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Dynamic Response of a Three-Way Catalytic Converter

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Abstract

In an engine transient condition, effects of different exhaust mass flows, inlet signal amplitudes and periods on dynamic responses of the three-way catalytic converter were investigated experimentally. Experimental results show that exhaust mass flows, inlet signal amplitudes and periods have important influence on engine emissions and oxygen storage capacity of Ceria for the three-way catalytic converter with CeO2 catalyst in the washcoat. With the increase of the exhaust mass flow, the lambda outlet signal increases nonlinearly; emissions are better at the beginning and then turns deteriorated in the case of a high mass flow after the lean-rich transition. Outlet lambda increases almost linearly with the increase of exhaust mass flows and lambda outlet signal amplitudes after the rich-lean transition.

Keywords:three-way catalytic converter; dynamic; oxygen storage capacity

1.Introduction

An efficient way to reduce the emissions of the spark-ignition combustion engine is to use a three-way catalytic converter and suitable control system [1]. Because of the "window" feature of the three-way catalytic converter (TWC), the engines are usually controlled in the lambda closed-loop (λ fluctuates between 1±1% [2]), which will be hard to reduce the fuel consumption. Taking use of converter dynamic characteristic of oxygen storage and release on the ceria well, not only emissions are reduced, but also economy is developed. Some scholars have done many researches on dynamic characteristic of the catalyst CeO_2. Based on the variation of inlet and outlet emissions of the catalytic converter, Descorme [3] developed the detection method of oxygen storage capacity of the catalytic converter in the transient condition. Harmsen et al. [4-6] constructed the catalytic converter kinetic model at the cold start condition, and computed the concentrations on the surface of Pt, CeO_2, γ-Al_2O_3. James [7] proposed to combine the oxygen storage model with statistics to diagnose whether the catalytic converter is at fault. Using the oxygen storage capacity of the converter, Wang et al. [8] developed a new on-board diagnostics (OBD) algorithm.

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Researches above have constructed kinetic model at the cold start condition and solved oxygen storage capacity of the catalytic converter which is used for the OBD. However, these methods are complexes to compute and apply. In this paper, the catalytic converter transient characteristics after light-off are studied, the influence factors of the dynamic and oxygen storage capacity were analyzed theoretically, and the mechanism of the converter dynamic characteristics were explored. This paper is meaningful for the real time dynamic control.

2.Design of Engine Test Bench and Test Program

2.1.Design of Engine Test Bench

Fig. 1 shows the Schematic diagram of the engine test bench. The applied engine was 2.237 liter, 4 cylinder gasoline engine, with bore × stoke of 91mm × 86mm, maximal power of 76 kW / 4300~4600 r/min and maximal torque of 193 Nm / 2000~2600 r/min. Engine lambda values were changed with the quantity of the injection pulse width which was controlled by a 16-bit microcontroller unit. Data acquisition system was composed of acquisition card PCL-818HG and terminal board PCLD-8115 produced by Advantech. Lambda signals in front of and behind the converter were measured by λ sensor and meanwhile the inlet lambda was observed by LAMBDA.LA4 produced by ETAS. Inlet and outlet concentrations of exhaust emissions were measured by AVL exhaust gas analyzers (CO, NO, HC, CO_2, and O_2).

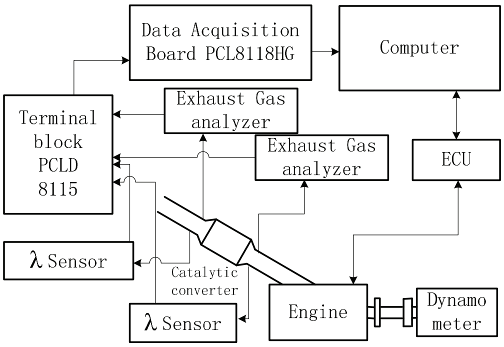


Figure 1. Schematic diagram of the engine test bench

2.2.Test Program

If oxygen storage capacity on the ceria of the converter needs to be investigated, from the theory of the oxygen absorption and release on the ceria researched by Herz [9], inlet lambda and injection quantity of fuel should be changed. A calibration was designed to adjust the injection pulse width in this paper. When the inlet lambda signals measured by LAMBDA.LA4 arrives a given threshold, the corresponding value of pulse width was recorded. The pulse width was controlled by 196KC and changed between the rich and lean conditions, and then lambda would vary around stoichiometry. Dynamic response characteristic of the catalytic converter was investigated under the variance of the mass flows, lambda amplitudes and periods.

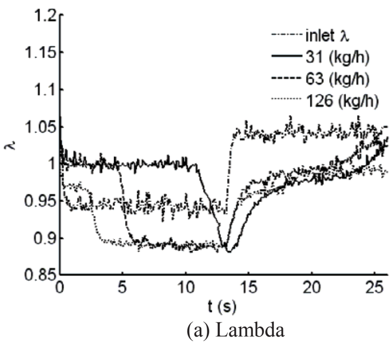
3.Test Results and Analysis

3.1.Effect of Exhaust Mass Flows on the Three-Way Catalytic Converter

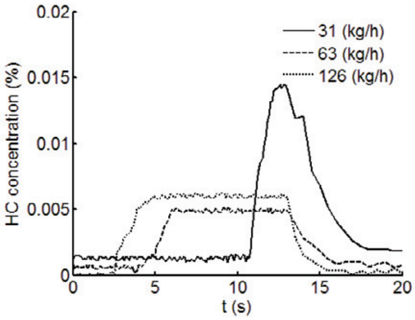
Experiments were performed with the ambient temperature of 11 ℃, engine speed of 1200 r/min, inlet lambda amplitude of 0.95-1.05. The responses of outlet lambda and concentrations of hydrocarbon, carbon monoxide, nitric oxide to inlet lambda of different exhaust mass flows of 31 kg/h, 63 kg/h, and 126 kg/h are shown in Fig. 2. The lambda signals upstream and downstream of the catalytic converter should be same nearly in the steady state, but Fig. 2 (a) shows the errors in the rich region are larger because the hydrogen concentration is higher and the λ sensor was deceived. The water-gas shift and steam-reforming reactions could explain the reason why hydrogen is produced in the high temperature [9]. Because the quantity of catalyst is the constant to a catalytic converter, variance of the exhaust mass flow is equivalence to vary space velocity.

During lambda was controlled to switch between rich and lean, the duration of the downstream lambda at stoichiometry of the different mass flows were compared, at that plateau where the converter efficient is high and emissions are low (area between the inlet and outlet lambda is the oxygen storage capacity). In the bigger exhaust mass flow condition, the duration of lambda at stoichiometry and the cost time of outlet lambda to be the steady state turn to diminution and oxygen storage capacity is less after a rich-lean transition. If the exhaust mass flow is doubled, the plateau is shortened two times, but the emissions of the converter are nonlinear. As the exhaust mass flow increases, the needed oxygen to transfer from ceria would have to be increased to convert all the emissions at the same rate. Since the transfer rate is limited by the concentration of oxygen on the ceria, the concentration of oxygen is not increased linearly and the conversions of the emissions are not increased twice.

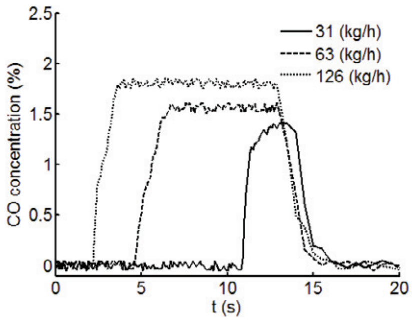
In the case of the low exhaust mass flow, because the absorption of oxygen and carbon monoxide is constrained and worse, outlet concentration of hydrocarbon is reduced and conversion turns to high after lean to rich transitions. Because the activity of hydrocarbon is stronger than carbon monoxide [9], which constrained the absorption of carbon monoxide, the concentration of hydrocarbon absorbed on the noble metal is increased with the increase of the exhaust mass flow. The amount of unused oxygen from the ceria surface in the front part of the converter also increases because of the inhibition, so outlet concentration of hydrocarbon is low, and the conversion of hydrocarbon is high. In the rich and steady state, because of the constraint of the noble metal coverage site, desorption of hydrocarbon is low with the increase of the exhaust mass flow. In the case of high exhaust mass flow, deposition of carbonizations on the noble metal increases which lead to outlet concentrations of carbon monoxide and hydrocarbon increase and the conversions of them are reduced.



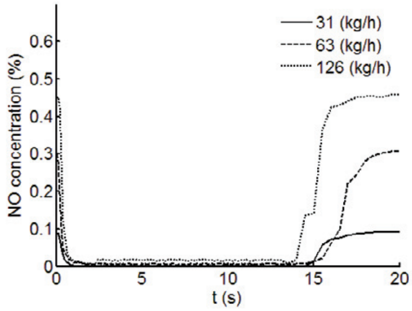
(a) Lambda



(b) HC



(c) CO



(d) NO

Figure 2. Outlet gas concentrations and lambda signals during the step tests with different exhaust mass flows

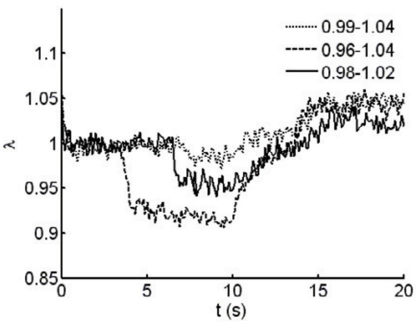
In the case of the rich to lean transitions, because oxygen is absorbed in the front of the ceria first, conversion of oxygen on the ceria is high with the high exhaust mass flow is shown in Fig. 2 (a). Carbon monoxide and hydrocarbon absorbed on the noble metal surface, so less oxygen on the noble metal leads to desorption of carbon monoxide and hydrocarbon are low. In the case of higher space velocity, oxygen is increased in the exhaust and more oxygen is absorbed on the noble metal surface [10, 11], so the conversions of carbon monoxide and hydrocarbon turn high and the converter would be soon arrived the steady state. In the case of the low exhaust mass flow, the reason of low conversions of carbon monoxide is as follow: first, oxygen is easy to absorb the ceria surface and the concentration of oxygen on the ceria is increased, because of the restraint of hydrocarbon, and the oxygen storage capacity is improved. Secondly the lower mass flow leads to a longer carbon monoxide desorption after the rich-lean step, because it takes longer time for oxygen to fill the oxygen storage. Thus, the conversion of carbon monoxide during the transient is not favored by decreasing the mass flow.

In the case of the high mass flow, inlet concentration of nitric oxide is high in the high mass flow. Oxygen, hydrocarbon and carbon monoxide are increased in the rich engine condition. Hydrocarbon and carbon monoxide absorbed on the ceria are increased which lead to quantity of nitric oxide absorbed on a noble metal and the ceria is reduced. Dissociation of nitric oxide needs an extra empty site on the noble metal [12], because lack of the empty noble metal site, the conversion of nitric oxide is low. Meanwhile the conversion of carbon monoxide is inhibited by the high concentration of nitric oxide. When inlet lambda stepped from rich to lean, nitric oxide could not dissociate because the oxygen covered most ceria surface. The conversion is reduced to 20 percent quickly in the steady state, because of few empty noble metal sites for nitric oxide dissociation.

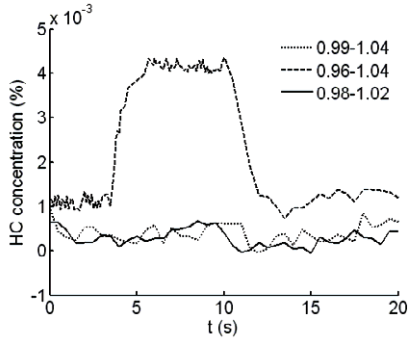
3.2.Effect of Inlet Lambda Amplitudes during Step Test on the Three-Way Catalytic Converter

Experiments were performed on the engine dynamometer test bench with the ambient temperature of 11 ℃, engine speed of 1200 r/min, exhaust mass flow of 31 kg/h and the catalytic converter temperature of 315 ℃. The responses of outlet lambda and concentrations of hydrocarbon, carbon monoxide, nitric oxide to inlet lambda of different amplitudes of 0.98-1.02, 0.96-1.04, and 0.99-1.04 are shown in Fig. 3.

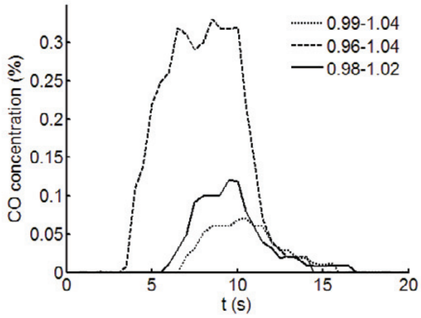
In the case of rich to lean transition, the responses of outlet lambda are increased linearly with the inlet lambda amplitudes and oxygen storage capacity. In the case of lean to rich step, outlet lambda is nonlinear. The outlet lambda plateau at stoichiometry after lean to rich step increases more than two times when the inlet lambda is set to 0.98 instead of 0.96. In the case of inlet lambda stepped from 0.99 to 1.04, when inlet lambda is set to 1.04, oxygen on the ceria is not exhausted and outlet lambda almost stays at stoichiometry. Fig. 2 (c) and Fig. 3 (c) show that exhaust mass flows are much more important than lambda amplitudes to the emissions, absorption and desorption of oxygen on the ceria.



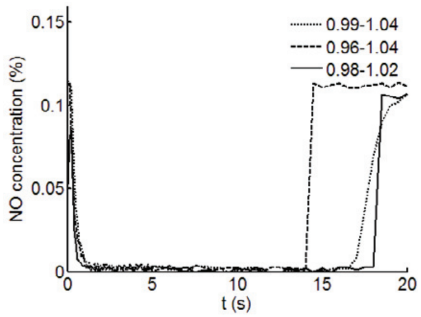
(a) Lambda



(b) HC



(c) CO



(d) NO

Figure 3 Outlet gas concentrations and lambda signals during the step tests with different inlet lambda amplitudes

3.3.Effect of Inlet Lambda Periods during Step Test on the Three-Way Catalytic Converter

Experiments were performed with the ambient temperature of 11 ℃, engine speed of 1200 r/min, engine torque of 40 Nm, exhaust mass flow of 64 kg/h. and the catalytic converter temperature of 315 ℃. The responses of outlet lambda to inlet lambda stepped periods of 20 seconds, 25 seconds, and 30 seconds are shown in Fig. 4.

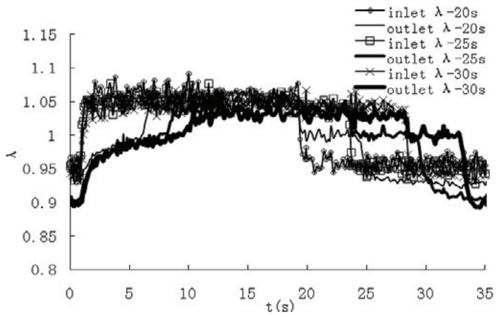


Figure 4. Outlet lambda signals during the step tests with different inlet lambda periods

Comparing the area between inlet and outlet lambda curves of different periods in Fig. 4 indicates that the oxygen storage capacity of the catalytic converter under rich to lean conditions is bigger than the one under lean to rich conditions. The periods are determined durations of the downstream lambda at stoichiometry.

This influence could be due to existence of various layers of ceria, namely a layer closer to the surface and deeper in the bulk. The longer the rich period, the larger the observed oxygen storage capacity is. Oxygen from the ceria bulk has to be used after the surface oxygen has been depleted, but the process proceeds at such a slow rate. Therefore, if the bulk becomes completely exhausted after a long rich step, the observed oxygen storage capacity during lean steps increases. The oxygen storage capacity did not seem to be dependent on the length of the lean input before the lean to rich step, because oxygen in the bulk moves fast. Effects of periods are similar to the mass flows and lambda amplitudes, so there is no need to explain any more.

Conclusions

(1) After lean to rich transitions, emissions reduce with the increase of the exhaust mass flow and turn to be deteriorated till the increase to a value.

(2) After rich to lean transitions, the downstream lambda increases linearly with the increase of the exhaust mass flows and inlet lambda amplitudes, since the oxygen storage capacity of the catalytic converter on the ceria increases linearly with the exhaust mass flows and inlet lambda amplitudes.

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