Engine Performance Improvement on Fuel Economy and Exhaust Emissions Using Lean Burn Control Technologies

ZHENGMAO YE[1], ZHIJUN LI[2], HABIB MOHAMADIAN[1]
[1]College of Engineering, Southern University
Baton Rouge, LA70813, USA
zhengmaoye@engr.subr.edu, mohamad@engr.subr.edu
[2]State Key Laboratory of Engines, Tianjin University
Tianjin City, 300072, P.R.China
lizhijundd@163.com

Abstract: - To enhance fuel economy and reduce the exhaust emissions, a lean burn gasoline engine system using novel catalyst design has been developed, which is used for NOx emission aftertreatment. The goal is to investigate the impact of this catalytic system on emission characteristics and BSFC (break specific fuel consumption) across a broad engine speed and load operating region under diverse arrangement schemes of the new catalyst converter. It can be indicated from experimental results that the upstream placement of three way catalyst ahead of the NOx adsorber catalyst is the best solution, which gives rise to the highest converting efficiency to reduce the NOx emission level of the lean burn gasoline engine. The role of engine speed on exhaust emissions and fuel economy is also reflected by the periodic operating time of lean burn and rich burn as well as the time ratio between the two. Engine load has served as a major factor in affecting exhaust emission characteristics and fuel economy of the lean burn gasoline engine. The heavier the engine load, the higher the NOx emission level, the less the NOx converting efficiency and the lower the BSFC. This technology also has the potential to be applied to all other types of lean burn engines.

Key-Words: - Lean Burn, Gasoline Engine, Adsorber-Reduction Catalyst, NOx Emission, BSFC

1 Introduction

To meet more and more stringent engine emission regulations and upcoming energy crisis worldwide, it is hard to rely on some engine operation stefficiencygies exclusively to improve the quality. Instead, many countries have developed new exhaust emission after-treatment systems to reduce emission levels. In the mean time, other aspects of engine performance must be retained [1-2]. Traditional TWC can be used to reduce CO, HC and NOx simultaneously and effectively when the gasoline engines operate under the stoichiometric A/F ratio condition.

Lean burn is an internal combustion of lean air-fuel mixtures. Engine combustion is considered lean when excess air is introduced into the engine along with the fuel. It occurs at high A/F ratios, which is beneficial to fuel economy. The major drawback of lean burn is the relatively large amount of NOx generated, the catalytic converter system is thus required. Lean burn engines do not work well with only TWC converters under the ultra lean A/F ratio. As a result, exhaust aftertreatment systems should be designed in order to implement both oxidation and reduction reactions. At present, the dominant technologies to reduce NOx emission of lean burn gasoline engine are EGR [3-5] and catalyzing [6-7]. Since a high EGR efficiency decreases the velocity of diffusion flame, obviously it can make the BSFC worse. Cylinder temperature affects the efficiency, emission, and performance of Spark Ignition engine. nonlinear transient model is needed. Control system for the electronic ignition and injection of a 4-stroke mono-cylinder internal combustion engine has been developed, which is to control the ignition advance, injection timing and period and the fuel flow rate. Ricardo develops a variable tumble CCVS system [5] that obtains a high EGR efficiency of 70% with good exhaust stratified combustion. The structure of this system is complicated and NOx emission is also hard to satisfy the strict emission regulations. For other methods of NOx decomposing and selective catalyst reduction (SCR) for exhaust systems, both the NOx catalyst converting efficiency and the thermal stability of the catalyst are hard to satisfy the practical requirement. Compared with these two methods, the developed NOx adsorber reduction catalyst combined with TWC can cleanse the NOx efficiently within a wide temperature window. The BSFC of a lean burn gasoline engine might deteriorate slightly, while the catalyst converting efficiency can reach 97% in a short period of rich condition [8-14]. A modified 16 valve EFI Quasi-

Homogenous lean burn gasoline engine is currently studied on effects of different placement schemes of a NOx converter and TWC, engine load and engine speed on exhaust emissions and BSFC with a combination of the NOx converter and TWC [14].

2 Experimental Test Bench

An experimental study is conducted to investigate the effects of engine load, engine speed, TWC and adsorber catalysts on characteristics of the exhaust emissions and BSFC. Combined with the traditional TWC, the research on NOx emission control in lean burn exhaust is carried out. Ahead of and after the NOx adsorber catalyst, devices for temperature and emission measuring are installed. During engine tests, catalyst entrance exhaust gas temperature is changed between 300ºC and 600ºC using the temperature regulator. At different locations of the exhaust pipeline, the gas temperature and NOx emission are measured to investigate the effects of catalyst arrangement schemes and catalyst entrance temperature on the NOx converting efficiency.

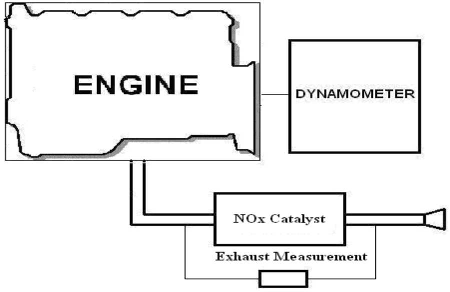

Fig. 1a Layout of Lean Burn Engine Test Bench

The developed 16-valve EFI Quasi-Homogenous lean burn gasoline engine system is employed. The structure of this exhaust system is shown in Fig. 1b, with new design of the lean burn NOx adsorber catalysts. Locations of component 2 and component 3 along with the tailpipe system can be swapped. There are three schemes of component arrangement for the exhaust tailpipe. At Scheme 1, the sequence order is 1-5-2-4 with NOx adsorber and no TWC. The sequence order is 1-5-2-3-4 at scheme 2, where the NOx adsorber is placed ahead of TWC. On the other hand, in scheme 3, the NOx adsorber is placed downstream after the TWC with a sequence order of 1-5-3-2-4. All arrangements are tested.

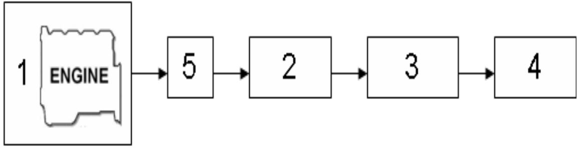

Fig. 1b Schematic of Engine Exhaust Systems
1. Engine, 2. Lean NOx Adsorber Catalyst, 3. TWC, 4. Muffler, 5. Temperature Regulator.

In Fig. 2, all three types of catalyst arrangement will lower the NOx emission level of the lean burn gasoline engine. The NOx emission is $800*10^{-6}$ or so before the catalyst system is introduced. After converting, the NOx emission level decreases significantly regardless of the actual time ratio of t_{lean} (lean mode) to t_{rich} (rich mode). For example, when the time ratio of t_{lean} to t_{rich} is 200s:20s, the NOx emission level is reduced to about $300*10^{-6}$ for Schemes 1 and 2, with a percentage drop of 62.5%, while for the Scheme 3, the NOx emission level is reduced to $50*10^{-6}$, with a percentage drop of 93%. It is shown that Scheme 3 is better than Schemes 1 and 2 in this case. When the time ratio t_{lean}/t_{rich} is reduced from 200s:20s to 40s:4s, the NOx emission level after the catalyst decreases from $300*10^{-6}$to $50*10^{-6}$ for Schemes 1 and 2, while it is reduced from $50*10^{-6}$ to $15*10^{-6}$ for the Scheme 3. These experiment results indicate that all three catalyst arrangement schemes can achieve remarkable NOx emission reduction. Furthermore, as the absolute time ratio t_{lean}/ t_{rich} decreases, the NOx emission level is also reduced.

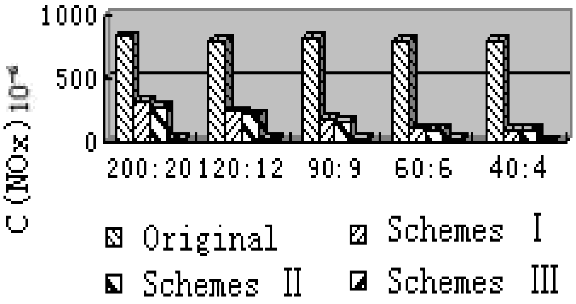

Fig. 2 Effects of Arrangement on NOx Emission (n=1800rpm and Pe=0.2MPa)

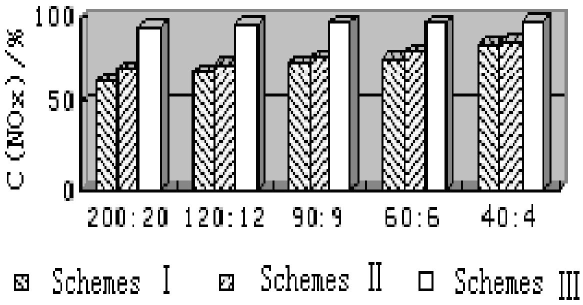

Fig. 3 Effects of Arrangement on NOx Converting Efficiency (n=1800 rpm and Pe=0.2MPa)

In Fig. 3, the NOx converting efficiency C_{NOx} in Schemes 1 and 2 are almost equal, however less than the NOx converting efficiency C_{NOx} in the Scheme 3. In addition, as the absolute time of t_{lean} and t_{rich} decreases, the NOx converting efficiency C_{NOx} in all three schemes increase: the NOx converting efficiency in the Scheme 1 increases from 61.9% (200s:20s) to 83.5% (40s:4s); the NOx converting efficiency in the Scheme 2 increases from 70% (200s:20s) to 85.2% (40s:4s); and the NOx converting efficiency in the Scheme 3 increases from 94% (200s:20s) to 97.3% (40s:4s). The NOx converting efficiency C_{NOx} in the Scheme 3 is better than those of the other two schemes.

The scheme 3 is found to be the best scheme for NOx purification. From theoretical point of view, when TWC is placed ahead of the NOx adsorber-reduction catalyst, the exhaust gases flow through TWC at first before reacting with the reducing agent rhodium. Accordingly, even though oxygen is rich among the exhaust gases, the converting process of NOx is restricted and the NOx converting efficiency C_{NOx} is reduced. On the other hand, this arrangement can reduce the concentration of O_2, HC and CO as well as the absolute inlet NOx emission level for the lean burn NOx adsorber-reduction catalyst, so as to reduce the level of oxygen adsorbed, alleviate the load of lean burn NOx adsorber-reduction catalysts and prolong the saturation time of the NOx catalyst. When the time ratio t_{lean}/ t_{rich} is fixed, as the absolute time of t_{lean} and t_{rich} drops, the absolute NOx emission level is low, so there is little possibility of NOx overflow within a short period of time. In the mean while, there is a NOx reduction process in each short period, making chances of NOx overflow even smaller. Along with the rich process of NOx reduction, the NOx adsorbed is almost deoxidized. When the gasoline engine switches to lean burn mode, the adsorber capacity of catalyst is enhanced again. Thus, the NOx emission level consequently decreases. In other words, as the absolute time of t_{lean} and t_{rich} drops, the emission level of NOx in this system also decreases.

3 Electronic Throttle Control Systems and Baseline Engine Maps

Using the same set of sensory systems, the original ECU is substituted by one more flexible to regulate the A/F ratio for lean burn control. The electronic controlled throttle and the linear A/F sensor are also used for special demands of the NOx adsorber-reduction catalyst and lean burn operation. The A/F ratio and operating time are set beforehand according to requirements of experiments. Throttle angle and injection pulse width can be adjusted by the current ECU to ensure the required A/F ratio and the steady power output. The linear A/F ratio sensor keeps the engine operating condition in a suitable range of A/F ratio via the feedback control signal.

When the engine operates at lean mode, regular engine control parameters are selected. When the engine operates at rich mode, the throttle position and spark timing will be adjusted. In order to keep the engine power output and torque output stable under an allowable fluctuation range of engine speed, the throttle opening is reduced and spark timing is retarded. At the same time, the spark advance angle retarding is helpful to avoid engine knock. For the optimization purpose, the step motor is used to adjust the throttle angle with priority, then a fine tuning is made by adjusting the spark advance angle. Base on intelligent control principles, a self-learning algorithm is used to determine both the increment and decrement offsets to the baseline engine maps. The baseline engine maps for lean mode (A/F ratio: 21) and rich mode (A/F ratio: 12) in this research are shown in Fig. 4 and Fig. 5. For any specified throttle angle, the engine map can be obtained by interpolation.

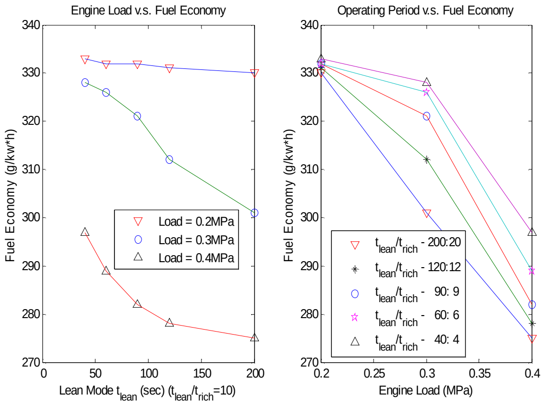

Fig. 4 Baseline Engine Map 1 (Rich and Lean)

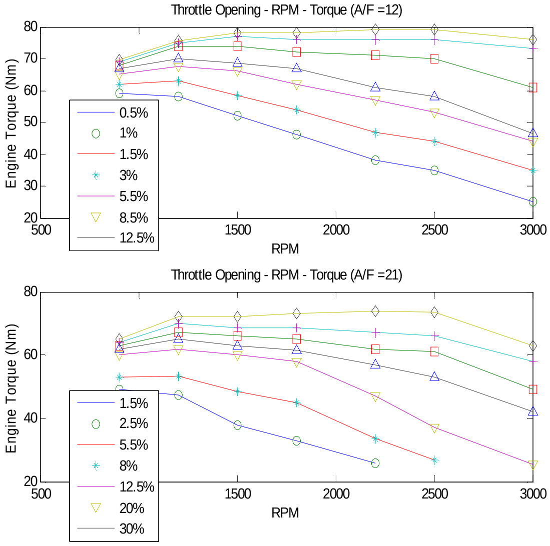

Fig. 5 Baseline Engine Map 2 (Rich and Lean)

4 Effects of Engine Speed on Exhaust Emissions and BSFC

With respect to the scheme 3, effects of engine operations on exhaust emission characteristics and BSFC are both investigated. In Fig. 4 and Fig. 5, effects of exhaust emission and the NOx converting efficiency have been shown under different engine speed (1500, 1800, 2500 rpm) with the fixed engine load in the Scheme 3. The x-axis denotes the ratio of absolute lean mode operating time t_{lean} and rich mode operating time t_{rich}. The y-axis denotes the concentrations of exhaust emission levels of CO, HC, NOx, the NOx converting efficiency and BSFC, respectively. Operating conditions of the lean burn engine are: engine load is selected to be 0.2MPa; engine speed is 1500, 1800 and 2500 rpm, respectively; A/F ratio is 21 in lean burn and 12 in rich burn; time ratio t_{lean}/t_{rich}=10.

In Fig. 6 to Fig. 8, when the time ratio of t_{lean}/ t_{rich} and the absolute time of t_{lean} and t_{rich} stay the same, and engine load is set to be 0.2Mpa, as engine speed increases (1500, 1800, 2500 rpm), emission levels of CO and HC decrease while the NOx level increases slightly. But with the absolute time of t_{lean} and t_{rich} decreased, the emission levels of CO and HC increase while the NOx level decreases slightly. This is because the increased engine speed leads to the oxidation condition sufficiently to oxidize CO and HC, therefore the CO and HC emissions of the lean burn gasoline engine decrease. Owing to the placement of the NOx adsorber-reduction catalyst, emission levels of CO and HC in the exhaust system is slightly higher than that of from the lean burn gasoline engine exclusively.

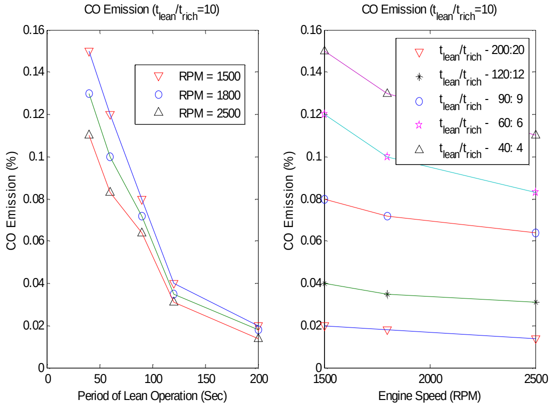

Fig. 6 Effects of Engine Speed on CO emission

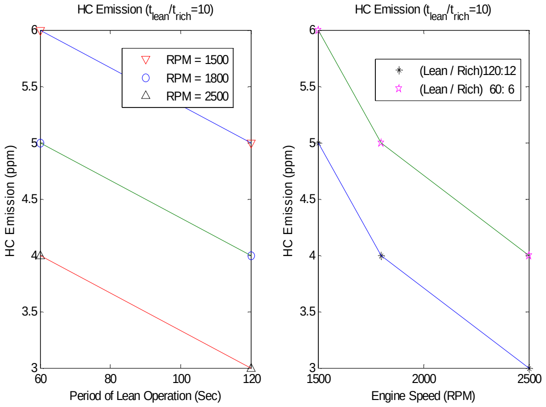

Fig. 7 Effects of Engine Speed on HC emission

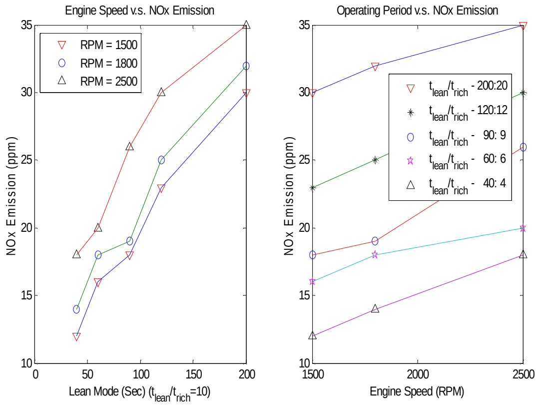

Fig. 8 Effects of Engine Speed on NOx emission

As engine speed increases, engine operation cycle turns out to be a shorter period, making in-cylinder temperature slightly higher with the increased NOx concentration. On the other hand, with the absolute time of t_{lean} and t_{rich} decreased, the A/F ratio transient processes occur more frequently, so emission levels of CO and HC increase. Since the shortening of t_{lean} and t_{rich} improves the converting efficiency in the adsorber-reduction catalyst system, the emission level of NOx will decrease in this case.

In Fig. 9, engine load is set to be 0.2Mpa. When the time ratio t_{lean}/ t_{rich} stays the same, the converting efficiency reaches 94.2% when the time ratio t_{lean}/t_{rich}=200:20 at 1500 rpm, 94% at 1800 rpm and 93.8% at 2500 rpm, which keeps decreasing slightly. The reason is that the NOx emission level increases while exhaust temperature also increases, which is beneficial for oxidation in catalyst systems but not helpful for the NOx restoration. At the same time, the converting efficiency increases with the decrease of the absolute time t_{lean} and t_{rich} (e.g. the time ratio t_{lean}/t_{rich} switches from 120:20 to 90:9).

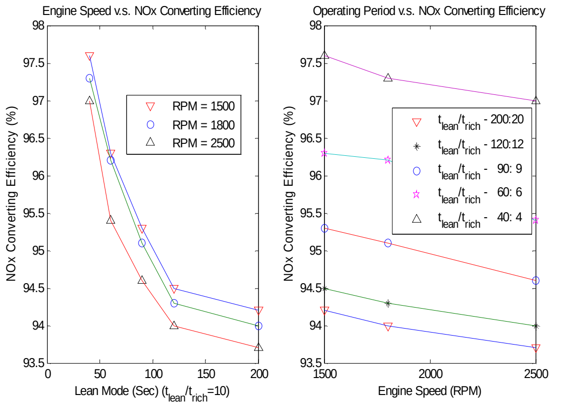

Fig. 9 Effects of Engine Speed on NOx Converting Efficiency

The shortening of the absolute time reduces the leakage of NOx through adsorber-reduction catalyst systems and enhances the absorbance of the NOx emission. The NOx level thus increases slightly. Under the fixed absolute time of t_{lean} and t_{rich}, the converting efficiency decreases slightly with the increasing engine speed, and vice versa. It indicates that the extra NOx emission level due to high speed can be improved by shortening the absolute time of t_{lean} and t_{rich}.

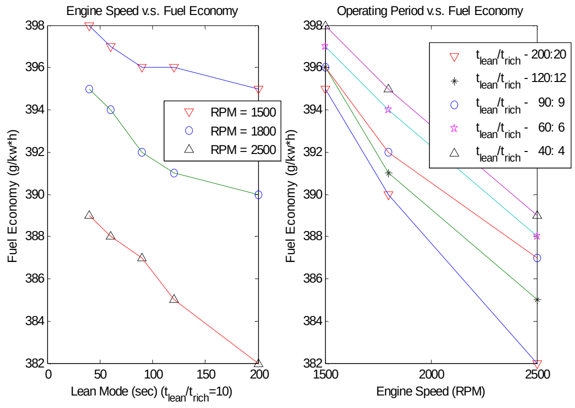

Fig. 10 Effects of Engine Speed on BSFC

In Fig. 10, when t_{lean}/ t_{rich} and the absolute time of t_{lean} and t_{rich} are fixed, if engine speed increases from 1500 to 2500 rpm, BSFC is slightly improved. Analyzing this phenomenon, when absolute time of both t_{lean} and t_{rich} stays the same, the in-cylinder turbulence intensity is enlarged so that combustion is improved which leads to the smaller BSFC. But if the engine speed is very high, the BSFC increment will be bigger because the strengthened in-cylinder air motion results in the heat loss. For the low and medium range of engine speed, the increment of engine speed will lead to the BSFC decrement. As the absolute time of t_{lean} and t_{rich} decreases with the fixed time ratio t_{lean}/ t_{rich}, the A/F ratio transient process occurs more frequently, the BSFC increases very slightly.

The impact of engine speed on the exhaust emissions and BSFC is related to the time ratio and absolute time t_{lean} and t_{rich}. For the fixed t_{lean} and t_{rich} condition, the CO and HC emission levels decrease and the NOx emission level increases with the increasing speed, while the converting efficiency in adsorber-reduction catalyst system decreases and its BSFC is improved. If the absolute time of t_{lean} and t_{rich} decreases, the CO and HC emission levels increase and the NOx emission level decreases, both the BSFC and converting efficiency increase.

5 Effects of Engine Load on Exhaust Emissions and BSFC

Using the Scheme 3, effects of different engine load (Pe=0.2, 0.3 and 0.4 MPa) on exhaust emission levels of CO, HC and NOx, converting efficiency and BSFC have been shown in Fig. 11, when engine speed is 1800 rpm, the time ratio t_{lean}/ t_{rich} is 10, A/F ratio of lean mode is 21 and that of rich mode is 12.

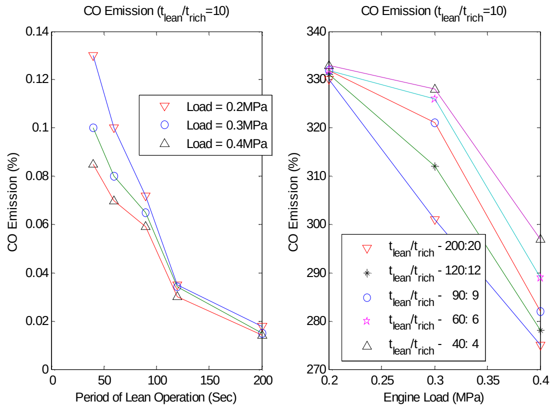

Fig. 11 Effects of Engine Load on CO emission

In Fig. 11 to Fig. 13, engine speed is set to be 1800 rpm. When the time ratio t_{lean}/ t_{rich} stays the same, if the absolute time of t_{lean} and t_{rich} is fixed, with the increasing engine load (0.2, 0.3, 0.4 MPa), emission levels of CO and HC will decrease and that of NOx will increase. For the shorter absolute time of t_{lean} and t_{rich}, emissions of CO and HC will increase and that of NOx will decrease slightly. This is mainly because that in-cylinder temperature rises due to additional engine load which enhances the fuel oxidation. The rise of cylinder wall temperature reduces the thickness of boundary layer attached, so the HC level adsorbed by this layer decreases. At the same time, the amount of the unburned in-cylinder fuel mixture decreases. As a result, the emission levels of CO and HC decrease and that of NOx increases. In the mean time, for a fixed engine load, when the absolute time of t_{lean} and t_{rich} decrease, the emission levels of CO and HC increase and that of NOx decreases.

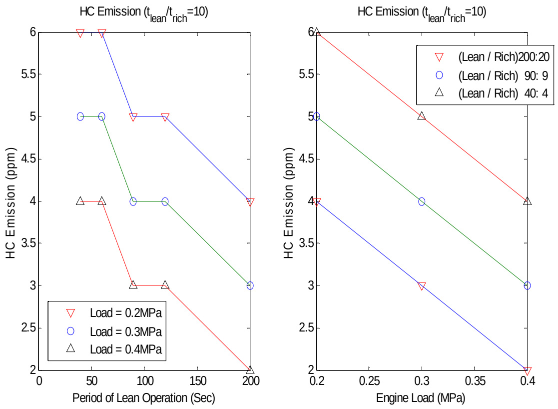

Fig. 12 Effects of Engine Load on HC emission

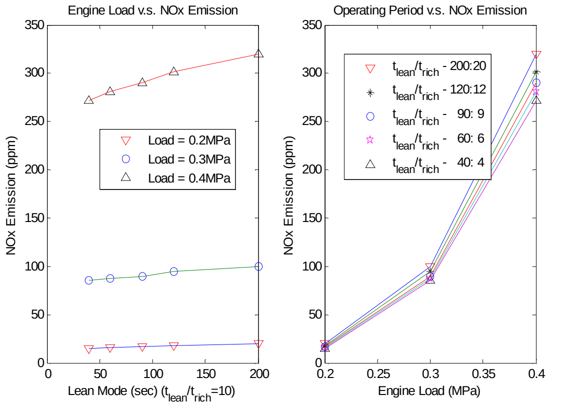

Fig. 13 Effects of Engine Load on NOx emission

The shorter absolute time of t_{lean} and t_{rich} decreases the reaction time of lean burn before the restoration and regeneration process starts. The transient condition occurs more frequently during certain time period, making slightly larger concentrations of CO and HC levels. The NOx concentration becomes smaller due to the less absolute time t_{lean} and t_{rich}, where NOx created during lean burn is converted to N_2 during restoration in terms of reactions inside the alkaline earth of the catalyst system. These improve both the absorbance capability of the NOx catalyst and the converting efficiency.

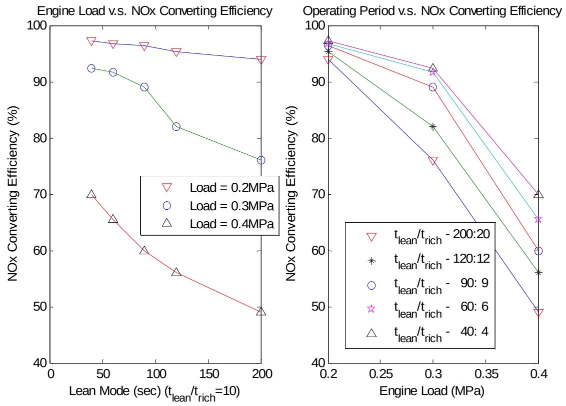

Fig. 14 Effects of Engine Load on NOx Converting Efficiency

In Fig. 14, engine speed is set to be 1800 rpm. The converting efficiency in the adsorber-reduction catalyst system is related to not only the absolute time of t_{lean} and t_{rich} but also the engine load. The heavier the load, the higher the NOx emission level, the lower the converting efficiency. For a fixed time ratio t_{lean}/ t_{rich}, if the absolute time of t_{lean} and t_{rich} stays the same and engine speed is 1800 rpm, with the increasing of engine load (0.2, 0.3, 0.4 MPa), the converting efficiency decreases. The converting efficiency drops from 94% to 85% and 49% (t_{lean}/t_{rich} =200:20). Compared with the effects of decreasing the absolute time of t_{lean} and t_{rich} in the adsorber-reduction catalyst system, engine load has shown much more significant impact on the converting efficiency. The heavier engine load, the smaller the converting efficiency.

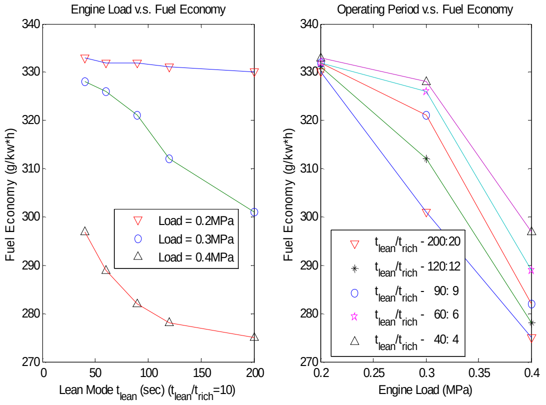

Fig. 15 Effects of Engine Load on BSFC

In Fig. 15, engine speed has been fixed (1800 rpm), engine load affects the BSFC remarkably. The heavier the engine load, the lower the BSFC. When engine load increases, in-cylinder temperature rises, from one aspect, the heavier load improves fuel pulverization and combustion conditions. From another aspect, the accumulation of engine load reduces the relative cooling loss and pumping loss of the engine, thus the thermal efficiency increases. In addition, the engine load accumulation improves the engine mechanical efficiency and also improves fuel economy.

With the fixed time ratio t_{lean}/t_{rich} and engine load, when absolute time of t_{lean} and t_{rich} decreases, BSFC is increased slightly since the shorter absolute time of t_{lean} and t_{rich} prolongs the total engine transient operating period within the same time period.

6 Conclusions

A novel catalyst system has been developed to investigate the impact of various schemes of the NOx converter arrangement, engine speed and engine load on the BSFC and exhaust emission characteristics of a lean burn gasoline engine. The aftertreatment system consists of a traditional TWC and catalyst converter for NOx adsorber-reduction. These conclusions are useful for the potential engine modeling and control.

1) The arrangement Scheme 3 leads to the lowest NOx emission of $50*10^{-6}$ and the highest converting efficiency of 97.3%. Thus, to reduce NOx emission level in lean burn gasoline engine via TWC and the lean burn adsorber catalyst, an upstream placement scheme of TWC ahead of the adsorber-reduction catalyst is the best solution.

2) For a fixed t_{lean}/t_{rich} ratio, if absolute time of t_{lean} and t_{rich} stays the same, the emission levels of CO, HC decrease and that of NOx increases slightly with the increasing engine speed. Its BSFC is improved as well. The change of NOx converting efficiency is negligible. With the absolute time of t_{lean} and t_{rich} decreasing, emission levels of CO and HC increase and that of NOx decreases slightly, the converting efficiency increases and the BSFC is improved.

3) For a fixed t_{lean}/t_{rich} ratio, if the absolute time of t_{lean} and t_{rich} stays the same, the emissions of CO and HC decrease and that of NOx increases with the increased engine load. With the absolute time of t_{lean} and t_{rich} decreasing, emission levels of CO and HC increase and that of NOx decreases slightly, the converting efficiency increases, however the BSFC becomes worse.

4) The NOx converting efficiency is related with not only the absolute time of t_{lean} and t_{rich} but also the engine load. The heavier the load, the higher NOx emission level, the lower the converting efficiency. Fuel economy has been improved using this new NOx adsorber-reduction catalyst system.

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