INVESTIGATION INTO LEAN BURN ABILITY OF FOUR-STROKE SPARK- IGNITION ENGINES FOR SEMI-DIRECT INJECTION SYSTEM USING AIR - ASSISTED INJECTORS

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Abstract - This paper presents the possible combinations of advantage factors from PFI and GDI system by applying an air-assisted injector on Semi-direct Injection System (SDI). Firstly, an adaptor that uses compressed air to improve the atomization of conventional injector and reduce droplet size is made. Secondly, the modifications of intake port by using vortex plate and the other by closing one intake valve increase swirl ratio of in-cylinder air motions which help to form rich mixture around spark plug and lean mixture at other locations. This combination transforms traditional PFI system into SDI one. The engine then is tested on test bench at 3000 rpm engine speed and 2 Nm torque. Experiment results indicate that lean limit increases from air-fuel ratio (AFR) 17.1 to 23.7 while brake specific fuel consumption and coefficient of variation are reduced significantly.

Key words - Air-assisted fuel injector; Semi-direct Injection System; Swirl; Lean Burn; GDI.

1. Introduction

In recent years, the human has faced the pollutant emissions from general vehicle engines that became a serious environmental problem in the world. Therefore, more stringent criteria as well as regulations in exhaust emission and fuel consumption have been launched gradually by governments from other countries. Consequently, there have been many investigations over the last decade to practically apply new energy such as electric vehicles and fuel cell and these have provided the zero pollutant emissions. However, these are not only many disadvantages as limited battery, endurance, duration of charging, engine torque, horsepower etc. but also many other ones which have not yet investigated into measures of the shortcoming. Thus, the improvements of present technologies in internal combustion engines are urgent matters. In recent years, studies related to internal combustion engine have been being vigorously investigated in spacious areas such as engine combustion system, exhaust emission treatment and especially fuel injection development to achieve the targeted values.

Many researches have been taken to improve fuel injection characteristics by examining available problems and developing new systems. For example, Brehm et al [1] broadened the understanding of air and fuel characteristics in intake port of MPI spark-ignition engines by both laser-Doppler anemometer method and experiment on test bench. They found that fuel droplet during intake valve closing which forms film coalesced to valve body were unaffected by pressure wave in the port. The improvement of GDI has solved disadvantages of traditional MPI system. Fry et al [2] showed that positioning the fuel injector is the key consideration for GDI engines which improved engine performance at full-loaded operation compared to MPI system. Moreover the study also proved that Air Assist low pressure GDI (AAGDI) was more flexible in its operation at part load, tolerating greater ranges of injection timing, air fuel ratio (AFR) and exhaust-gas recirculation (EGR), whilst maintaining stable combustion. The weak point of such systems is their structural complexity and high production costs. Nevertheless, it is still possible to built very simple systems on some components of stratified charge combustion system.

A lean-burn system with catalytic pre-chamber that made possible unfailing ignition and flame development of the lean charge included in main combustion chamber was presented by Jarosinski et al [3]. Its improvement was attested by extending the operation range up to λ=1.65 while reducing 50% unburned hydrocarbon at part load. The other method - SDI system which is previously developed on 2-stroke SI engine [4], [5] indicated that SDI could decrease engine emissions while maintaining its performance and improve idle operating condition by stabilizing the combustion, minimizing cyclic variation. SDI, on the other hand, the same as MPI, has some advantages due to the location of fuel injection which is outside of combustion chamber. It will reduce carbon deposition on the injectors and require smaller injection pressure because of the unnecessity of overcoming in-cylinder high pressure as one in GDI. In addition, the idea of air-assisted injection system applied on conventional MPI SI engines [6], [7] has shown a potential application with little modification and low-cost while having positive effect on fuel atomization, combustion stability and exhaust emission in a gasoline engine.

Therefore, a concept of SDI system which combined air-assisted injection on 4-stroke added-swirl generator in SI engine was worth examining. In this paper, the first section presents experiment apparatus and procedures including the observation of the fuel spray pattern and the effect of fuel atomization, swirl motion development and engine experiment set up. Experiment results and discussion will be demonstrated in the following section. The last section will be conclusions and future works of this study.

2. Atomization method

In this research, improving spray nozzle's atomization effect achieved the layered combustion in SDI. There are three kind of mechanics disruption of droplet fuel as wall surface collision, spray nozzle's characteristic and the passage collision air. So fuel atomization is decided by some elements such as spray nozzle's characteristic, pressure of injection, stricken with wall surface of intake port and compression air of blowing out. The atomization behavior is created by the passage collision air intakes in wall's surface. The passage disruption condition is (1)

$$D = \frac{8\sigma}{C_d \rho_g u_d^2} \quad (1)$$

Where: C_d is constant factor; u_d is gas and fluid velocity; ρ_g is density of gas; σ is passage surface tension and D is passage diameter; so the passage diameter has to be smaller. The cone angle of injector and penetration distance of injection will increase fuel atomization and droplet size distribution. In this investigation, the assistant air is fed into the chamber flows through the grooves to be ejected around injector nozzle tip. The outlet of air is tapered so that assisted air will be mixed with fuel being sprayed by collision.

To improve the fuel atomization of SDI engine's injector spray, an air-assisted injection adapter was designed and manufactured as shown in Figure1. This type of adapter can be made easily so that it can be used widely as conventional injectors and reasonably for the low-cost mass production.

3. Fuel atomization using Air-Assisted injection

Adapter Design - The original MPI system then has been modified to become air-assisted injection. In order to understand the effect of passage length and diameter on the fuel atomization of injection spray, firstly, various types of special adapter which merged compressed-air and fuel flows were designed and manufactured following the concept shown in Figure 1. The adapter was made by aluminum and fortified tightly with injector by adequate tolerance. The hole on the perpendicular side of the adapter is to supply compressed air from a surge tank via plastic tube where an air nipple is fastened with tapping. Merging angle between fuel flow and compressed-air flow is fixed at 90˚. The design principles are divided into two ways: keeping the passage length (L) constantly while increasing its diameter (D) and conversely keeping D while increasing L.

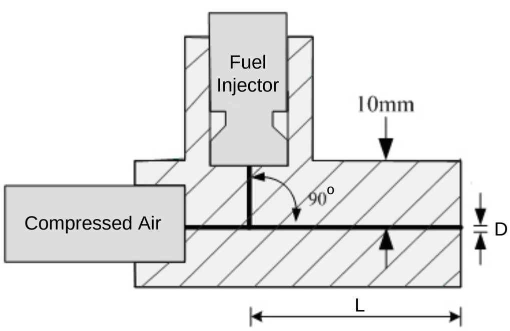

Figure 1. *Adapter of Air-assisted Injection System*

Detail dimensions of adapter are presented in Table 1.

Table 1. *Dimensions of Adapters*

Type	L (mm)	D(mm)
1	10	1.5
2	10	2.0
3	10	2.5
4	15	2.0
5	20	2.0

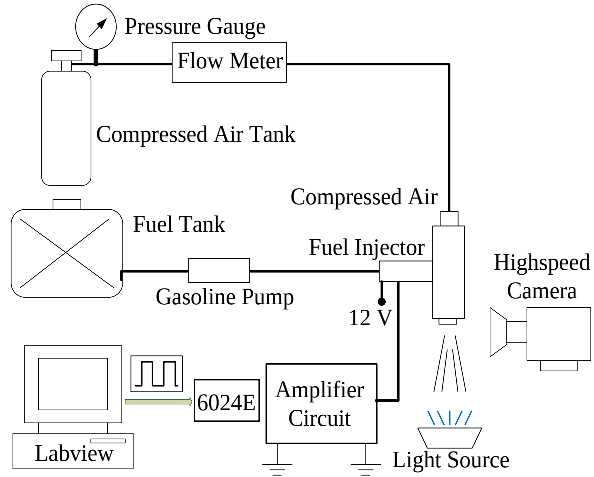

Figure 2. *Fuel Atomization Analyzing System*

Fuel Atomization Analyzing System - To observe the spray behavior and atomization of air-assisted fuel injection, a system has been set up by using Fastec Imaging's Troubleshooter HR high-speed camera as shown in Figure 2. Injection duration and frequency are controlled by a computer using Labview software. A 6024E interface card made by NI Corporation was used to connect computer and amplifier circuit. To control the injection, square-wave signals created by Labview were sent to circuit to amplify square-waves which control injector power source to make injection happen. Fuel was injected by the frequency of 100 Hz duty cycle 50% of the 12V square-wave-driven injector. Compressed air was controlled by an electric valve following the signal from injector. Due to the high speed of injection, an adjustable high- luminance halogen lamp which was placed at the opposite side of fuel spray direction was used as the light source for the clear and adequate brightness of images. The comparison of nozzle atomization with difference auxiliary air and flowing pressure is shown in the photo 1.

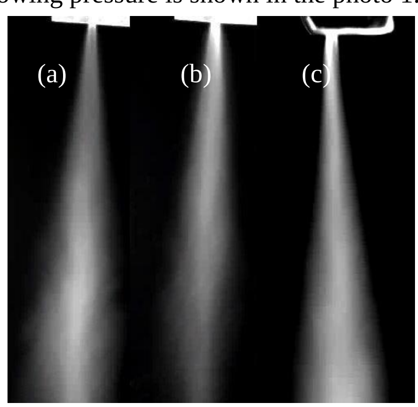

Photo 1. *nozzle atomizing effect compares (a) auxiliary air 20 L/min, flowing tubing head pressure 2.5 kg/cm2 (b) auxiliary air 10 L/min, flowing tubing head pressure 2.5 kg/cm2 (c) auxiliary air 20 L/min, flowing tubing head pressure 1.0 kg/cm2*

4. Experiment apparatus and procedures

STRATIFIED CHARGE GERERATION

Test engine – SDI system was developed using single cylinder engine to exclude the influence of cycle-per-cycle variation. Original specification of 125cc commercial engine is listed in Table 2.

Table 2. *Engine Specification*

Engine Type	124.6cc, Air Cooled
Valve System	4 Valves - SOHC
Bore x Stroke	52.4mm ×57.8mm
Compression Ratio	10.5：1
Compression Pressure	12±2 kg/cm²
Max Power	10.1ps/8500rpm
Max Torque	0.93kg-m/7000rpm
Ignition System	Direct-current crystal

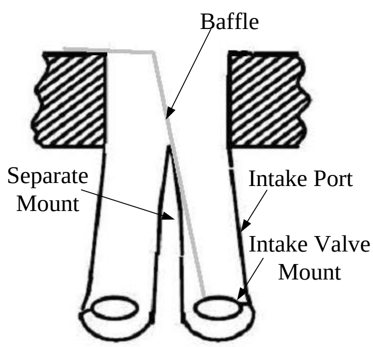

Figure 3. *Swirl Generation Baffle*

To achieve lean combustion, only using nozzle atomization is not good enough even though good in-cylinder atomization and identical mixture is created. For further extension of the lean limit, stratified charge created by swirl motion was preferred to form rich mixture around the spark plug. In this study, two possible concepts shown in Figure 3 and photo 2 are preferred based on the swirl generation theory. The first one which uses special baffle is placed in front of separate mount will guide the intake-air flowing twistingly into cylinder. And the second one is closing one intake valve by cutting one rocker arm. Those design characteristics then were investigated using steady flow bench.

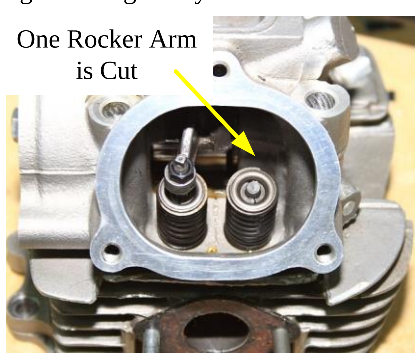

Photo 2. *Cylinder head with one Intake Valve permanently closed*

The experiment layout – Equipment used in this study is shown in Figure 4. The AVL Indi Com 619 high-speed combustion-analyzer which can capture four different channels of signals is being used. Its maximum sampling rate is 1MHz. In-cylinder pressure signal following crank angle is tracked by using piezoelectric pressure transducer and encoder. To control ignition timing, injection timing and duration, a programmable ECU is used.

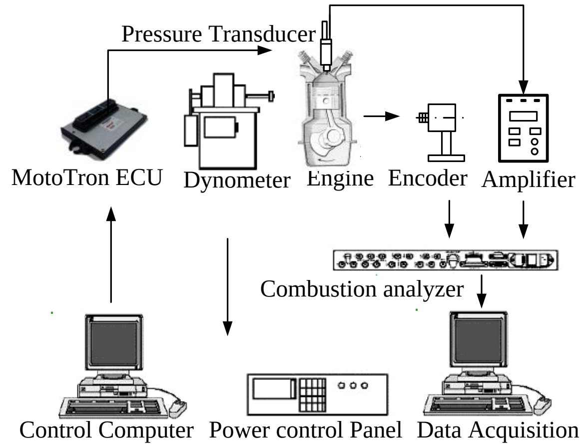

Figure 4. *Cylinder head with one Intake Valve permanently closed*

5. Result and discussion

EFFECTS OF INJECTION TIMING ON LEAN BURN LIMIT- The experiment condition of engine was kept constantly at 3000 rpm, 2 Nm, injection pressure at 2.5kg/cm2 with different swirl, nozzle atomizing effect and injection timing, each situation obtains best injection angle as shown in Table 3.

At partial load conditions, with original PFI, the injection timing could not seem to effect on lean burn limit. But after improving swirl of intake air, the lean burn limit would increase because when intake valve opened, only pure air was charged toward in the cylinder firstly, and then the fuel was inhaled in upper region of cylinder lately with swirl.

Table 3. *Best Injection timing*

Test condition	Best Injection timing (ATDC °)
Original PFI	200
Rs = 2.032 / Air 10 L/min	40
Rs = 2.032 / Air 20 L/min	40
Rs = 3.5 / Air 10 L/min	40
Rs = 3.5 / Air 20 L/min	60

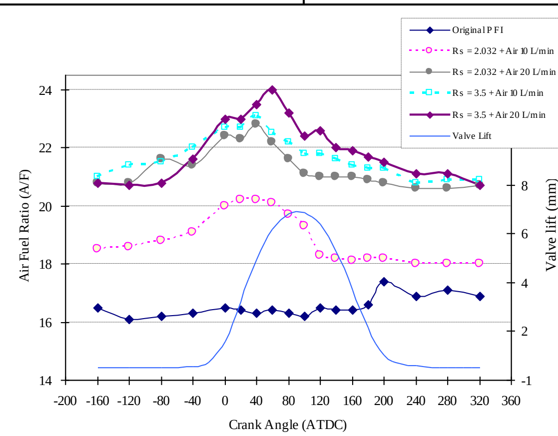

Figure 5. *Effect of injection timing on lean burn limit*

The Figure 5 indicates that air fuel ration was increased maximum at swirl motion 3.5 because within high swirl port, most of fuel remains at combustion chamber and upper cylinder region without being affected by injection timing. Actually, at the beginning of the induction, the fuel appears at the center of cylinder and reaches the opposite wall. Afterwards, the fuel moves along the center axis of cylinder due to piston going down. In spite of early injection, small part of fuel reaches the bottom of cylinder, most fuel remains at the upper cylinder area.

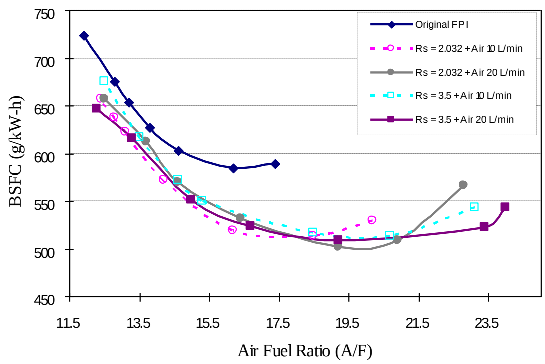

Figure 6. *Effect of lean burn limit on break specific fuel consumption (BSFC)*

Effects of lean burn on engine performance - After the test for optimization of injection timing angle, each optimum angle is used in engine experiment. The test conditions was kept in 3000rpm, 2N.m and fixed advance ignition angle and only changed the air-fuel ratio to appreciate the effect of lean burn limit on the engine performance. Figure 6 illustrates the relations of lean burn limit and the break specific fuel consumption (BSFC).It can be clearly seen that the strengthening of swirl flow and the atomization effect may cause the combustion of mixture completely. Therefore, the whole BSFC is lower than the original PFI. However, along with increased air-fuel ratio, combustion stability increased. For example, the air-fuel ratio is higher than 19, SDI BSFC will start to rise.

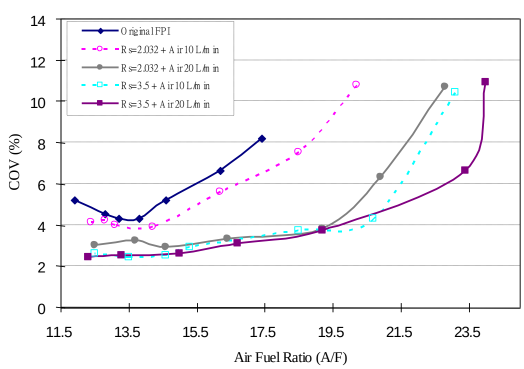

Figure 7. *Effect of lean burn limit on coefficient of variation (COV)*

In Figure 7, the effect of lean burn limit on coefficient of variation (COV) is shown. When air-fuel ratio increases, COV slightly rises. However, the improvement of the swirl flow in the cylinder had the obvious effect regarding the enhancement combustion stability. The curve fitting of original PFI engine without swirl can only achieve lean burn limits at AFR 17.28. If the swirl flow increases to the Rs = 2.032 with air-assisted current capacity at 20L/min, the lean burn limit can increase to AFR 21.82. When the swirl flow was increased up to Rs = 3.5 with air-assisted current capacity at 10L/min and 20L/min, the lean burn limits achieved higher AFR 22.54 and 23.7 respectively.

Effects of lean burn on exhaust emission - Engine exhausted emissions of carbon monoxide (CO), hydrocarbons (HC) and oxides of nitrogen (NOx) were measured by Horriba MEXA-584L exhaust analyzer.

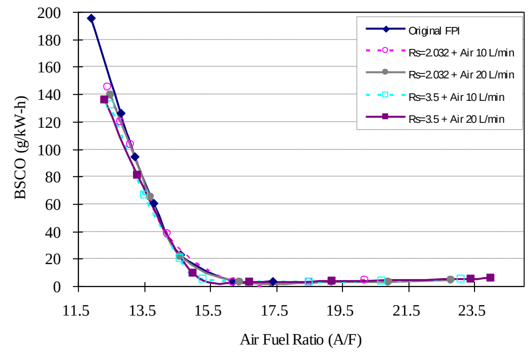

Figure 8. *Effect of lean burn limit on breaks specific CO emission (BSCO)*

CO emission quantity depended greatly on the air-fuel ratio, because this is the product of hydrocarbon reactions in the combustion process. Firstly, the carbon was associated with surplus oxygen to produce CO emission. Then CO emission will react with the surplus oxygen to produce CO_2. Therefore, when the air-fuel ratio is smaller than the stoichiometric AFR, it will create much more CO emission during combustion. But when the air-fuel ratio is bigger than the stoichiometric AFR, reactions between surplus oxygen and the CO emission will create more CO2 emission. Therefore CO emission will reduce as seen in Figure 8. The experiment investigated that with swirl Rs=3.5, CO emission concentration achieved lower than original PFI at the rich mixture.

BSHC (brake specific hydrocarbon) is shown in Figure 9.The data of BSHC at air fuel ratio less than 23.5 were eliminated in Figure 9 because its value is too high to be plotted in this figure. The minimum BSHC occurred at AFR from 14 to 15. After the AFR greater than 19, the BSHC of ports (a) and (c) increase rapidly.

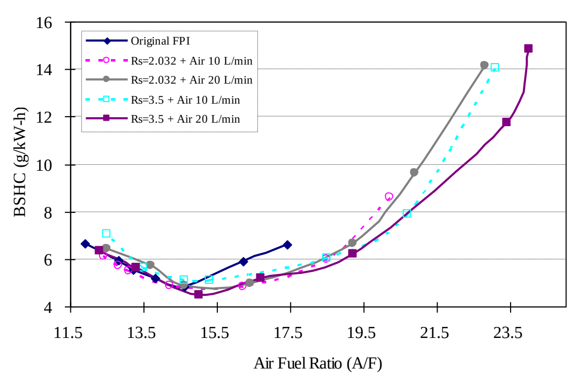

Figure 9. *Effect of lean burn limit on breaks specific HCemission (BSHC)*

The Figure 9 also indicates effect of lean burn limit on breaks specific HC emission (BSHC). When the air-fuel ratio (AFR) is smaller than stoichiometric AFR value, HC emission will decrease slightly. Because oxygen and the carbon did not response, HC emission quantity along with the AFR is trendy to increase. But after the AFR is bigger than the stoichiometric value, its primary factors of creation are the combustion's stability and the combustion efficiency. Strengthening the swirl flow and the atomization effect may cause the combustion completely. By this figure, it is obvious that when the strength of vortex is the same, the promotion atomization effect will improve HC the emissions. When the atomization effect is the same, the promotion strength of vortex also has the same effect. After the air-fuel ratio is higher than 19, burns the unstable rise as well as the rapidity of combustion slow down, complete combustion being discharged together with the exhausted HC will also increase along with it.

NOx (nitrous oxides) emissions are dominated by the maximum temperature and the concentrations of oxygen and nitrogen. The swirl ratio 3.5 has high level of charge motion, high heat release rate, and maximum pressure. The maximum temperature of swirl ratio 3.5 must be higher than that of the others. Thus, the BSNOx of swirl ratio 3.5 is the highest in Figure 10. Moreover, when putting in its high temperature in the environment and giving the full reaction time, the nitrogen then responding with the oxygen produces NOx. Therefore, the higher combustion temperature is, the more quantity of NOx is produced. The promotional atomization effect may complete the mixture of the combustion. Combustion temperature rises along with its rise, and also the NOx withdrawal increases.

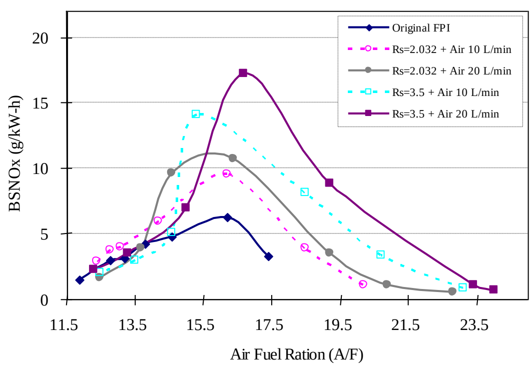

Figure 10. *Effect of lean burn limit on breaks specific NOx emission (BSNOx)*

However along with the air-fuel ratio rise, the excessive dilution AFR will reduce the flame speed. Moreover, its participation will also reduce the combustion temperature. Therefore, at the AFR bigger than 17, NOx withdrawal will have large reduction.

6. Conclusion

Swirl flow in the cylinder is important for improving the engine combustion. The summation of swirl ratio is good, that means in-cylinder charge motion and the level of charge motion are related to the engine combustion directly. This research focuses on effect of atomization by gantry test on the influence of air auxiliary spray nozzle factor in SDI system. Swirl ratio of in-cylinder air motions was increased, which helped to form rich mixture around spark plug and lean mixture at other locations. And the reduction of droplet size made by an adaptor which used compressed air has improved the atomization of conventional injector.

The design of passage diameter of the injector changing interior flow channel for SDI engine should reduce as far as possible and increase the flow velocity if the passage is long enough, then it should reduce the pipe wall total area. That may reduce the pipe wall interior wall wet (Wall Wetting) phenomenon, promote the nozzle atomizing effect. When interior caliber of injector is 1.5mm and passage length is 15mm with air current capacity of 20 L/min. It can obtain the good atomization to spray ties.

In the experiment, it is illustrated that if the auxiliary air current capacity is bigger, the atomization effect will be also better, but excessively too much air will have the possibility to have the influence on the engine. This research uses 20th L/min air auxiliary spray nozzle at idle speed operation. If the air input is 50 L/min, it will possibly cause the engine idling system to be excessively high. Therefore, current capacity of the auxiliary air must consider that it is better by the air-assisted influence.

The proper design of adapter of air-assisted injection system in the SDI engine has achieved high level of charge motion at light load operation. By testing at engine speed of 3000rpm, 2N.m torque, the improvement of swirl ratio in the cylinder and spray nozzle's atomization effect may promote engine's lean burn limits. When the intake swirl increased to 3.5 and used 20 L/min compressed air with improvement of nozzle atomization, the lean burn limits was increased from original engine AFR of 17.28 to 23.7, and largely reduced BSFC and COV.

The future works are to develop the SDI system with controlling the assisted air by solenoid valve and reducing to the layered air intake influence to achieve lean burn limitat 30 AFR or above.

Acknowledgments

This work was supported by grants from the National Science Council of Taiwan, R.O.C. under the contract No. NSC-96-2221-E-027-037-MY3.

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(The Board of Editors received the paper on 09/06/2017, its review was completed on 26/06/2017)