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ABSTRACT

In preparation for compliance with California's SULEV standard and the Euro STAGE-4 standard, which will take effect in 2004 and 2005, respectively, a planar air fuel ratio (A/F) sensor has been developed. By using technology established for the planar oxygen sensor already in practical use, the A/F sensor realizes light-off time of 10 seconds, faster than any conventional A/F sensors. In addition, with its newly developed gas diffusion structure, the planar A/F sensor provides high detection accuracy for a wide A/F range, from rich to lean.

INTRODUCTION

With the intensifying focus on environmental preservation, emission regulations have become increasingly stringent in recent years. In line with this trend, automobile manufacturers have developed a wide variety of emission control systems. Of these, the most widely adopted system adjusts A/F ratio to an optimal point (stoichiometric A/F ratio) using an oxygen sensor. However, the sensor can detect the only stoichiometric A/F ratio. When the A/F ratio is suddenly deviated from the stoichiometric point under transient conditions, such as in acceleration or deceleration, the sensor cannot detect the deviation, so cannot correct it. To solve this problem, the system shown in Fig. 1 has been proposed, in which an A/F sensor is installed upstream of a catalytic converter to quantitatively detect deviation from the stoichiometric A/F ratio under transient conditions, and to adjust fuel injection accordingly[1].

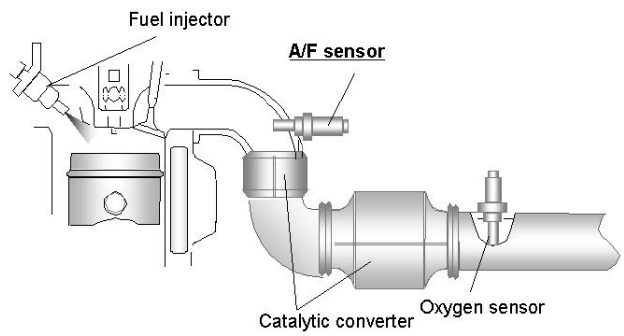


Fig. 1: Emission Control System with A/F Sensor

For this system's A/F sensor, in 1996 we developed the world's first practical single-cell limited-current type A/F sensor[2] (Fig. 2), which is low cost and easy to control. However, since emission regulations are expected to become more stringent in future, it is essential to reduce large quantity hydrocarbon (HC) emissions at engine cold start[3]. To this end, it is important to control A/F ratio as quickly as possible after engine start. This demands a fast light-off A/F sensor.

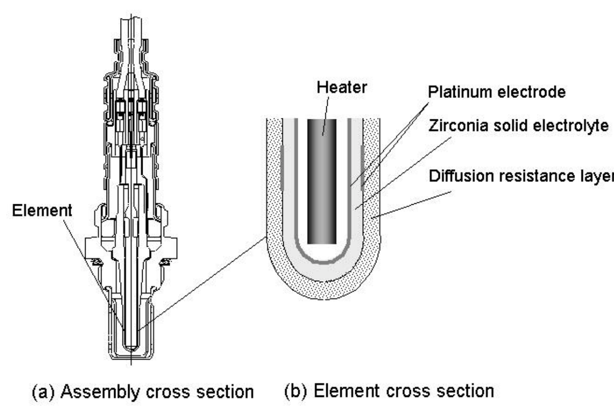


Fig. 2: Sectional Views of Conventional Cup-Shaped A/F Sensor

The conventional A/F sensor comprises a cup-shaped sensor element and a heater to heat it. Due to the indirect heating, however, the heater provides poor heating efficiency, hampering fast activation or light-off. To overcome this problem, we have developed a planar A/F sensor in which a sensor element and a heater are laminated using the alumina/zirconia-joining technique developed for the planar oxygen sensor and already in practical use[2]. While the conventional A/F sensor with cup-shaped sensor element takes approximately 20 seconds to activate, the planar A/F sensor takes only 10 seconds, which is sufficiently fast to reduce the HC to meet future emission regulation requirements.

In developing a planar A/F sensor, a key requirement is optimal design of the gas diffusion structure, since the structure influences detection accuracy and other important characteristics of the planar A/F sensor. A new gas diffusion structure suitable for a planar A/F sensor has been developed, and a technology to control diffusion resistance layer micropore diameter has been established.

This paper describes the new technologies established to improve planar A/F sensor fast light-off performance, detection accuracy and detection range.

GENERAL STRUCTURE AND PRINCIPLE OF AIR FUEL RATIO SENSOR

The single-cell limited-current type planar A/F sensor assembly developed in the present instance is shown in Fig.3, which also shows sensor and heater element cross sections. The basic portion of the sensor element comprises a planar zirconia solid electrolyte sandwiched between platinum electrodes. This structure is virtually the same as that of the planar oxygen sensor element, with the exception that, in place of the protection layer in oxygen sensor element, the A/F sensor element contains a diffusion resistance layer to restrict gas diffusion.

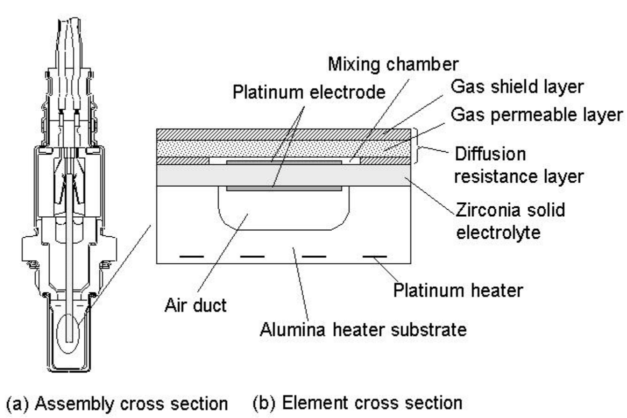


Fig. 3: Sectional Views of Planar A/F Sensor

Seen in Fig. 4 is the operating principle of the planar A/F sensor in lean A/F condition. When voltage is applied between the platinum electrodes, oxygen in the exhaust gas is ionized as it reacts with the exhaust-gas-side electrode, flows in the form of oxygen ion current through the zirconia solid electrolyte, and reaches the opposite (air-side) electrode. Since the diffusion resistance layer restricts oxygen diffusion, limited current (IL) in proportion to the oxygen concentration is obtained as ion current (i). The limited current can be calculated by equation (1):

$$IL = C\,\frac{D_{O_2}}{T} \cdot \frac{PS}{L}\,\ln\frac{1}{1-P_{O_2}/P} \quad \text{--- (1)}$$

in which

C: constant
D_{O2}: diffusion coefficient of oxygen molecules in a diffusion resistance layer
T: absolute temperature
S: cross-sectional area of a diffusion resistance layer
L: diffusion length
P: absolute exhaust gas pressure
P_{O2}: oxygen partial pressure of exhaust gas

The voltage-current characteristic in lean A/F thus has a flat region, as shown in Fig. 5.

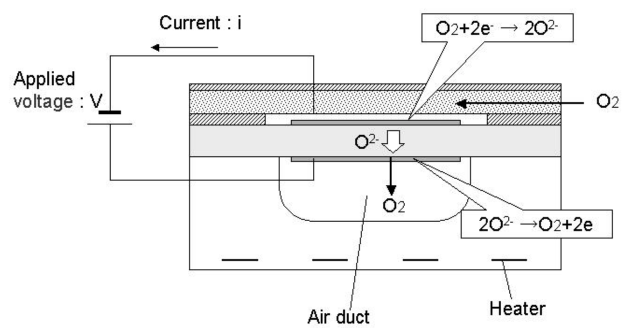


Fig.4 :Operating Principle for Lean A/F Detection

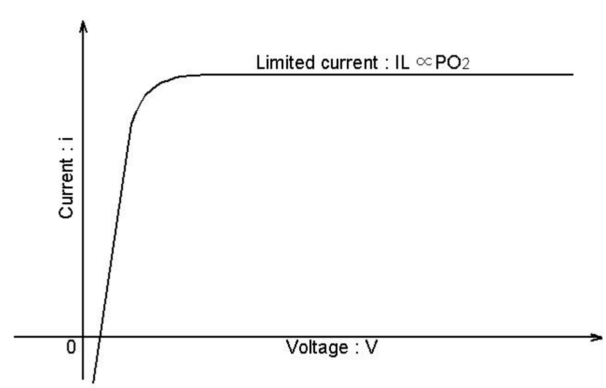


Fig. 5: Applied Voltage-Current Characteristic in Lean A/F

In rich A/F condition, as shown in Fig. 6, oxygen in the air duct atmosphere is ionized by the air-side electrode, oxygen ion current flowing through the electrolyte to the exhaust-gas-side electrode where it reacts with unburned gases such as HC and CO. The diffusion resistance layer restricts the diffusion of unburned gases, yielding limited current (IL) in proportion to the unburned gas concentration. In rich A/F condition, limited current is negative, as shown in Fig. 7.

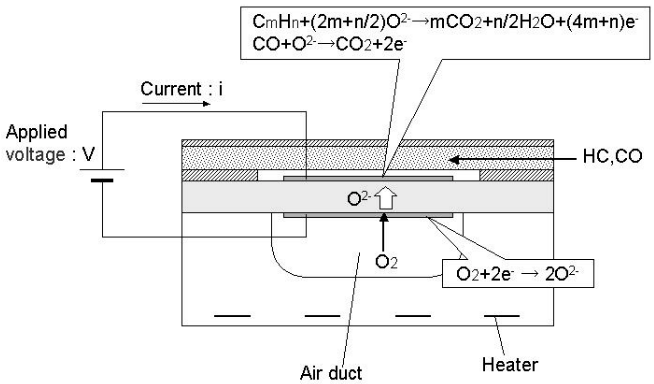


Fig. 6: Operating Principle for Rich A/F Detection

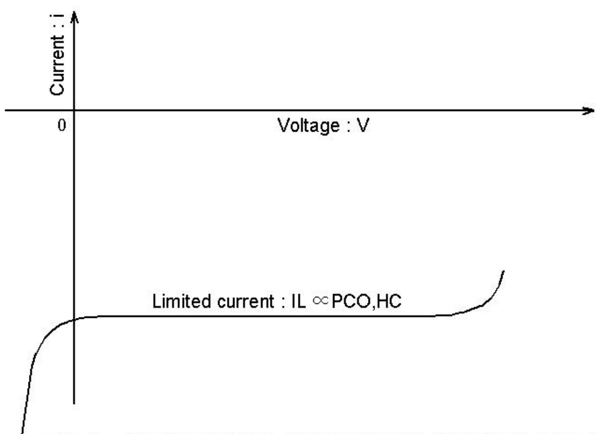
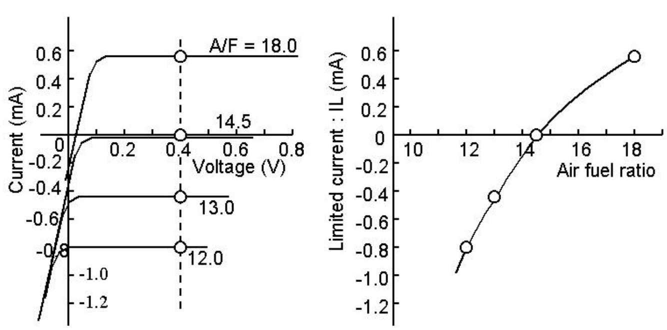


Fig. 7: Applied Voltage-Current Characteristic in Rich A/F

Since there is positive correlation between IL and A/F as shown in Fig. 8, the planar A/F sensor can detect A/F at high accuracy in a wide range from rich to lean.



(a) Applied voltage - current characteristic

(b) Air fuel ratio - limited current characteristic

Fig. 8: Output Characteristics of A/F Sensor

STRUCTURE OF EACH SECTION

ALUMINA / ZIRCONIA JOINING

A fast light-off A/F sensor requires integration of a zirconia sensor element with an alumina heater element. To achieve this, we used the alumina/zirconia-joining technique, developed for the planar oxygen sensor, to create the rigid joining between alumina/zirconia shown in Fig. 9. This technique was realized by conforming the alumina sintering shrinkage and thermal linear expansion coefficient to those of zirconia[4].

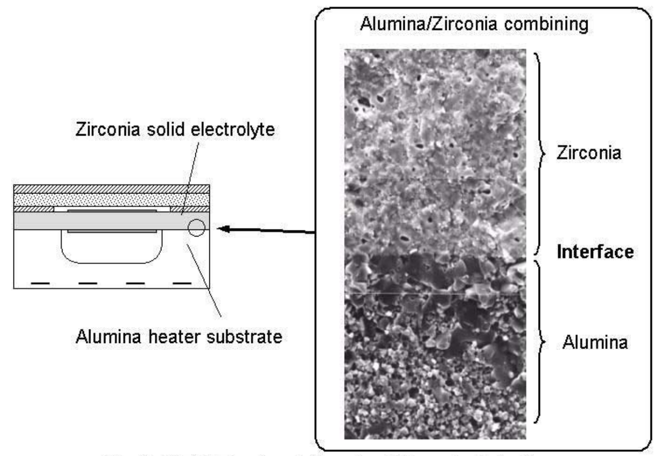


Fig.9: SEM Photo of Alumina/Zirconia Interface

GAS DIFFUSION STRUCTURE

Reduced thermal capacity

Sensor element thermal capacity reduction by minimizing element size is also important for realizing a fast light-off A/F sensor. Use of the same diffusion structure as in the planar oxygen sensor (Fig. 10) would require an extremely thick gas-permeable resistance layer (1 mm or more) in order to effect sufficient diffusion resistance. This would increase the thermal capacity, possibly resulting in long light-off time. To avoid this, a new diffusion structure was developed that can provide sufficient diffusion resistance without significant increase in sensor element thermal capacity. As shown in Fig. 11, the developed diffusion structure is a duplex diffusion resistance layer comprising a gas shield layer formed on a gas-permeable thin porous layer. Exhaust gas entering the sensor element laterally reaches the exhaust-gas-side electrode as it diffuses through the gas-permeable porous layer. This structure permits a diffusion resistance layer of smaller cross-sectional area while increasing diffusion length, thereby achieving the required diffusion resistance. The result is the thin diffusion resistance layer shown in Fig. 12.

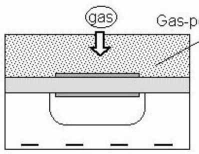


Fig. 10: Conventional Gas Diffusion Structure

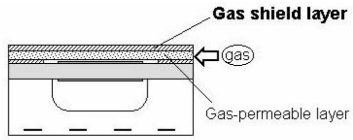


Fig. 11: Newly Developed Gas Diffusion Structure

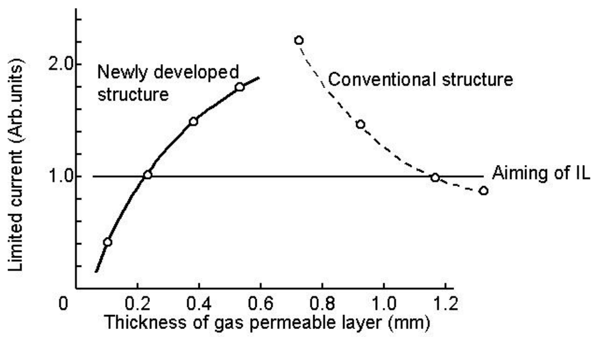


Fig. 12: Relation between Diffusion Gas-Permeable Layer Thickness and Limited Current

Improved flatness of limited current

For a limited-current type A/F sensor to provide high detection accuracy, the sensor current response to the applied voltage characteristic (voltage-current characteristic) curve must be flat in the limited-current portion. Limited-current flatness can be hampered by uneven oxygen concentration distribution over the exhaust-gas-side electrode, this unevenness resulting from various diffusion lengths. In the newly developed duplex diffusion structure (comprising porous permeable layer and gas shield layer), gas diffusion length varies widely depending on diffusion route, which makes it difficult to obtain flatness of limited-current. To solve this problem, a mixing chamber was formed around the exhaust-gas-side electrode in order to mix gas reaching the electrode, thereby canceling out diffusion-length variation (Fig. 13).

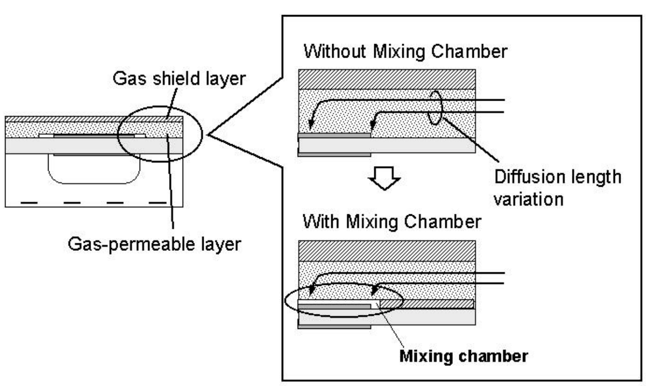


Fig. 13: Diffusion Length Variance Cancellation Effect of Mixing Chamber

Figure 14 shows FEM analysis results of oxygen concentration distribution over the exhaust-gas-side electrode, with and without mixing chamber. Clearly the mixing chamber is effective in attaining uniform oxygen concentration distribution.

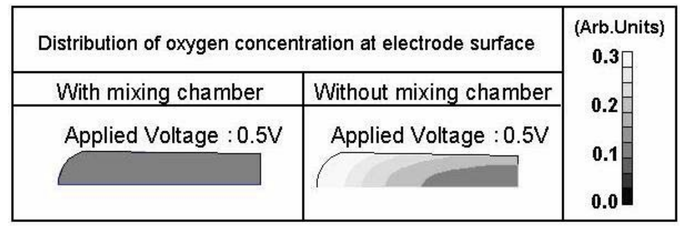


Fig. 14: Oxygen Concentration Distribution at Exhaust-Gas-Side Electrode Surface

Figure 15 compares the voltage-current characteristic of experimentally manufactured planar A/F sensors, with and without mixing chamber. The results show that the mixing chamber is extremely effective in improving flatness of limited-current.

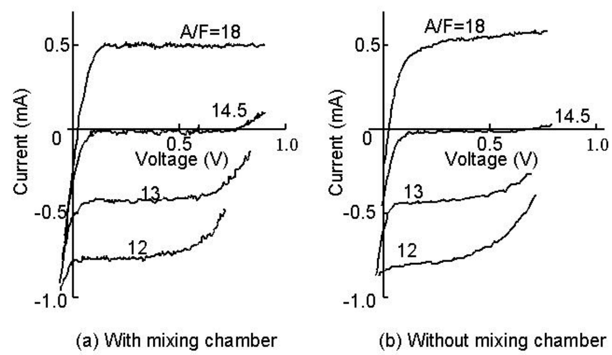


Fig. 15: Effect of Mixing Chamber on Voltage-Current Characteristic

Decreased temperature dependence of sensor output

Since an A/F sensor functions in an exhaust gas environment, it is exposed to extremely wide temperature fluctuations. The lower the temperature dependence of sensor output, therefore, the more accurate the A/F detection. The temperature dependence is determined by gas-permeable layer micropore diameter. For various micropore diameters, we measured the temperature dependence of a planar A/F sensor output with the abovementioned newly developed diffusion structure. Figure 16 shows the result. On the basis of the result, we set the mean micropore diameter (d_{50}) in the gas-permeable layer at 100 to 140 nm.

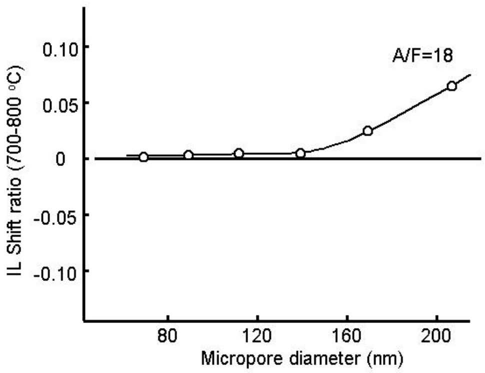


Fig.16: Diffusion Resistance Layer Micropore Diameter and Temperature Dependence

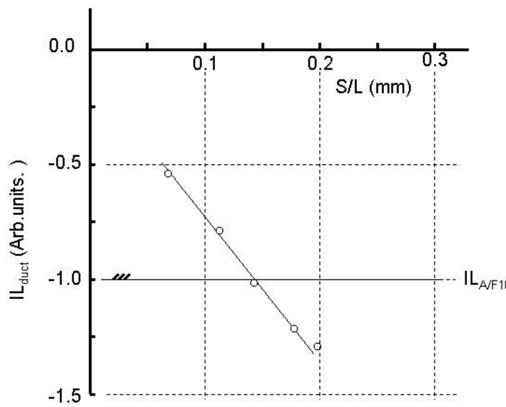


Fig. 17: Relation between Air Duct Configuration and Oxygen Feed Capacity

AIR DUCT

The A/F detection range of the developed planar A/F sensor is determined by the detection limit in the rich region (in the lean region, the sensor can detect A/F = ∞, i.e., the same A/F ratio as in the atmosphere). In the rich region, oxygen in the air duct atmosphere is ionized on the air-side electrode and flows to the exhaust-gas-side electrode in accordance with the A/F ratio. The rich-region detection limit is therefore determined by the air duct's oxygen feed capacity, which can be measured by the following method. Voltage is applied to the sensor to allow oxygen ions to flow in the same direction as for detecting rich A/F, i.e., from the air-side electrode to the exhaust-gas-side electrode. Oxygen diffusion is restricted by air duct resistance, yielding limited current. This limited current value, taken as the air duct oxygen feed capacity, is expressed as IL_{duct}. To attain the detection limit goal of A/F = 10 set for the planar A/F sensor, the oxygen feed capacity must satisfy the following requirement:

$$| IL_{duct} | \geqq | IL_{A/F10} | \text{ --- (2)}$$

in which $IL_{A/F10}$ represents the limited current of the sensor at A/F = 10. IL_{duct} is determined by the air-duct configuration. Specifically, IL_{duct} is proportional to the ratio of air duct cross-sectional area (S_{duct}) to length (L_{duct}). Increase in the S_{duct} / L_{duct} ratio therefore results in increase detection range. For the conventional cup-shaped A/F sensor, oxygen is fed through the clearance between a sensor element and a heater. Increased clearance cross-sectional area decreases heater heating efficiency, resulting in longer light-off time. With the planar A/F sensor, in which heater and sensor elements directly contact each other, heating efficiency loss resulting from increased air duct cross-sectional area is small, which allows greater design freedom than the conventional cup-shaped sensor. Figure 17 shows the relation between S_{duct} / L_{duct} and IL_{duct} of the planar A/F sensor. It is clear from this relation that the detection limit goal of A/F = 10 can be achieved when S_{duct} / $L_{duct} \geqq$ 0.14. In view of this, S_{duct} / L_{duct} was set at 0.18 mm.

Figure 18 compares voltage-current characteristic between planar and conventional cup-shaped A/F sensors, measured as installed on an engine bench, for various A/F ratios from 10 to 18. Figure 19 shows the A/F-IL characteristic of planar and conventional cup-shaped A/F sensors, respectively. Owing to sufficient oxygen feed capacity, the planar A/F sensor clears the detection limit of A/F = 10, whereas the conventional cup-shaped sensor cannot detect A/F lower than 12, at which output saturates.

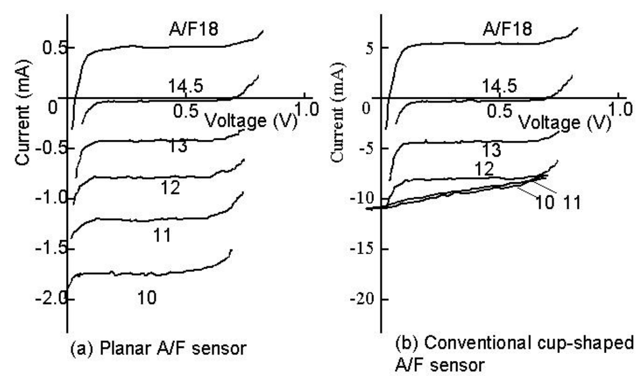


Fig. 18: Comparison of Voltage-Current Characteristic between Planar and Conventional Cup-Shaped A/F Sensor on Engine Bench for Various A/F Ratios

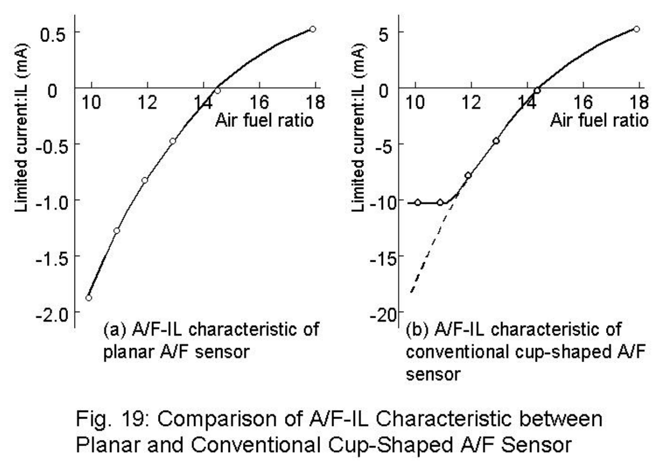


Fig. 19: Comparison of A/F-IL Characteristic between Planar and Conventional Cup-Shaped A/F Sensor

CHARACTERISTICS

LIGHT-OFF TIME

Seen in Fig. 20 is the sensor output profile of the planar A/F sensor at engine start, in comparison with the conventional cup-shaped sensor. For this profile measurement, direct current voltage at 14 volts was applied to the heater at engine start, and engine A/F was adjusted to 18. As shown, the planar A/F sensor becomes active in less than 10 seconds. This fast activation (light-off) is the result of high heating efficiency realized through the alumina/zirconia joining technique and thermal capacity reduction realized by the newly developed diffusion structure. In contrast, the conventional A/F sensor light-off time is approximately 17 seconds, owing to large thermal capacity (five times that of the planar A/F sensor), and poor heat transfer efficiency due to a heater and a sensor element separation.

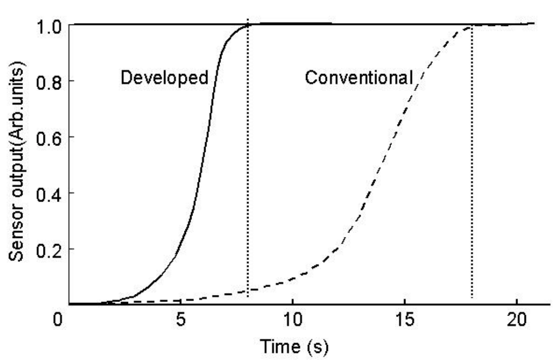


Fig. 20: Sensor Output Build up Characteristic after Application of 14 VDC Heater, Measured on Engine Bench with A/F Adjusted to 18

DETECTION ACCURACY

Figure 21 compares the planar A/F and conventional cup-shaped sensors as regards detection accuracy at A/F = 18. Since in the conventional A/F sensor the plasma spray coating method is used to produce the diffusion resistance layer, it is difficult to form a mixing chamber. Without a mixing chamber formed, the conventional sensor provides poor limited-current flatness. In addition, the plasma spray coating method is not compatible with fine control of micropore diameter. The conventional A/F sensor output is therefore highly temperature dependent, rendering the conventional A/F sensor inferior to the planar A/F sensor in terms of detection accuracy.

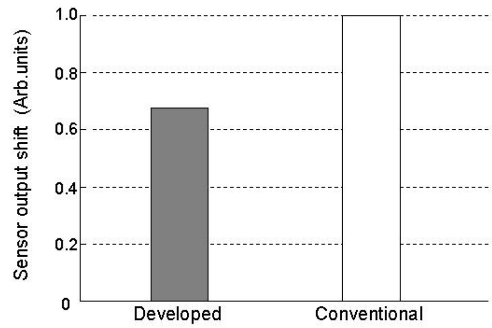


Fig. 21: Comparison of Output Change between Planar and Conventional Cup-Shaped A/F Sensors, with Sensor Temperature Fluctuation of ±50 °C and Applied Voltage Fluctuation of ±0.05 V

DETECTION RANGE

Figure 22 compares the detection range between planar and conventional cup-shaped A/F sensors. As described earlier, the conventional A/F sensor does not provide sufficient oxygen feed capacity, since its gas diffusion cross-sectional area is small because of the heater provided in the element. As a result, its rich-side detection limit is A/F = 12. The planar A/F sensor, in contrast, has a larger detection range, with a rich-side detection limit of A/F = 10, thanks to optimized air-duct configuration.

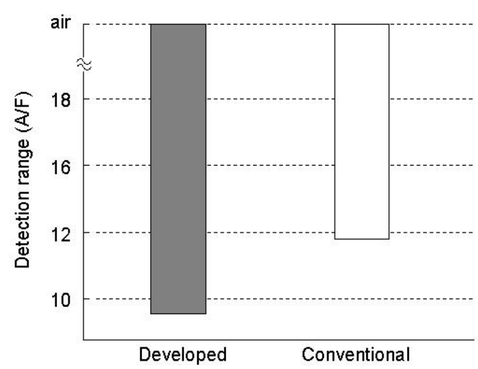


Fig. 22: Comparison of Detection Range between Planar and Conventional Cup-shaped A/F Sensors

EMISSIONS

Figure 23 compares NMHC and NOx emissions between a system equipped with the planar A/F sensor and one equipped with the conventional cup-shaped A/F sensor. Both NMHC and NOx emissions are lower with the planar A/F sensor than with the conventional cup-shaped A/F sensor. Presumably, decreased NMHC and NOx emissions are the result of the planar A/F sensor's faster light-off and improved detection accuracy, respectively.

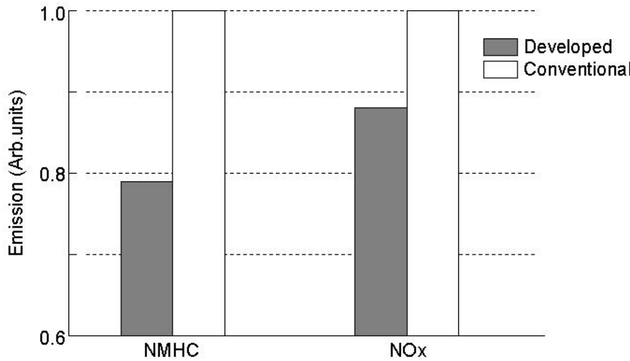


Fig. 23: Comparison of FTP-mode[5] NOx and NMHC Emissions between System with Planar A/F Sensor and System with Conventional Cup-shaped A/F Sensor

CONCLUSION

By joining the alumina heater and zirconia sensor elements directly and adopting a newly developed structure for the diffusion resistance layer, we have developed a single-cell limited-current type planar A/F sensor that attains fast light-off time (10 seconds) and high detection accuracy over a wide A/F range. This sensor enables precision A/F control for vehicle emission control system in compliance with future emission regulations, which are likely to become increasingly stringent.

Since a hydrocarbon detection sensor called a HC sensor and a nitrogen oxide detection sensor called a NOx sensor, which will come into practical use in the near future, are also of the limited-current type, the diffusion resistance control technique developed for the planar A/F sensor will be applied to those sensors.

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