International Journal of Automotive Technology, Vol. 3, No. 1, pp. 33–39 (2002)

A STUDY ON A CATALYTIC CONVERTER OBD BEFORE LIGHT-OFF

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(Received 28 July 2001)

ABSTRACT–Increasingly stringent emission regulations of EU and CARB (California Air Resource Board) require mandatory OBD (On Board Diagnostics) for the catalytic converters of a vehicle. It demands that MIL(Malfunction Indication Light) should be turned on to inform the driver of catalytic converter failures. Currently dual oxygen sensor method is widely used for the converter OBD. However, since it works only after converter light-off, it has a serious limitation when applied to TLEV or more stringent emission regulations where more than 85% of total emission is coming out before converter light-off. In addition, a recent development in catalyst material, coating technology and additive catalysts leads to a much improved OSC (Oxygen Storage Capacity) after converter light-off, current methods are very difficult to determine levels of converter aging. Therefore, it is desired to develop an OSC detecting method before converter light-off to diagnose converter failures with higher reliability. In this study, OSCs of converters are measured by an absolute measuring method and a dynamic measuring method, and some of fundamental ideas are suggested about converter OBD before converter light-off. The converters are aged with two different aging methods; those are a furnace aging and an engine bench aging to represent aging conditions in actual field applications. Dual oxygen sensor method at the lower temperature than light-off is also studied at a model gas bench with the converters. It is found that there is a certain point in temperature lower than light-off where difference due to aging level becomes maximum, thus a proper dynamic method to effectively monitor catalytic converters could be implemented for the range lower than light-off temperatures. With this result, the aging level of converters is examined at an engine bench.

KEY WORDS : OSC, OBD, Dual oxygen sensor, Converter light-off

1. INTRODUCTION

In an effort to reduce air pollution caused by automotive exhaust emissions, many developed nations are implementing more and more stringent exhaust emssion regulations. They are now requiring not only reduction in harmful exhaust emissions but also warrant for reliable operation of emission related parts for 100 K miles and OBD (On-Board Diagnostics) function to inform the driver of failures of these parts. The core of OBD function is for the on-board systems to monitor and to identify malfunction or failures of emission related parts. One of the emission related parts that requires diagnostics is a catalytic converter. Modern vehicles monitor the converter function using two sensors, a method known as dual oxygen sensor method. This approach compares the signals from a pre-converter sensor with those of a post-converter sensor. However, since this approach is based on the assumption that OSC (Oxygen Storage Capacity) of a catalytic converter is a linear function of conversion performance, it has serious limitations, especially for HC emissions at ULEV (Ultra Low Emission Vehicles) and SULEV (Super ULEV) applications. (Hepburn *et al.*, 1994; Hepburn *et al.*, 1997; Rieck *et al.*, 1998) One of the most important limitations comes from the fact that the rate of the loss of OSC with aging is much more rapid than that of HC conversion performance, which results in a highly nonlinear relationship between HC emissions and OSC. The conversion efficiency of HC has been largely improved thanks to progress in engine control and catalyst coating technologies, including additive catalysts, which gives a slower deterioration rate of HC conversion performance compared to that of OSC. Even for the catalyst aged over 100 K miles, it now shows conversion efficiency higher than 90% after light-off mainly due to precise A/F control and partial oxidation of OSC components. Generally, 80~90% of emissions from brand new vehicles for LEV application is coming out during the cold start period, *i.e.* within less than a minute right after the engine start. Reduction of this cold start emission using the dual oxygen sensor method is a challenging task, as it can only be applied at specific engine operating

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**Corresponding author.* e-mail: *don52@neophotech.com* conditions after converter light-off. Due to aforementioned reasons, the relationship between OSC measured by dual oxygen sensor method and HC emissions shows a highly nonlinear characteristic for a vehicle equipped with advanced catalyst and engine control system.

In this paper, the absolute OSC and dual oxygen sensor methods of aged converters are investigated to examine the fundamentals of OSC characteristics of commercial catalysts with a model gas bench. Amplitude method is carefully reviewed from the standpoints of the diagnostics of catalysts or converter deterioration before converter light-off.

2. OSC AND CONVERTER MONITORING AT COLD START CONDITION

2.1. Converters Preparation

The converter prepared is a 0.47L 400 cpsi (cells per square inch) ceramic substrate with precious metal coating for a TLEV vehicle. The converter is installed at CCC (Close Coupled Catalyst) position. Rieck *et al.* (1998)'s study shows that the aging environment has a significant effect on the relationship between OBD index and HC performance of a catalytic converter. A quick furnace aging method (Son *et al.*, 1997), and an engine bench aging method are used to simulate various aging conditions in actual field applications. For engine bench aging, fuel-cut and extra CO supply are used to elevate converter temperature. The aging methods are summarized in Table 1.

2.2. Absolute OSC Measuring Method

The absolute OSC measures the available oxygen amount that can be used for HC and CO oxidation at a certain temperature. Figure 1 shows the schematic of test equipments for measuring the absolute OSC. Here, the whole converter is used as a specimen unlike the previous

Table 1. Converter aging method.

Method	Condition	Duration
Furnace aging	IAE Mode	2 cycles 5 cycles 10 cycles
Engine bench aging	A mode	Simulated 50K mile

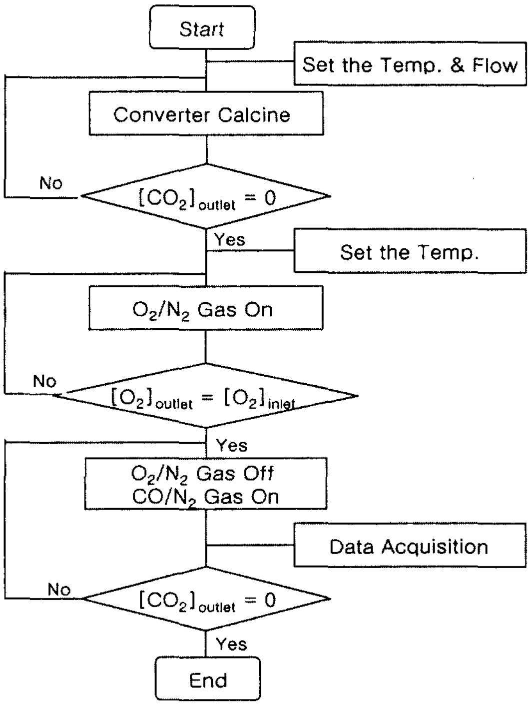

Figure 2. Absolute OSC test algorithm.

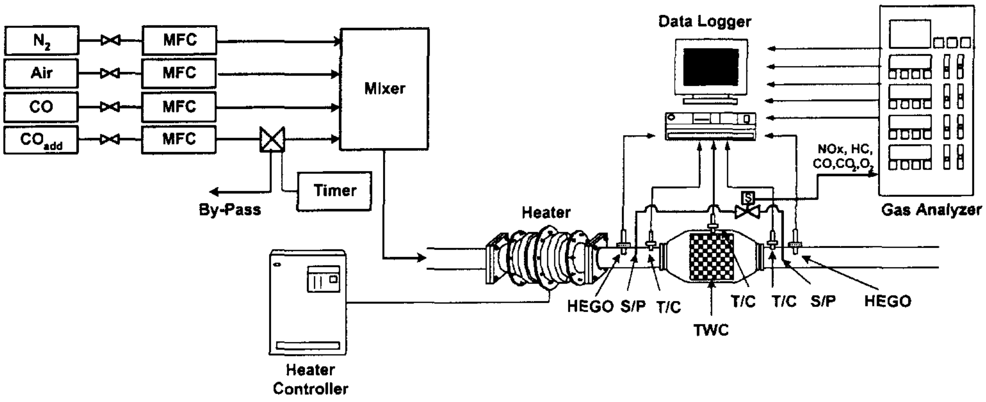

Figure 1. Test Apparatus for converter OSC monitoring.

studies (Lee *et al.*, 1997) where a part of the converter core has been used as a specimen. Previous study has shown that depending on positions in converter cores, even the same aging process could show different deterioration level. Thus it could not properly represent aging level as a whole if test specimens are partially taken from the converter cores. Therefore, when the whole converter is used as a specimen, it would be possible to exactly represent the OSC of a converter. To oxidize and reduce OSC components, air and CO are used and these gases are controlled by solenoid valve and MFC (Mass Flow Controller) that can control each gas concentration by 1 ppm. To eliminate unwanted substances that are attached or adsorbed on the catalyst surface, the converter has been calcined at 500°C before the test. The inlet gas temperature is 350°C for the test and space velocity is 10,000 1/hr.

Horiba MEXA 9100 is used as a gas analyzer and the data are recorded on a data logger.

$$CO + \frac{1}{2}O_2 \rightarrow CO_2 \qquad (1)$$

Equation 1 shows CO oxidation reaction that 1/2 mol of oxygen makes 1 mol of CO_2 with 1 mol of CO consumption. From the CO_2 mol concentration, the available oxygen on a converter can be calculated.

The measuring algorithm is shown in Figure 2. The test is done twice for a converter and the mean values are used.

2.3. Converter Monitoring using Dual Oxygen Sensors at Model Gas Bench

To monitor a converter OSC, HEGO (Heated Exhaust Gas Oxygen) sensors are located at pre-converter and post-converter positions as shown in Figure 1. The inlet gas temperature is elevated from ambient temperature to 300 °C to simulate cold start condition. After each test run, the system has been soaked at least for 12 hours for the accuracy of tests. The signals are obtained every 20 ms and stored at a data logger. From these signals, time delay and amplitude ratio are obtained. Figure 3 shows the pre- and post-converter sensor signals. The amplitude ratio is obtained by Equation (2).

$$\text{Amplitude Ratio} = \frac{1}{n}\sum_{i=1}^{n}\frac{b_i}{a_i} \qquad (2)$$

To get time delay between two sensors, Equation (3) is used. The reference voltage to calculate the time delay between two sensor signals is 0.2 V.

$$\text{Time Delay} = \frac{1}{n}\sum_{i=1}^{n}(T_{front} - T_{rear})_i \qquad (3)$$

where, T_{front} : the time when front sensor signal exceeds 0.2 V,

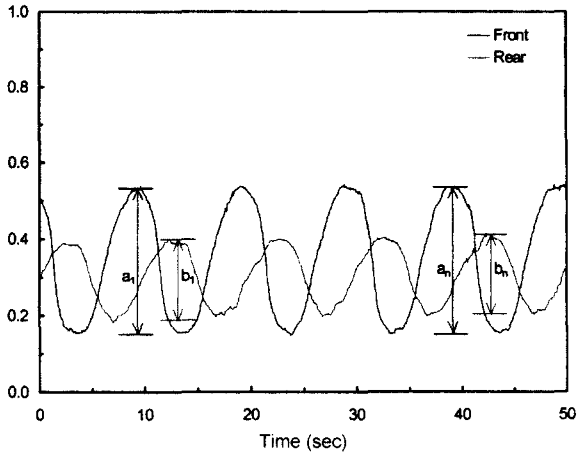

Figure 3. An example of pre- and post-converter oxygen sensor signals.

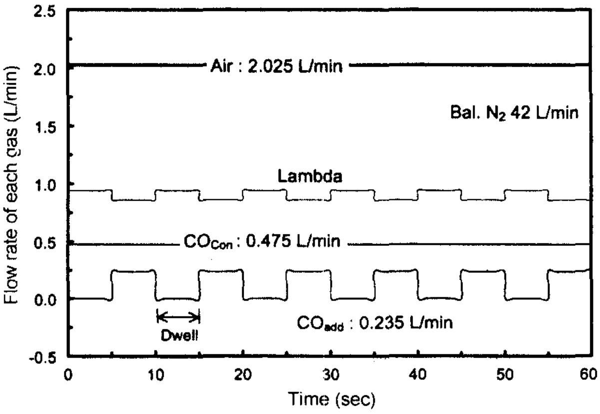

Figure 4. Gas supply conditions for A/F fluctuation.

T_{rear} : the time when rear sensor signal exceeds 0.2 V.

The air fuel ratio, λ, is changed from 0.89 to 0.99. The air fuel ratio is defined as Equation (4), where subscripts a and stoi denote actual and stoichiometric conditions respectively.

$$\lambda = \frac{\left(\frac{O_2}{CO}\right)_a}{\left(\frac{O_2}{CO}\right)_{stoi}} \qquad (4)$$

where, *a* : actual air fuel ratio
stoi : stoichiometric air fuel ratio

To get rich air fuel ratio, extra CO gas is supplied. The gas supply conditions are presented in Figure 4. As a

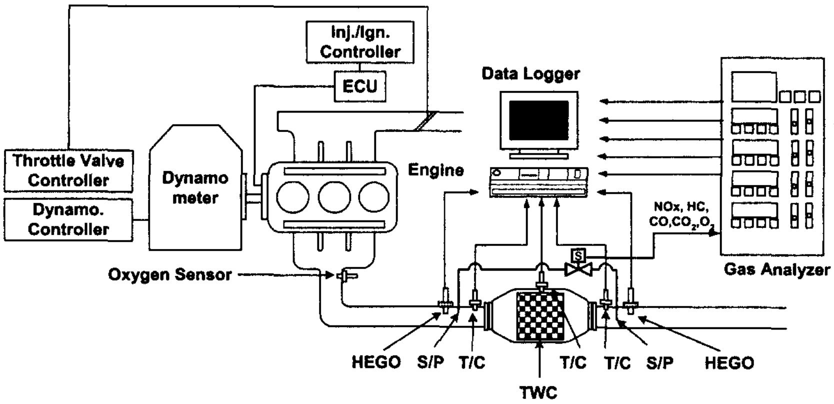

Figure 5. Schematic of test equipments for OSC measuring with engine bench.

balance gas, 99.999% N_2 is used and extra CO gas is supplied to get air fuel ratio fluctuating like a square wave. All gases are controlled by MFC and solenoid valve with digital timer.

2.4. Converter Monitoring using Dual Oxygen Sensors at Engine Bench

Figure 5 shows the schematic of test equipments for OSC measuring with engine bench. An 800 cc, 3-cylinder engine is mounted with an ECU for EU market. Two HEGO sensors are located at inlet and outlet of a catalyst converter to monitor oxygen level of exhaust gas. From these sensor signals, amplitude ratio is calculated according to engine speed and load. To measure the temperatures of the converter a thermocouple is located at the center. And two temperature sensors are located at inlet and outlet of the converter to measure temperature difference. All data are collected on a PC with a data logger by every 50 ms.

3. RESULTS AND DISCUSSIONS

3.1. Absolute OSC

Figure 6 shows the normalized absolute OSCs of aged converters. The "normalized" value means the value of the aged converter in Table 1 is divided by that of a fresh converter. 2 cycle aging with IAE mode is shown to remove 93% OSC of a converter. When the number of aging cycle increases, the OSC decreases, however, there is no linear relationship between the number of aging cycles and OSC. It may be due to sintering characteristics of Ce material. Usually sintering speed of the initial and middle stage of finely dispersed material is higher than that of the final stage. Compared with a furnace quick aging, an engine bench aging shows a lot more severe OSC deterioration in this case.

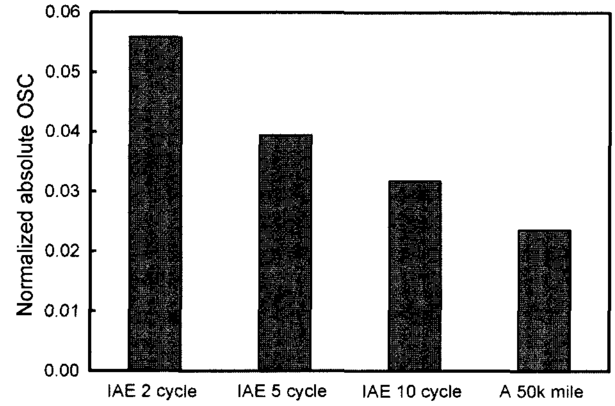

Figure 6. Normalized absolute OSC of aged converters.

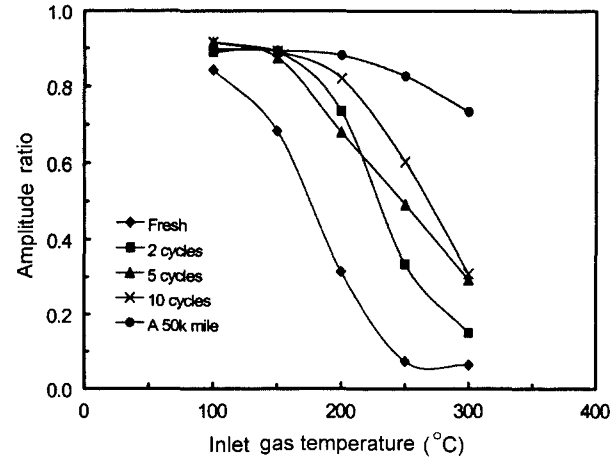

Figure 7. Amplitude ratio according to inlet gas temperature of aged converters.

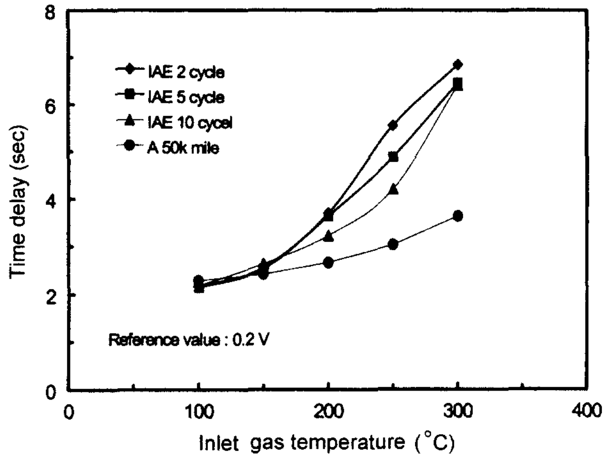

Figure 8. Time delay according to inlet gas temperature of aged converters.

3.2. Dynamic OSC at Model Gas Bench

Figure 7 shows amplitude ratios of the aged converters as a function of inlet gas temperatures. At low temperature of 100°C, there is no difference between fresh and aged converters since oxygen storage material has not been activated due to low thermal energy. As the inlet gas temperature increases, the amplitude ratio decreases. Also, as the absolute OSC is decreasing, the amplitude ratio also decreases. At 250°C, depending upon the level of aging, *i.e.* the numer of aging cycles, amplitude ratios show maximum difference. However, if the temperature goes up to 300°C, this difference is narrowed again and 5 and 10 cycle aged converters show similar amplitude ratios. This is due to the fact that once the oxygen storage material reaches to fully activated states, the aging effect becomes less dominant.

Figure 8 shows time delay of the aged converters as a function of inlet gas temperatures and it shows the same trends as amplitude ratio. At low temperature of 100°C, time delay shows no difference between fresh and aged converters since oxygen storage material has not been activated yet. However, as inlet gas temperature increases, time delay also increases as high thermal energy causes oxygen storage material to be activated. Also, it can be noted that time delay decreases as the absolute OSC decreases. At 250°C, time delay differences also become maximum depending upon the level of aging. This means that measurement resolution of time delay is the highest at this temperature. At 300°C inlet temperature, fresh and aged converters show similar amplitude ratios, implying that once oxygen storage material has been fully activated, there would be little difference due to aging.

At temperatures lower than 250°C, thermal energy is too low to activate Ce, difference in oxygen storage site has no effect on amplitude ratio. Again, there shows no big difference in amplitude ratio, once Ce has been fully activated, this effect becomes dominant over the aging effect with partial oxidation process at temperatures higher than 250°C. This result explains why the OBD index used in mass production vehicles shows nonlinearity with THC emissions. When the operating conditions, such as engine speed, load and converter activation are matched with preset values, the OBD algorithm used in mass production vehicles starts being turned on. Usually when the inlet gas temperature goes higher than 700°C, there will be almost no difference regardless of the level of converter aging. Therefore, in order to make the best use of the maximum measurement resolution between aged converters, it is desired to develop an OBD logic that works at lower inlet temperatures where thermal energy is too low to fully activate oxygen storage material of the converter.

3.3. Dynamic OSC at Engine Bench

Figure 9 shows amplitude ratio of IAE 10 cycle aged converters as a function of bed temperatures. Engine speed is 2,200 rpm and throttle open angle is 4 degree. There is no big difference when the bed temperatures are lower than 210°C. At this temperature, Ce material has not been activated. From temperatures higher than 210 °C, the amplitude ratios decrease rapidly. This means that Ce starts to be activated from this temperature and it becomes fully activated higher than 250°C.

Figure 10 shows the amplitude ratios as a function of engine speed of IAE 10 cycle aged converter. As the engine speed is increasing, the amplitude ratios are also increasing. This means that as the exhaust flow rate increases, the influence of aged Ce becomes smaller. It may be that the high flow rate does not allow sufficient reaction time required for the Ce oxidation process

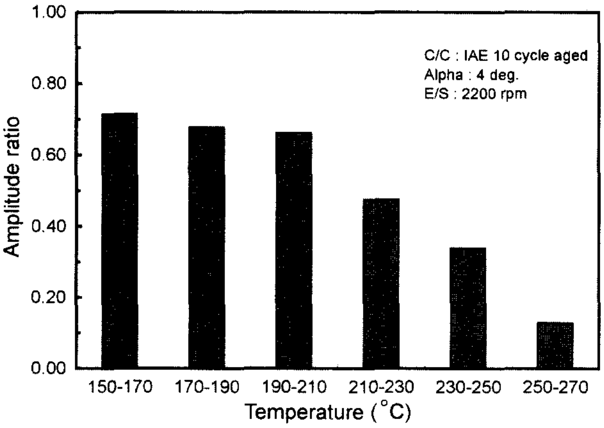

Figure 9. Amplitude ratios of IAE 10 cycle aged converter as a function of bed temperatures.

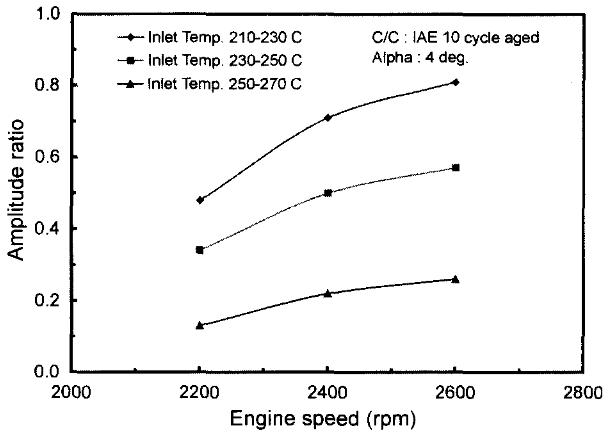

Figure 10. Amplitude ratios as a function of engine speed of IAE 10 cycle aged converter.

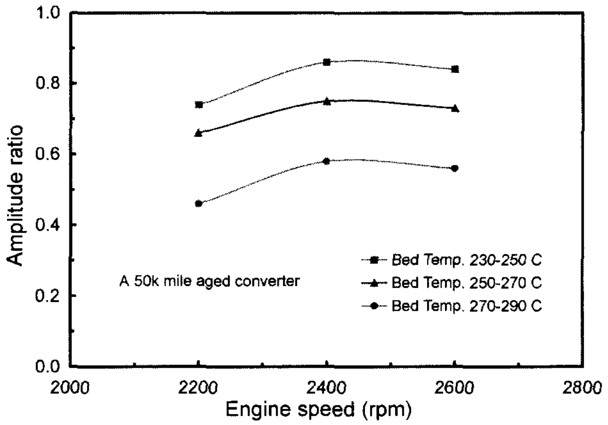

Figure 11. Amplitude ratios as a function of engine speed of A 50 K mile aged converter.

described in Equation (5). However, if the flow rate is low, then there could be sufficient time for the reaction and it can compensate A/F (Air to Fuel) ratio fluctuations. As the converter temperature goes up, particle sizes grow due to so-called sintering effect, thereby reducing the activation site of Ce, and the particle size distribution becomes too irregular to predict. In addition to this sintering effect, the poisoning of Ce caused by engine oil could negatively affect activation capacity of Ce.

$$CeO_2 + \frac{1}{2}O_2 \Leftrightarrow Ce_2O_3 \tag{5}$$

Figure 11 shows the amplitude ratios as a function of engine speed of A 50 K mile aged converter. The 50 K mile aged converter is showing the tendency of more deterioration than the IAE 10 cycle aged converter as shown in Figure 6. As the engine speed increases, the amplitude ratios increase up to 2,400 revolutions per minute (rpm), but at 2,600 rpm the amplitude ratio shows almost the same value as 2,400 rpm. This means that as deterioration continues to occur, the OSC of catalyst at high flow rate is not enough to compensate the A/F fluctuation. Also it means that the amplitude ratios at 2400 rpm are maximum with A 50 K mile aged converter. Compared with results of Figure 10, A 50 K mile aged converter shows higher value than IAE 10 cycle aged converter at the same temperature. And differences in amplitude ratios according to temperature ranges of IAE 10 cycle aged converter are also bigger than those of A 50 K mile aged converter. This means that with mild aging conditions Ce could still retain enough capacity to hold oxygen at lean conditions, however, with severe aging conditions, Ce would lose almost of its storage capacity. Therefore, when the engine speed is low, the difference becomes insensitive to increase of temperature. To show this clearly, the data is expressed as a function of stored energy in the catalytic converter. Figure 12 shows the amplitude ratios of IAE 10 cycle and A 50 K mile aged converters as a function of accumulated energy. The accumulated energy is calculated by Equations (6) and (7) before converter light-off of IAE 10 cycle aged converter.

$$q_t = m_{cat} \times C_{p_{cat}} \times \Delta T_{t=t_i} \tag{6}$$

$$Q_{acc} = \sum_{t=0}^{n} q_t \tag{7}$$

where, m_{cat} : mass of catalytic converter

C_{pcat} : the constant-pressure specific heat of catalytic converter

ΔT is the temperature difference of bed center between time $t = i$ and time $t = i + 1$

In this calculation, two assumptions have been made; 1) When the converter is more deteriorated, the higher becomes the light-off temperature. 2) The temperatures at the bed center is representative of the converter temperature as a whole.

As aging continues to occur, the amplitude ratio also increases. With low accumulated energy, there shows no big difference, since thermal energy delivered from exhaust gas to catalyst is not sufficient. As energy delivered is increases, the difference also starts becoming bigger. If there remains sufficient energy to activate OSC material in the converter, the difference would be narrowed again. However, before the converter light-off, the amplitude ratios show big differences enough to clearly distinguish the aging level between two aged converters. Even though the absolute OSC shows small difference between

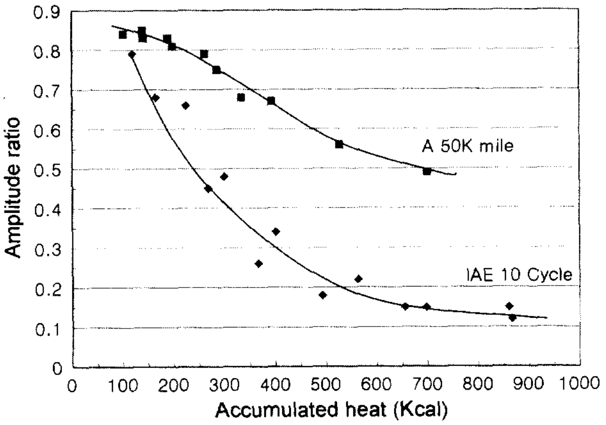

Figure 12. Amplitude ratios of IAE 10 cycle and A 50 K mile aged converters as a function of accumulated energy.

two aged converters (See Figure 6), the amplitude ratios show big differences. Because the absolute OSC represents the oxygen storage capacity at fully activated temperature of catalysts, it shows small difference. However, the differences in amplitude ratios measured before converter light-off are big enough to give a good measurement resolution according to aging level of converters.

4. CONCLUSIONS

In this study, OSCs of converters are measured by an absolute measuring method and dynamic measuring method on a model gas bench to suggest some of the fundamental ideas about a converter OBD before converter light-off. The converters are aged with two different aging methods; those are a furnace aging and an engine bench aging to represent aging conditions in actual field applications. From this study, the following conclusions are obtained;

(1) At low temperatures of 100°C, no difference is found in the amplitude ratio and time delay due to aging cycles, since oxygen storage sites are not activated due to low thermal energy.

(2) At temperatures higher than 250°C, there is also no big difference due to aging cycles, because once oxygen storage sites reach fully activated states, this becomes a dominant factor over the effect of aging.

(3) It is found through the model gas bench tests, there is an appropriate temperature to monitor a converter with a maximum measurement resolution according to catalyst aging before converter light-off.

(4) Engine test results are shown to confirm that there exists a certain temperature that can maximize measurement resolution.

(5) One of the methods maximizing measurement resolution of OSC of aged converters, the method of using amplitude ratio as a function of accumulated energy before converter light-off can be used.

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