

Reduce NO_x Emissions by Adsorber-Reduction Catalyst on Lean Burn Engine

Dongpeng Yue¹, Qing Chang^{2*}, Lei Liu², Wen Zhang^{2,3}, Shaoshu Chen², Zhijun Li²

¹School of Automotive and Transportation, Tianjin University of Technology and Education, Tianjin 300222

²State Key Laboratory of Engines, Tianjin University, Tianjin 300072

³Tianjin electronic information vocational technology college, Tianjin 300350

*Corresponding author, e-mail: matrixfuture@sina.com, Telp: +86 022 27406781, Fax: +86 022 27383362

Abstrak

Pengaruh sistem katalis baru yang terdiri dari tiga cara tradisional konverter katalis dan adsorber-reduksi konverter katalisis pada karakteristik emisi dan BSFC (Breake Specific Fuel Consumption-BSFC) dari sebuah mesin bensin yang ramping untuk membakar diteliti dalam makalah ini, dimana skema yang berbeda dari katalis pengaturan sebuah konverter dan kecepatan yang berbeda-beda dan juga bebannya. Hasil menunjukkan bahwa posisi terbaik dengan tiga cara Catalyst adalah sebelum NO_x diserap oleh Catalyst dengan sebuah skema untuk mengatur konverter ternyata adalah cara terbaik. Dengan cara mengefisienkan konverter dan mengurangi emisi NO_x dalam mesin bensin tersebut. Dimana terdapat efek dari kecepatan pada emisi gas buang dan BSFC juga terkait dengan rasio pewaktuan dalam proses membakar dan nilai absolut dari kedua waktu dari konverter katalis tersebut. Beban mesin adalah faktor utama yang berpengaruh terhadap karakteristik emisi gas buang dan BSFC dari mesin tersebut. Didapati semakin banyak emisi NO_x, maka nilai NO_x berkurang untuk tingkat konversi (C_{NO_x}) dan akan mendapatkan nilai BSFC yang lebih baik.

Kata kunci: membakar lemak, mesin bensin, katalis adsorber-reduksi, NO_x, emisi

Abstract

The effect of a new catalyst system composed of traditional three way catalyst converter and adsorber-reduction catalysis converter on the emission characteristics and BSFC (Breake Specific Fuel Consumption- BSFC) of a lean burn gasoline engine operated were investigated in this paper under different schemes of catalyst converter arrangement and different speeds and loads. The results show that the position of Three Way Catalyst is before the NO_x adsorber Catalyst was the best scheme of catalyst converter arrangement. Which has the highest converter efficiency of reduction NO_x emission in lean burn gasoline engine. The effects of speed on the exhaust emission and BSFC were also related to the ratio of lean burn time to rich burn time and the absolute value of both time of the adsorber-reduction catalyst converter. The load of the engine was the main influential factor to the exhaust emission characteristics and BSFC of lean burn gasoline engine, and the more load of the engine was, the more NO_x emission, the less NO_x conversion rate (C_{NO_x}) and the better BSFC were.

Keywords: lean burn, gasoline engine, adsorber-reduction catalyst, NO_x, emission

1. Introduction

As the emission regulation becomes more and more strict, it's too hard to reduce exhaust emissions only depending on improving internal operation process of engine. Consequently, many countries have developed the exhaust after-treatment technology to reduce exhaust emissions, meanwhile, retain other performance of the engine [1].

Traditional three-way-catalyst (TWC) synchronously reduces CO, HC and NO_x effectively only when the gasoline engine is working under stoichiometric air/fuel ratio condition [2]. Excess air ratio of lean burn is more than one, so NO_x emission can not be reduced by three-way-catalyst. Currently, the main technologies of reducing NO_x emission of lean burn gasoline engine are EGR[3-7] and catalyze[8-13]. But the high EGR rate decreases the velocity of flame diffusion, and consequently worsens the BSFC. Although the Ricardo developed an variable tumble CCVS system [3] and good exhaust stratified combustion was obtained with high EGR rate of 70%, The structure of this system was complicated and NO_x emission was also hard to satisfied the request of stricter emission regulation. For the methods of NO_x decomposing [14] and selective catalyst reduction (SCR) [15] using for vehicle exhaust, the

NOx catalyst conversion rate and the thermal stability of the catalyst are all hard to satisfied the practical request. Compared with these methods of reducing lean burn NOx, The NOx adsorber reduction catalyst combined with TWC can purify the NOx high efficiently within wide temperature scope. With this method, the BSFC of lean burn gasoline engine is deteriorated little, while the catalyst conversion rate of NOx CNOx can be 97% during the short time of fuel rich condition. The Authors using a modified 16 valves EFI Quasi-Homogenous lean burn gasoline engine studied the effect of different schemes of arrangement NOx adsorber converter and TWC, different loads and speeds on exhaust emission characteristics and BSFC with the combination of NOx adsorber catalyst and TWC.

2. Research Method

Experimental research on the effect of different combination schemes of lean burn adsorber catalyst and TWC, loads and speeds on exhaust emission characteristics and BSFC were conducted on a modified 16 valves EFI Quasi-Homogenous lean burn gasoline engine with the lean burn gasoline engine electronic control system developed by the authors colleagues [8]. Figure 1 shows the schematic of exhaust pipeline design of the lean burn NOx adsorber catalyst experiment system. C_i , T_i represent the concentration and temperature of exhaust emission at the i place respectively. The parts 2 and 3 in the pipeline can be changed each other. There are three scheme of the parts arrangement in the exhaust pipeline. In the scheme 1, the parts sequence is 1-5-2-4 with NOx adsorber but without TWC. In the scheme 2, the parts sequence is 1-5-2-3-4, that is, the NOx adsorber is set before TWC. On the contrary, in the scheme 3, the NOx adsorber locates after the TWC with the sequence of 1-5-3-2-4.

The original engine sensor and wires were preserved, and the original ECU was replaced by the lean burn gasoline engine control ECU which can regulate the A/F ratio easily. The electronic control throttle and linear A/F sensor were also used for the special demand of the lean burn NOx adsorber-reduction catalyst and lean burn gasoline engine operation. Set the value of A/F and operating time in advance according to the demand of experiment. Throttle and the injection pulse can be modified by lean burn gasoline engine ECU to ensure the required A/F and a steady output power. Linear A/F sensor keep the engine working in the right range of A/F via feedback signal.

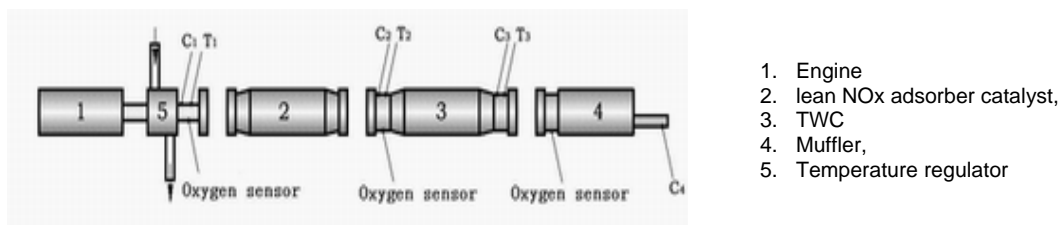


Figure 1. Schematic of experimental system in lean NOx adsorber catalyst in exhaust pipe

3. Results and Discussion

3.1 The Effect of Different Combination Schemes of NOx Adsorber-reduction Catalyst and Three Way Catalyst on Exhaust Emission Characteristics

The effects of catalyst system arrangement of different scheme on NOx emission and NOx conversion rate C_{NOx} were shown in Figure 2 and Figure 3. The x-axis denotes the ratio of the absolute lean burn operating time t_{lean} and the absolute rich condition operating time t_{rich} . The y-axis denotes the concentration of NOx emission (1) and the NOx conversion rate C_{NOx} (%) respectively.

As showed in Figure 2, all of the three different catalyst arrangements can reduce NOx emission of lean burn gasoline engine. The NOx emission is about 800×10^{-6} before catalyst. After conversion, the NOx emissions reduce significantly no matter the ratio of t_{lean} to t_{rich} . For example, when the ratio of t_{lean} to t_{rich} is 200s:20s, NOx emission scheme 1 and scheme 2 was reduced to about 300×10^{-6} , lower 62.5%. NOx emission of scheme 3 reduced to 50×10^{-6} , lower 93%. The scheme 3 is better than the scheme 1 and 2. And as the absolute time of t_{lean}/t_{rich} decreased from 200s: 20s to 40s: 4s, NOx emission after catalyzed also reduced from

300×10^{-6} to 50×10^{-6} for scheme 1 and 2, and reduced from 50×10^{-6} to 15×10^{-6} for scheme 3. The above experiment results illuminate that catalyst arrangement as three scheme can achieve better effect of NOx emission reduction, further more, as the absolute time of t_{lean}/t_{rich} decreased, NOx emission reduced.

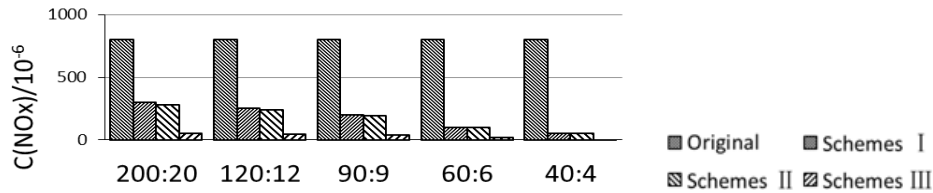


Figure 2. Effects of different schemes on NOx emission ($n=1800\text{r/min}$, $p_e=0.2\text{MPa}$)

These results can be explain as: when the three ways catalyst is located before the lean burn NOx adsorber-reduction catalyst, the exhaust emission enters three ways catalyst at first, and reacts with the reducing agent rhodium. Although the oxygen is rich in the exhaust gas, the conversion process of NOx is restricted to some extent, and the NOx conversion rate C_{NOx} is decreased. But this arrangement can reduce the concentration of O_2 , HC, CO and the absolute value of NOx emission entering the lean burn NOx adsorber-reduction catalyst, so as to reduce the vacancy of oxygen adsorbed, alleviate the load of lean burn NOx adsorber-reduction catalyst, and prolong the time before the catalyst's saturation. While t_{lean}/t_{rich} is constant, as the absolute time of t_{lean}/t_{rich} diminishing, on the one hand, the absolute quality of NOx emission is small, and the time is short, so the possibility of NOx overflowing is little; on the other hand, there is a process of NOx reduction in every short time, which make the possibility of NOx overflowing smaller. In the process of NOx reduction, all the NOx adsorbed is almost deoxidized. When the engine turns to lean burn condition again, the adsorber capacity of catalyst is enhanced. Thus, the NOx emission consequentially reduces. In other words, as the absolute time of t_{lean}/t_{rich} diminishing, the NOx emission of the catalyst system reduces.

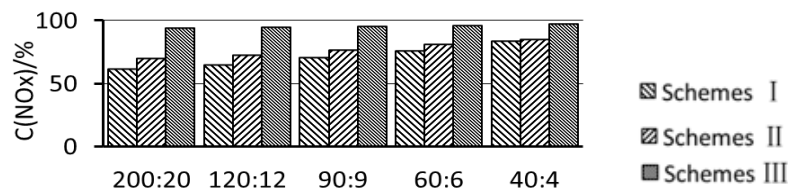


Figure 3. Effects of different schemes on NOx conversion efficiency C_{NOx} ($n=1800\text{r/min}$, $p_e=0.2\text{MPa}$)

As shown in Figure 3, the NOx conversion rate C_{NOx} of catalyst arrangement of scheme 1 and 2 is almost equal, but both less than the NOx conversion rate C_{NOx} of scheme 3. Not only such, as the absolute time of t_{lean}/t_{rich} diminishing, the NOx conversion rate C_{NOx} of the three scheme all increase, the NOx conversion rate C_{NOx} scheme 1 enlarges from 61.9% (200s: 20s) to 83.5% (40s: 4s); the NOx conversion rate C_{NOx} of scheme 2 enlarges from 70% (200s: 20s) to 85.2% (40s: 4s); and the NOx conversion rate C_{NOx} x of scheme 3 enlarges from 94% (200s: 20s) to 97.3%(40s: 4s). The NOx conversion rate C_{NOx} of scheme 3 is better than the other two schemes; it is mainly because of the different arrangement of the catalysts.

3. 2 The Effect of Different Speeds on Exhaust Emission Characteristics and BSFC

As above, scheme 3 is the best scheme among scheme 1 to scheme 3. Under scheme 3, the author studied the effect of different operations on BSFC and exhaust emission characteristics. Figure 4 and Figure 5 show the effect of exhaust emission and the NOx conversion rate C_{NOx} in scheme 3 on different speeds (1500 rpm, 1800 rpm, 2500 rpm) under

the load being constant. The x-axis denotes the ratio of the absolute lean burn operating time t_{lean} and the absolute rich condition operating time t_{rich} . The y-axis denotes the concentration of exhaust emission include CO, HC and NOx (1×10^{-6}), the NOx conversion rate C_{NOx} (%) and the BSFC respectively.

Operating conditions and mode of the lean burn gasoline engine are: load (PMEP) $P_e = 0.2$ MPa, speed are 1500 rpm, 1800 rpm, and 2500 rpm respectively. A/F in lean burn is 21, and that of rich burn is 12, $t_{lean}/t_{rich} = 10$. As shown in Figure 4, when the ratio of t_{lean}/t_{rich} and the absolute time of t_{lean}/t_{rich} keep steady, as the speed of gasoline engine increased ($P_e = 0.2$ Mpa, the speed are 1500 rpm, 1800 rpm, and 2500 rpm respectively), in the exhaust emission of the lean burn gasoline engine, the CO, HC reduce and NOx increase slightly. But with the absolute time of t_{lean}/t_{rich} decreased.

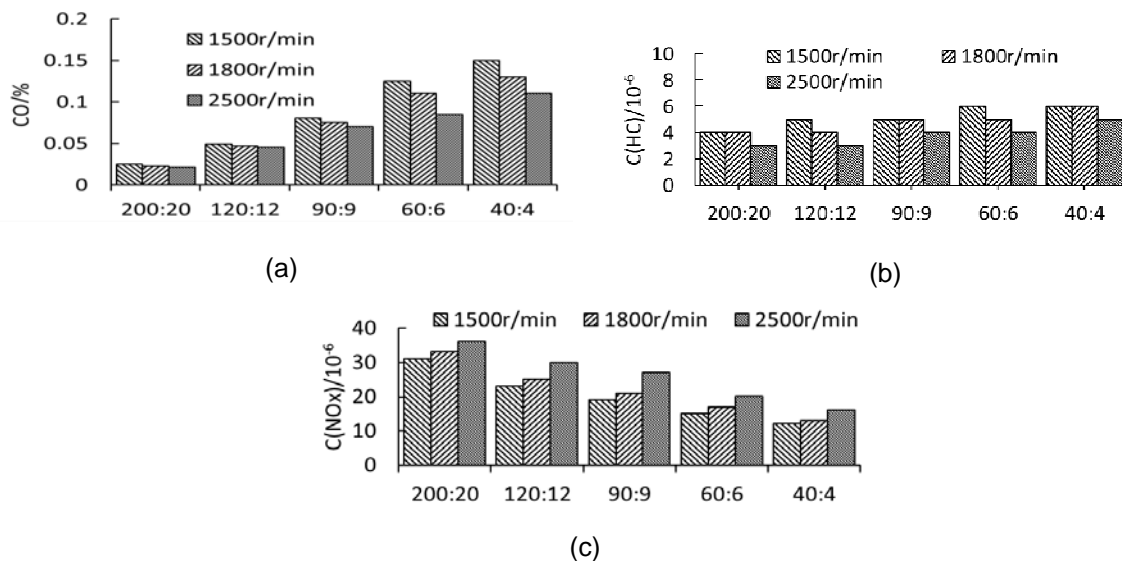


Figure 4. Effects of different speeds on exhaust emission ($P_e = 0.2$ MPa)
 (a) Effects of different speeds on CO emission, (b) Effects of different speeds on HC emission
 (c) Effects of different speeds on NOx emission

The CO and HC increased but NOx decreased slightly. This is mainly because the speed of the lean burn gasoline engine increased, which made the oxygenous condition in the cylinder better, that's better to the sufficient oxidation of CO and HC, so the CO and HC emission of the lean burn gasoline engine decreased. Because the engine adopt the the lean burn NOx adsorber-reduction catalyst system, the concentration of CO and HC in the emission of the lean burn gasoline engine is a little higher than that of pure lean burn gasoline engine. After the speed of engine increase, in the adsorber-reduction process of lean burn gasoline engine, because the time ratio of lean burn and rich burn t_{lean}/t_{rich} is a constant, the times of engine operation cycle in the same period increased, which will make the temperature inside the cylinder a little higher and the concentration of NOx increased. But with the absolute time of t_{lean}/t_{rich} decreased, the times of A/F transformed process in the same period increased and the total time of engine operation in transitional period increased, so the CO and HC emission of the engine increased. As the decrease of t_{lean} and t_{rich} improved the conversion rate of NOx C_{NOx} in adsorber-reduction catalyst system, so the NOx emission decreased with the decrease of the absolute time of t_{lean} and t_{rich} .

As shown in Figure 5, when the ratio of t_{lean}/t_{rich} keep steady, the conversion rate of NOx C_{NOx} reached 94.2% when $t_{lean}/t_{rich} = 200:20$ ($n = 1500$ rpm). With the increase of engine speed ($C_{NOx} = 94\%$ when $n = 1800$ rpm, and $C_{NOx} = 93.8\%$ when $n = 2500$ rpm), the conversion rate of NOx C_{NOx} changed little. This is mainly because the NOx will increase with the speed of engine increased, but the temperature of exhaust into the catalyst system rise what is the better for improve the oxygenous condition of the catalyst system and the worse for the restore of NOx emission. When the ratio of t_{lean}/t_{rich} keep steady, the conversion rate of NOx C_{NOx} rise with the

decrease of t_{lean}/t_{rich} absolute time (for example : t_{lean}/t_{rich} decrease from 200:20 to 40:4). This is because that the decrease of t_{lean}/t_{rich} absolute time reduced the leak of NOx through lean burn adsorber-reduction catalyst system and improved the adsorbability of NOx emission. The NOx emission of lean burn gasoline engine which has rise slightly due to the increase of speed can be improved by shorten the t_{lean}/t_{rich} absolute time. So if the t_{lean}/t_{rich} absolute time keep steady, the conversion rate of NOx C_{NOx} in adsorber-reduction catalyst system reduce a little with the speed of engine rise. On the contrary, the conversion rate of NOx C_{NOx} in adsorber-reduction catalyst system will rise a little if decrease the t_{lean}/t_{rich} absolute time. That is means that the increasing NOx exhaust emission with the rising of speed can be improved by decrease of t_{lean}/t_{rich} absolute time.

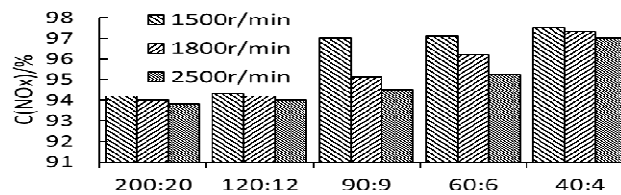


Figure 5. Effects of different speeds on NOx conversion efficiency C_{NOx} ($P_e=0.2$ MPa)

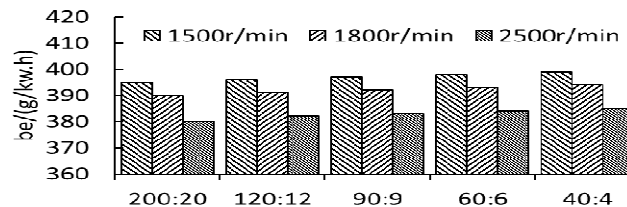


Figure 6. Effects of different speeds on BSFC ($P_e=0.2$ MPa)

As shown in Figure 6, when t_{lean}/t_{rich} and the absolute time of t_{lean}/t_{rich} keep steady, if the speed of engine rise (from 1500 rpm to 2500 rpm), BSFC be improved. In other words, the speed rised. But the BSFC will rise a little with the absolute time of t_{lean}/t_{rich} reduce. Analyzing this phenomenon, we deem that : when t_{lean}/t_{rich} keep steady, if the absolute time of t_{lean}/t_{rich} stay the same, the turbulence intensity inside cylinder of the lean burn gasoline engine will largen and the combustion condition will be better what lead to the smaller BSFC. But if the speed of engine is much too high, the BSFC will grow the bigger because that the strengthen movement of air inside the cylinder lead to the transferred loss of the quantity of heat inside the cylinder. The range of speed in this experiment belong to the middle and lower range of the engine speed, so the rise of speed lead to the BSFC decreased. As the absolute time of t_{lean}/t_{rich} decrease, because t_{lean}/t_{rich} stays at a constant that the percentage of the total time of the same lean burn gasoline engine operating in lean burn and rich burn condition stays at a constant but the times of A/F transforming process in the same period increased and the total time of engine operate in transitional period increased what large the BSFC of lean burn gasoline engine a little although not notable.

These result can be explain as (compared to following load factor): the impact of the increase of lean burn gasoline engine speed on the exhaust emission and BSFC of lean burn gasoline engine have to do with the ratio and absolute time of t_{lean}/t_{rich} . When t_{lean}/t_{rich} keep steady, if the absolute time of t_{lean}/t_{rich} stay the same, with the speed of engine increase, the concentration of CO and HC will decrease and that of NOx increase a little. But with the absolute time of t_{lean}/t_{rich} decrease, the concentration of CO and HC will increase and that of NOx decrease a little. When t_{lean}/t_{rich} keep steady, if the absolute time of t_{lean}/t_{rich} stay the same, with the speed of engine increase (from 1500 rpm to 2500 rpm), the conversion rate of NOx C_{NOx} in adsorber-reduction catalyst system decreased little, although it's not notable. And the BSFC of lean burn gasoline engine turn better what means that the speed increased and the BSFC of lean burn gasoline engine decreased. If the absolute time of t_{lean}/t_{rich} decreased, both the

conversion rate of NOx C_{NOx} and the BSFC in adsorber-reduction catalyst system would be larger.

3.3 The Effect of Different Loads on Exhaust Emission Characteristics and BSFC

Figure 7, Figure 8, and Figure 9 shows the effect of exhaust emission CO, HC, NOx, the conversion rate of NOx C_{NOx} and the BSFC at the speed of 1800 rpm in scheme 3 on different loads ($p_e=0.2$ MPa, 0.3 MPa, and 0.4 MPa). the A/F ratio of lean burn is 21, the A/F of reduction process is 12, $t_{lean}/t_{rich} = 10$.

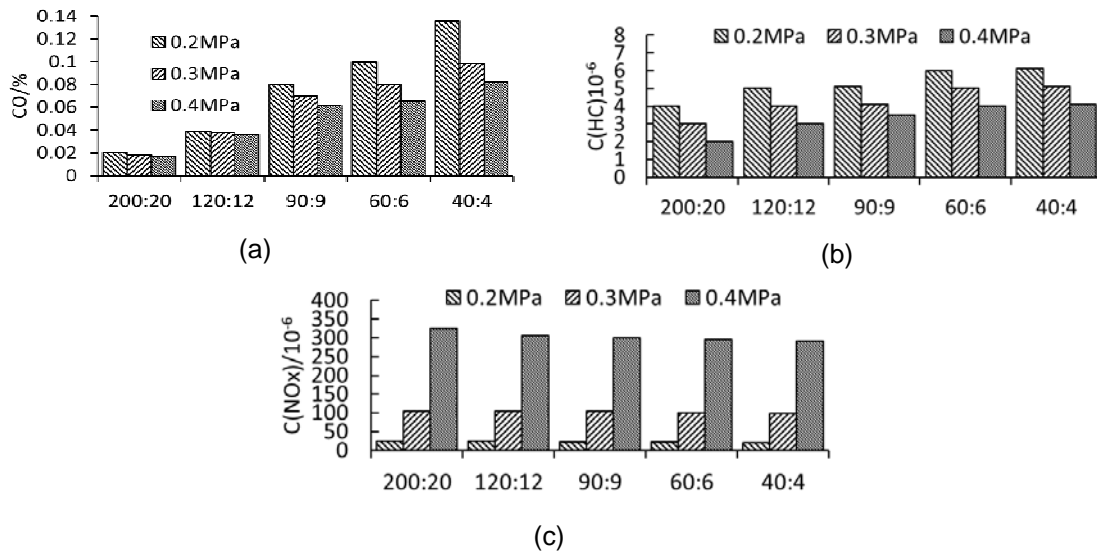


Figure 7. Effects of different loads on exhaust emission ($n= 1800$ rpm)
 (a) Effects of different loads on CO emission, (b) Effects of different loads on HC emission
 (c) Effects of different loads on NOx emission

As shown in Figure 7, when t_{lean}/t_{rich} keep steady, if the absolute time of t_{lean}/t_{rich} stay the same, with the load of engine increase (0.2 MPa, 0.3 MPa, and 0.4 MPa), the CO and HC will decrease and that of NOx increase. But with the absolute time of t_{lean}/t_{rich} decrease, the CO and HC will increase and that of NOx decrease a little. This is mainly because that the increase of engine load heighten the temperature inside the cylinder of the lean burn gasoline engine what enhance the fuel oxygenation competently, and the increase of cylinder inner wall temperature decreased the thickness of the layer attached to the wall of cylinder, so the amount of HC adsorbed by the layer attached to the wall of cylinder decreased. At the same time, the increase of load, decrease the unfired of fuel mixture in the cylinder. As a result, the CO and HC will reduce when the load increase, meanwhile, the increase of load and temperature inside the cylinder were favorable to the formation of NOx, so as to NOx increase; if the load keep steady, when the absolute time of t_{lean}/t_{rich} decrease, the CO and HC will increase and that of NOx decrease. This is because the decrease of the absolute time of t_{lean}/t_{rich} shorten the length of lean burn time that the lean burn catalyst system undergo (maybe the catalyst system hasn't adsorb to saturation), after that the restore and regeneration process in rich burn atmosphere started, the time of the engine operated in the transition condition during the same time-lag increased, which made the concentration of CO and HC a little bigger, but the NOx concentration became smaller, it's because that under favor of the decrease of the absolute time of t_{lean}/t_{rich} , the NOx which created in the process of lean burn (which has absorbed in the catalyst by the alkaline earth in the lean burn NOx adsorb and restore catalyst system and stored in the form of nitrate) converted to N_2 absolutely in the restore atmosphere, and in the alkaline earth of the lean burn NOx adsorb and restore catalyst system had no NOx left. All of these increased the adsorb capability of lean burn catalyst for NOx in the lean burn condition, that means the conversion rate of NOx C_{NOx} in adsorber-reduction catalyst increased.

As shown as Figure 8, the conversion rate of NOx C_{NOx} in adsorber-reduction catalyst system have relation with not only the absolute time of t_{lean}/t_{rich} but also the load of the engine in the adsorber-reduction catalyst system. The bigger the load, the higher the NOx emission, and the lower the conversion rate of NOx C_{NOx} . when t_{lean}/t_{rich} keep steady, if the absolute time of t_{lean}/t_{rich} stay the same, with the load of engine increase ($n=1800$ rpm, p_e is 0.2 MPa, 0.3 MPa, and 0.4 MPa respectively), the conversion rate of NOx C_{NOx} decrease. When load is 0.2 MPa, the C_{NOx} is 94%; when load is 0.3 MPa, the C_{NOx} is 85%; when load is 0.4 MPa, the C_{NOx} is only 49% (when $t_{lean}/t_{rich} = 200:20$). Compared with the increase of the C_{NOx} caused by the decrease of the adsorber-reduction catalyst system's absolute time of t_{lean}/t_{rich} , the load of lean burn gasoline engine have much more influence on the C_{NOx} . The bigger the load, the smaller the C_{NOx} . Fortunately, lean burn condition mainly work in the operating condition with middle and low speed and part load.

As shown in Figure 9, the load of engine has more influence on the BSFC. The bigger the load, the better. This is because with the load of engine increase, the combustion temperature in the cylinder rise, on the one hand, the accretion of load improve the fuel pulverization what improve the combustion condition; on the other hand, the accretion of load decrease the engine relatively cooling lose and pumping lose, the thermal efficiency of engine rise. Besides, the accretion of load improves the mechanical efficiency of engine. The accretion of load improved the thermal efficiency and the mechanical efficiency, that made the BSFC better.

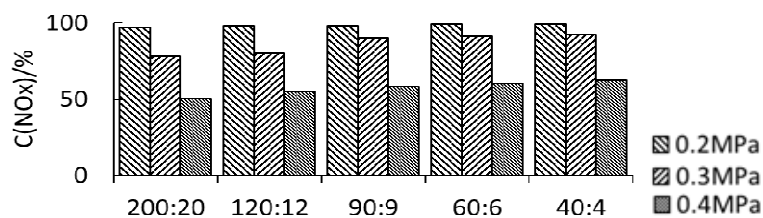


Figure 8. Effects of different loads on NOx conversion efficiency C_{NOx} ($n=1800$ rpm)

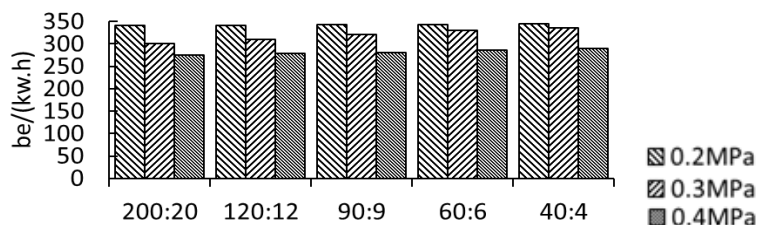


Figure 9. Effects of different loads on BSFC ($n=1800$ rpm)

When t_{lean}/t_{rich} keep steady, if the load stay the same, with the absolute time of t_{lean}/t_{rich} decrease, BSFC rise a little, what due to that the decrease of the absolute time of t_{lean}/t_{rich} largen the total time of engine works in transitional operating condition in the same time-lag.

4. Conclusion

Applying the new catalyst system composed of traditional three way catalyst converter and adsorber-reduction catalyst converter which is designed by author studied the effect of different schemes of catalyst converter arrangement and different speeds and loads on the exhaust emission characteristics and BSFC of a lean burn gasoline engine, we got the main conclusions below:

1. Under the condition of these experiments, catalyst converter arrangement scheme 3 which is designed by author can achieve the lowest NOx emission of $50 \cdot 10^{-6}$ and the conversion rate of is the highest to 97.3%. Therefore, when we use lean burn adsorber catalyst combined

- with three ways catalyst to reduce NOx emission in lean burn S.I. engine, the scheme that the lean burn NOx adsorber-reduction catalyst is arranged after the TWC should be adopt.
2. When t_{lean}/t_{rich} keep steady, if the absolute time of t_{lean}/t_{rich} stay the same, as the speed of gasoline engine increased, in the emission of lean burn gasoline engine, the CO, HC reduce and NOx increase slightly, the BSFC be improved. But the change of the conversion rate of NOx is not notable. With the absolute time of t_{lean}/t_{rich} decreased, the concentration of NOx emission decreased a little, and the conversion rate of NOx C_{NOx} largen, so is the BSFC .
 3. When t_{lean}/t_{rich} keep steady, if the absolute time of t_{lean}/t_{rich} stay the same, with the load of engine increases, the CO and HC will decrease and that of NOx increase. But with the absolute time of t_{lean}/t_{rich} decrease, the CO and HC will increase and that of NOx decrease a little, the conversion rate of NOx C_{NOx} increased and the BSFC be go to bad.
 4. The C_{NOx} have relation with not only the absolute time of t_{lean}/t_{rich} but also the magnitude of the engine load. The bigger the load, the higher NOx emission, and the lower the conversion rate of NOx C_{NOx} , but the BSFC be improved in lean burn NOx adsorber-reduction catalyst system.

Acknowledgements

This study was supported by the Nation Nature Science Foundation of China (50276042, 50776062, 51276128), the National High Technology Research and Development Program of China (863 Program) (2008AA06Z322), and the Tianjin Research Program of Application Foundation and Advanced Technology (11JCZDJC23200).

References

- [1] Hiromistu Ando, Kazunari Kuwahara. *A Keynote on Future Combustion Engines*. SAE Paper. 2001-01-0248.
- [2] Wu Z W. Analysis Vehicle TWC Light-off Characteristics on AMESim Platform. *TELKOMNIKA Indonesian Journal of Electrical Engineering*. 2012; 11(2): 367-372.
- [3] J Stokes, TH Lake, MJ Christle. *Improving the NOx/fuel economy tradeoff for gasoline engine with CCVS combustion system*. SAE paper. 1994; 940482.
- [4] JE Parks, Vitaly Prikhodko, William Partridge, Jae-Soon Choi, Kevin Norman, Shean Huff, Paul Chambon. Lean Gasoline Engine Reductant Chemistry During Lean NOx Trap Regeneration. SAE Paper. 2010-01-2267.
- [5] Chen Tao, Xie Hui, Li Le, Yu Wei-fei, Zhang Song, Zhao Hua. Combustion Mode Transition between HCCI and SI in Load Transition. *Journal of Tianjin University*. 2012; 45(4): 367-372.
- [6] Grant Lumsden, David Eddleston, Richard Skyes. *Comparing Lean Burn and EGR*. SAE paper. 1997; 970505.
- [7] Ma Z, Wang X. Influence of Fuel Injection on Gasoline Engine Performance. *TELKOMNIKA Telecommunication Computing Electronics and Control*. 2012; 11(4): 367-372.
- [8] He Bangquan, Du Yinwei. Simulation of the Characteristics of Exhaust Gas Flow in the Exhaust System of a Compressed Natural Gas Engine Ignited Each Cylinder at the First Cycle During Start. *Journal of Tianjin University (Science and Technology)*. 2013; 46(1): 87-94.
- [9] Gregory D, Marshall RA, Eves B, Dearth M, Hepburn JS, Brogan MS, Swallow D. *Evolution of lean NOx-traps on PFI and DISI lean burn vehicles*. SAE Paper. 1999-01-3498.
- [10] W Strehlau, J Leyrer, ES Lox. Lean NOx catalysis to gasoline fueled European cars. *Automotive Engineering*. 1997; 105(2): 133-135.
- [11] Liu Lei, Li Zhijun, Yue Dongpeng, Zhang Hongyang, Chang Qing, Ma Xiaoqiang, Lin Manqun. Simulink-based Simulations of LNT System of Lean Burn Gasoline Engine. *Journal of Tianjin University (Science and Technology)*. 2013; 46(12): 67-72.
- [12] Li Zhijun, Zhang Guangyu, Liu Shuliang. An Electronic Control System Development of Reducing NOx Emission in a Quasi_Homogeneous Lean Burn Gasoline Engine. *Journal of Combustion Science And Technology*. 2004; 10(5): 400-404.
- [13] Gieshoff J, Pfeifer M. *Advanced Urea SCR Catalysts for Automotive Applications*. SAE Paper. 2001-01-0514.
- [14] Matsumoto S. DeNOx catalyst for automotive lean-burn engine[J]. *Catalysis today*. 1996; 29(1): 43-45.
- [15] Gawade P, Alexander A M C, Silver R. Effect of Engine Exhaust Parameters on the Hydrothermal Stability of Hydrocarbon-Selective Catalytic Reduction (SCR) Catalysts for Lean-Burn Systems. *Energy & Fuels*. 2012; 26(12): 7084-7091.