected as an electric power-saving unit with high conversion efficiency.

The authors firmly believe that the high cost performance accomplished by completing the above-mentioned developmental work and the combination of the individual technologies will assure the advantage of metal supports over ceramic supports and will help metal supports to supplant ceramic supports in the catalytic support market.

Acknowledgments

Some of the results presented here are the outcome of joint development between Nippon Steel Corporation and Toyota Motor. The authors would like to express sincere thanks to Toyota Motor for providing much valuable information.

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