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Pollutant Emission Reduction and Engine Performance Improvement by Using a Semi-Direct Injection Spark Ignition Engine Fuelled by LPG

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ABSTRACT

Reducing motorcycle exhaust emissions to improve air quality is important in Asia, due to the large number of motorcycles. This study describes and proposes a lean-burn system for reducing pollutant emissions and improving motorcycle engine performance. The lean-burn system, called semi-direct injection (SDI), is comprised of high-swirl charge, injection during intake-valve opening, and liquefied petroleum gas (LPG) injection. A conventional motorcycle engine with port fuel injection (PFI) and spark ignition (SI) was retrofitted by designing a new intake port with a controllable plate to enhance the swirl of intake flow. The swirl ratio was increased to 3.4, enhancing the turbulence of air flow inside the combustion chamber, and the lean limit was extended to 1.7 of relative air/fuel ratio (lambda). The engine was tested at a low-load region which includes most operating points of the ECE-40 driving cycle. A complete engine performance map was produced and a comparison was undertaken between the new design and regular gasoline engines. The results show that brake-specific energy consumption (BSEC) decreased by 19.2%. Brake-specific exhaust emissions of CO_2, NO_x and CO were decreased by 27%, 47% and 94%, respectively. HC emissions were increased by 4.5%.

Keywords: Motorcycle; SI engine; Lean burn; LPG.

INTRODUCTION

Traffic exhaust emissions are significant sources of air pollution in the world and may threaten human health and cause global warming effect. Therefore, governments are compelled to minimize motor-vehicle pollution problems with more stringent emission standards for reducing pollution-related chemicals and improving air quality. In most Asian countries, motorcycles contribute to air pollution more than other vehicles (Chuang *et al.*, 2010). Previous research shows that three-way catalytic converter used in spark ignition (SI) engines could reduce most exhaust pollution, such as HC, CO and NO_x, towards achieving exhaust standards (Lou *et al.*, 2003; Kim *et al.*, 2011). However, converters are expensive to apply in motorcycles and would not reduce carbon dioxide (CO_2), a major cause of global warming effect. It may be more acceptable, especially cost wise, to address the problem in the design and manufacture of motorcycles.

Exhaust pollution from a motorcycle gasoline engine contains nitrogen oxides (NO_x), carbon monoxide (CO) and unburned hydrocarbon emissions (HC). HC emissions are the results of incomplete combustion and could be used to evaluate the combustion inefficiency (Huang *et al.*, 2003). NO_x emissions are affected by the air/fuel ratio, the burned gas fraction of the in-cylinder unburned mixture, and spark timing. Increasing the burned-gas fraction and decreasing spark timing could reduce NO_x emission levels (Hu *et al.*, 2009). These solutions, however, would reduce combustion rate and engine torque. Controlling the air/fuel ratio could have a greater effect on NO_x emission (Khan *et al.*, 2006) and could reduce NO_x levels up to 98% at an air/fuel ratio of 23.5. However, it is difficult to achieve so high an air/fuel ratio in a conventional gasoline engine (Wu *et al.*, 2009). Carbon monoxide (CO) emission of gasoline engine depends heavily on the air/fuel ratio. While a lean combustion decreases the amount of CO in exhaust gas, a spark-ignition engine is often operated closely to stoichiometric mixture, making CO emissions considerably difficult to reduce without an exhaust treatment like a catalytic converter. Nevertheless, a conventional motorcycle gasoline engine could reduce overall exhaust pollution if it could operate with high air/fuel ratio.

In a previous paper, Wu *et al.* (2010) introduced a new design system for gasoline fuel engines, called semi-direct injection (SDI) system for application in motorcycle engines. By increasing swirl ratio to 3.8 and injecting fuel when the intake valve is opened, the SDI system can make a stratified mixture and extend the air/fuel ratio lean limit to 24. CO is

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tremendously decreased by 92.9% and a relatively low combustion temperature in lean burn decreases NO_x by 32%. Furthermore, brake specific fuel consumption (BSFC) decreases to 11% compared with an original gasoline engine at low- and part load. As a result, SDI engine produces lower CO_2, as well. From this result, we can affirm that SDI system in motorcycle engine can help to improve air quality and reduce greenhouse gas.

To become a viable product, the SDI system should reduce CO_2, as well as exhaust pollution. This could be achieved with a method that allows switching between stratified mixture at low load, and a homogeneous mixture at full load. This cannot be done in the current design. The SDI engine could have better results with CO_2 and exhaust emission if there were an increase in the stratification of mixture. Ohm and Cho (2000) compared the lean limit of gasoline engine with different fuel types, the results of which showed that by decreasing Sauter mean diameter (SMD) of fuel drop, which allows enough time for the fuel to evaporate, or using an alternative fuel, which evaporates more completely, the result would be better stratification and increased lean limit. Khan *et al*. (2009) also had the same result.

However, using a high-pressure injector increases the cost of the system. Liquefied petroleum gas (LPG) in gaseous phase could be an alternative fuel for an SDI system. Previous research has observed that the brake mean effective pressure (BMEP) of gasoline is higher than LPG, while LPG fuel consumption and emission, which includes CO, HC and CO_2, are lower than gasoline (Saraf *et al*., 2009; Shanmugam *et al*., 2010). Campbell *et al*. (2004) compared the lean limit of a homogeneous mixture of gasoline and LPG at gaseous phase and the results showed that the lean limit of LPG is better than gasoline. Khan *et al*. (2006) compared the exhaust emission of new European driving cycle (NEDC) between gasoline and LPG of a V6 engine when the air/fuel ratio increases. The results show that the HC, NO_x and CO emission could be reduced by 30%, 98% and 90%, respectively, and achieve EURO 4 without the aid of a reducing catalyst. Also, the reduction of CO_2 achieves 33% at an air/fuel ratio of 17.6, and increases to 40% at an air/fuel ratio of 23.5. It could be concluded that using LPG in gaseous phase for SDI engine should improve air quality without the use of a catalytic converter.

The purpose of this research was to design a new SDI system, which allows control of homogenous and stratified modes, and to investigate experimentally the effects of SDI using LPG on fuel consumption and exhaust emission of a motorcycle engine with various engine speeds at low loads. A complete engine performance map under half-load operation was conducted for comparison between SDI and conventional gasoline engines.

EXPERIMENTAL SETUP

Test Engine

The experiments were carried out with a 125 cc single-cylinder, air-cooled, 4-valve motorcycle engine produced by SANYANG Industry Co., Ltd. Detailed specifications of the test engine are shown in Table 1. The fuel was supplied by an electronic fuel injection (EFI) system.

The experimental setup for engine testing is shown in Fig. 1. For the engine test, a Borghi & Saveri Srl FE150-S eddy-current engine dynamometer was employed to measure the engine output torque and speed. Dynamometer torque was calibrated to range from 0 to 30 Nm with several standard weights for precise torque measurement. Fuel flow rate was measured by using ONO SOKKI FX-1110 mass burette flow detectors. LPG flow was measured by thermal mass flow meter TF-4000 combined with digital indicator. A thermocouple was located on the LPG pipe to measure gas temperature. Exhaust emissions, including CO, HC, NO_x, CO_2, O_2, and air/fuel ratio were measured with a HORIBA MEXA-584L.

The cylinder pressure was measured using a Kistler 6051B uncooled piezoelectric pressure transducer. The crank angle (CA) was detected by a shaft encoder (BEI H25). The output signal of the pressure transducer was amplified using a charge amplifier. This amplified signal was transmitted to a data acquisition system which was an AVL IndiCom 619 combustion analyzer. The cylinder pressure was recorded every 1°CA for 100 cycles.

LPG with a composition of 50% propane and 50% butane was used. LPG pressure was controlled by a LPG pressure regulator. The gasoline fuel used for the comparison with

Table 1. Engine specifications.

Engine Type	Four-stroke, air cooled, four-valve, overhead camshaft (OHC)
Bore × Stroke	52.4 mm × 57.8 mm
Number of Valves	4
Displacement	124.6 cc
Compression Ratio	10.5
Idle Speed	1600 ± 100 rpm
Fuel System	EFI, port injection
Ignition Type	Direct Current Transistor
Intake Valve Open*	10° before top dead center (BTDC)
Intake Valve Close*	20° after bottom dead center (ABDC)
Exhaust Valve Open*	30° before bottom dead center (BBDC)
Exhaust Valve Close*	10° after top dead center (ATDC)

* Valve timing is defined at 1 mm of valve lift.

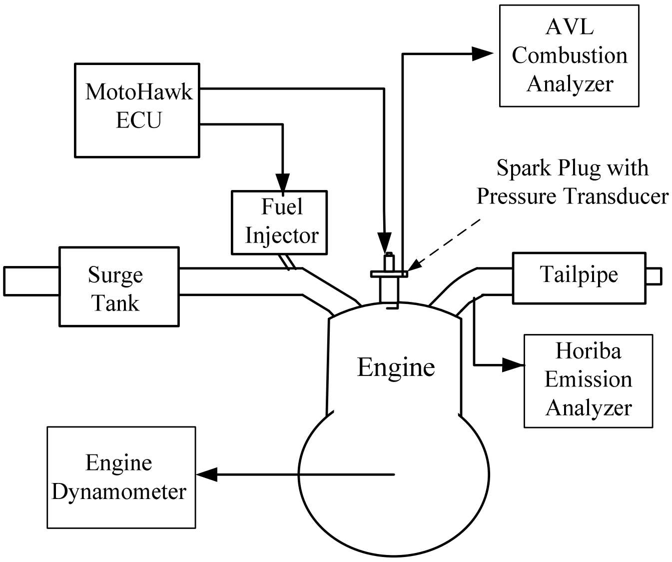

Fig. 1. Schematic diagram of engine test.

LPG in the experiment was RON 95 lead-free commercial gasoline. Table 2 lists the properties of gasoline and LPG fuels.

Engine control was accomplished by using a MotoHawk ECU 555-80 controller produced by Woodward to control the fuel injection rate and injection timing. The MotoHawk allows the user to automatically generate machine code from Simulink diagrams and operate control hardware in real-time operation.

Swirl Generation

Swirl is defined as rotation of the charge around the cylinder axis. Tumble is another charge motion, which refers to a rotational flow perpendicular to the cylinder axis. Both swirl and tumble can be induced by port geometry. They were measured on a steady flow bench SUPERFLOW SF-120. A couple of swirl and tumble adapters were designed based on the dimension of the target engine to simulate the flow from the intake port into the cylinder. Paddle wheels were installed in the adapters to measure the charge motion revolution. The swirl ratio and tumble ratio were calculated according to AVL system because it is the most popularly used (Xu, 2001).

The test engine had two intake ports without any swirl or tumble charge motion. In order to increase the swirl ratio, a controllable plate was designed, as shown in Fig. 2. The control plate location and direction were designed with computational fluid dynamics (CFD), validated on the flow bench and realized on the test engine. The control plate is opened for conventional port fuel injection (PFI), as shown in Fig. 2(a), and the mean of flow coefficient of the new design is 0.498, which approximates the original engine design of 0.501, and which is referred to as homogeneous mode. The control plate in SDI operation is closed at part load, as shown in Fig. 2(b). The swirl ratio reaches 3.4 and the mean of flow coefficient is 0.23, and is referred to as stratified mode. The result of flow coefficient for stratified mode is acceptable, because the stratified mode is applied to part load. Results of flow coefficient comparison are shown in Fig. 3.

Experimental Scheme

In order to investigate the effect of SDI system on engine torque, fuel consumption and exhaust emissions, engine tests conducted were twofold. First, the lean limit was investigated to compare the exhaust pollutions of three systems including original engine using gasoline as well as LPG, and SDI system using LPG. Second, a full engine performance map under half-load operation was conducted to compare the original gasoline engine with the SDI engine. Lean limit tests were conducted under two different conditions: 4,300 rpm at BMEP 1.6 bar and 5,000 rpm at BMEP 2.5 bar, following the road load for motorcycles.

Normal vehicle driving always operates the engine at part-load conditions. Unfortunately, the engine efficiency and exhaust emissions at part load are very poor. Kutlar *et*

Table 2. Properties of gasoline and LPG.

Parameter	Gasoline	Propane	Butane
Density (kg/m^3)	765	509	585
Lower heating value (MJ/kg)	44.04	46.34	45.56
Stoichiometric air/fuel ratio	14.7	15.8	15.6
Combustion rate (m/s)	0.35	0.4	0.4
Flammability limits (Vol. %)	1.3-7.6	2.1-9.5	1.5-8.5
Research octane number	95	111	103

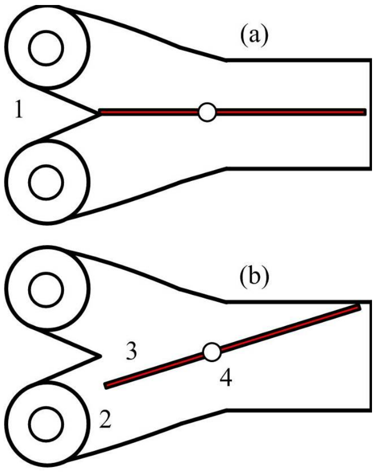

Fig. 2. Schematic of intake port: (a) Homogeneous mode, (b) Stratified mode.
1) Two intake valves; 2) Swirl port; 3) Swirl control plate; 4) Swirl control plate shaft.

al. (2005) reviewed a vast body of literature on the solution for the part-load problem and found that stratified charge was one of the most promising methods to decrease the fuel consumption at part load. Therefore, the engine performance map of SDI focuses on part load.

The motorcycle emission regulations of many countries follow the ECE-40 driving cycle. Fig. 4 shows the engine BMEP curve as a solid line and ECE-40 operating points as triangle markers of the target motorcycle's 125 cc engine. The square line in Fig. 4 is located within an engine speed of 3500 to 5500 rpm, and BMEP from 1 to 4 bar, which consists of most ECE-40 operating points. The engine performance map tests proceeded within this range; i.e., engine speed from 3500 to 5500 rpm with stepwise increments of 500 rpm, and BMEP from 1 to 4 bar with stepwise increments of 0.5 bar.

The gasoline injection pressure was 2.45 bar and LPG was 1.5 bar. The injection timing of PFI was set at 90° BTDC of exhaust stroke, and that of SDI was set at 180° end of intake stroke (Guo *et al*., 2011). The fuel injection duration of PFI was controlled to obtain stoichiometric air/fuel ratio, and that of SDI was controlled to run at lean combustion with a constraint of coefficient of variation (COV) less than 10%, which is the limitation of drivability. The spark advance was controlled at maximum brake torque (MBT).

The data taken from engine testing were: engine speed, torque, brake specific energy consumption (BSEC), brake specific CO_2 emission ($BSCO_2$), brake specific CO emission (BSCO), brake specific HC emission (BSHC), brake specific NO_x emission ($BSNO_x$). Here, the evaluation index of fuel consumption, BSEC (MJ/kW.h) was used because the lower heat value per unit mass was different between gasoline and LPG. Brake specific emissions are defined as the mass emission rates divided by the engine brake horsepower. The mass emission rates were calculated according to SAE J1088 and d'Ambrosio *et al*. (2011).

RESULTS AND DISCUSSION

Effect of Lean Burn on Exhaust Pollution

Fig. 5 shows the effect of relative air/fuel ratio on CO, NO_x and HC at 4300 and 5000 rpm low loads of the original gasoline engine, original LPG engine and SDI engine. Relative air/fuel ratio is the ratio of the actual air/fuel ratio to the stoichiometric ratio. The value of CO concentration increases steadily with decreased relative air/fuel ratio. From 1.3, the CO concentrations in the exhaust vary little with relative air/fuel ratio. Around 1.1, CO emission produced by SDI engine is even lower than original gasoline engine for two kinds of fuel. Lower CO emission may be due to high turbulence intensities in SDI engine combustion, so CO easily interacts with O_2 or OH to become CO_2.

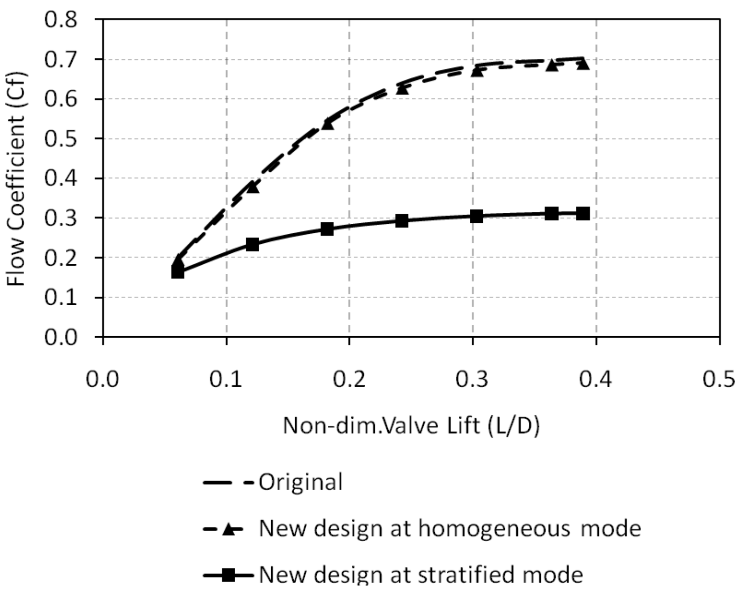

Fig. 3. Comparison of flow coefficient of original and new design intake port.

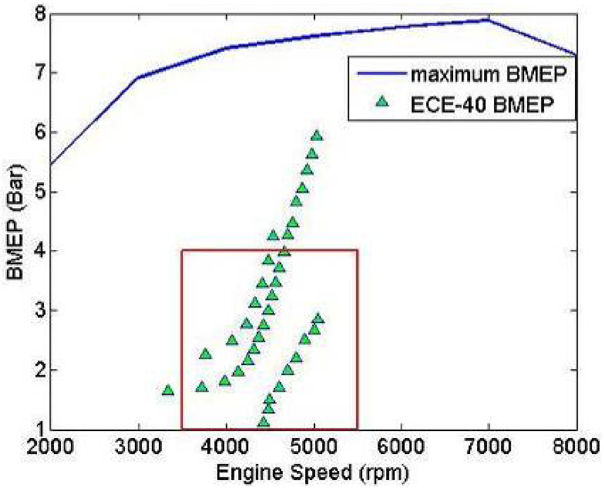

Fig. 4. 125 cc Engine map of ECE-40 cycle.

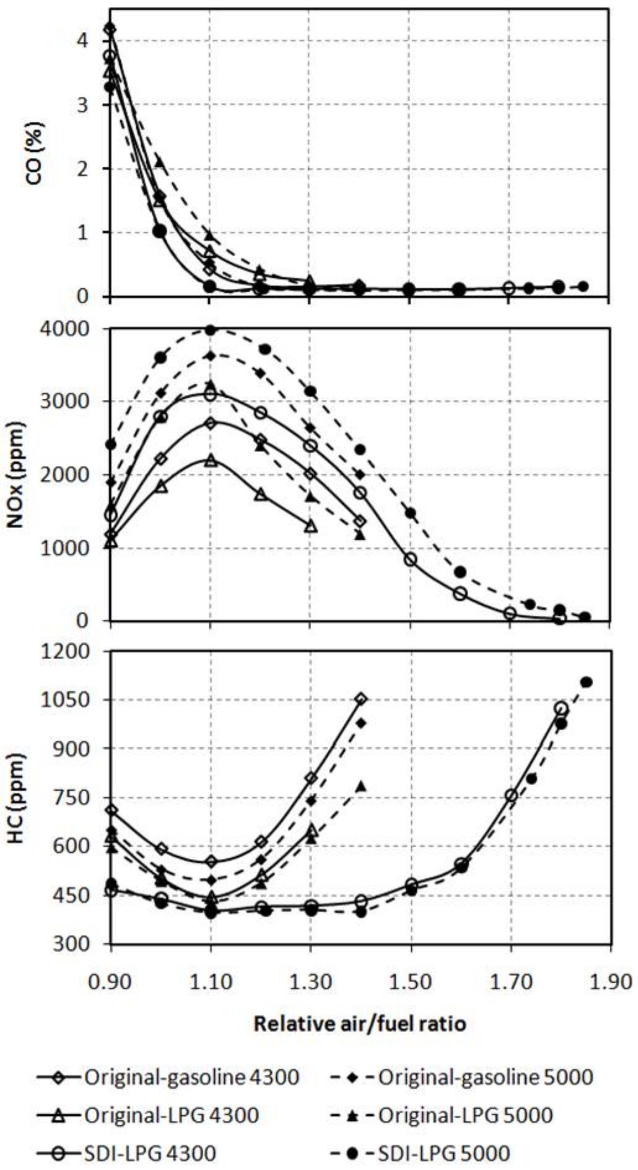

Fig. 5. Effect of relative air/fuel ratio on CO, NO_x and HC at 4300 and 5000 rpm.

The values of NO_x at 1.1 of relative air/fuel ratio show a clear distinction between two engine speeds. At the same relative air/fuel ratio value, high load will have a higher combustion temperature, so higher NO_x emission at 5000 rpm is produced than at 4300 rpm. At the same engine speed and low relative air/fuel ratio, NO_x in SDI engine is always higher than original engine. This comes from the high SDI engine combustion temperature (Guo *et al*., 2011). When relative air/fuel ratio increases, NO_x will be decreased, because the combustion temperature is decreased. The results regarding NO_x also indicate that NO_x emission from LPG is lower than gasoline for all ranges of relative air/fuel ratio and engine speed. Khan *et al*. (2006) had the same result, as well.

Since unburned hydrocarbon emissions (HC) are used as a full measure of combustion inefficiency, it is an important factor for evaluating combustion efficiency of SDI engine. Results indicate good combustion efficiency in original LPG engine compared to original gasoline engine. As relative air/fuel ratio increases, the original gasoline engine HC emissions increase rapidly compared to LPG engine, meaning that using LPG as an alternative fuel could increase the lean limit of original engine. For the SDI engine, the HC emission value from 0.9 to 1.5 of relative air/fuel ratio is lower than original gasoline and LPG engines. HC emissions in SDI engine from 1.6 to 1.7 of relative air/fuel ratio approximate original gasoline engine operating at stoichiometric mixture (relative air/fuel ratio ≈ 1). So the optimum operating range of SDI engine is around 1.6 to 1.7 of relative air/fuel ratio.

Engine Performance Map

A common way to represent the operating characteristics of an internal combustion engine is to plot BSEC, $BSCO_2$, BSCO, BSHC and $BSNO_x$ contours on a graph for brake mean effective pressure (BMEP) versus engine speed, where BMEP is obtained from engine torque and cylinder displacement.

Fig. 6 shows the BSEC maps of SDI engine and original gasoline engine at low loads. The triangle markers in the figure show the operating points of the ECE driving cycle. The result is clear that SDI engine has better energy consumption than original gasoline at part load. By taking the average of all testing points in the map, the reduction of energy consumption is 19.2% as compared between SDI and original gasoline engines. It is obvious that the SDI engine runs at lean burn with stratified mixture, so pumping and heat loss are decreased, also improving combustion (Khan *et al*., 2006).

Fig. 7 shows the $BSCO_2$ maps of SDI engine and original gasoline engine in low loads. Results show that CO_2 emission from SDI engine is reduced by 27% as compared with regular gasoline engine. The SDI engine results were achieved by combining two key factors of alternative fuel and improving engine efficiency. For alternative fuel, previous research concluded that LPG is a good alternative fuel to reduce CO_2 emissions (Pecqueur *et al*., 2008; Shanmugam *et al*. 2010), potentially an 11–15% reduction of CO_2. For engine efficiency, SDI engine could make a

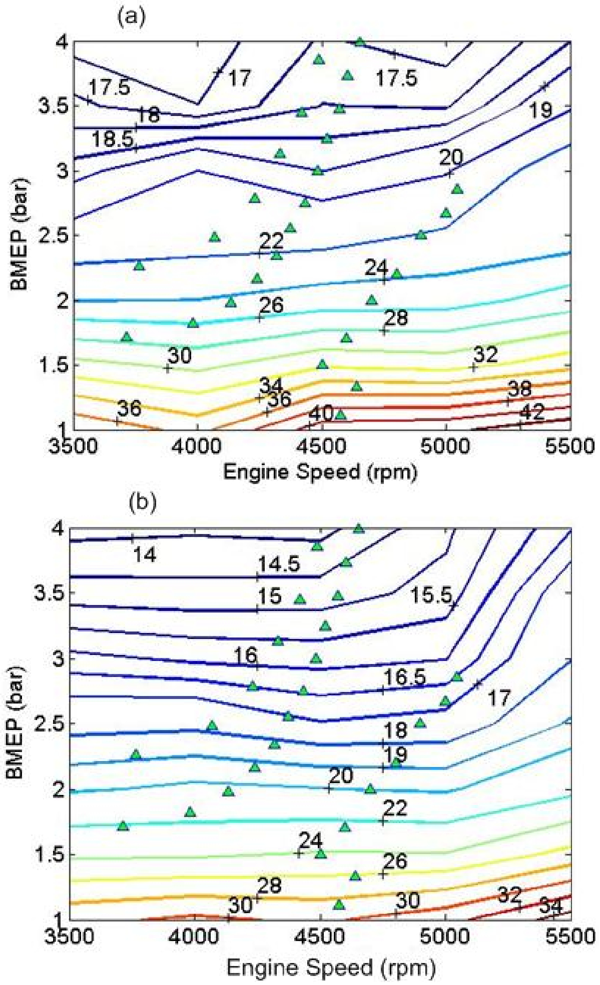

Fig. 6. Brake specific energy consumption (MJ/kW.h) maps and ECE-40 operating points (▲) in low-load region: (a) original gasoline engine, (b) SDI engine.

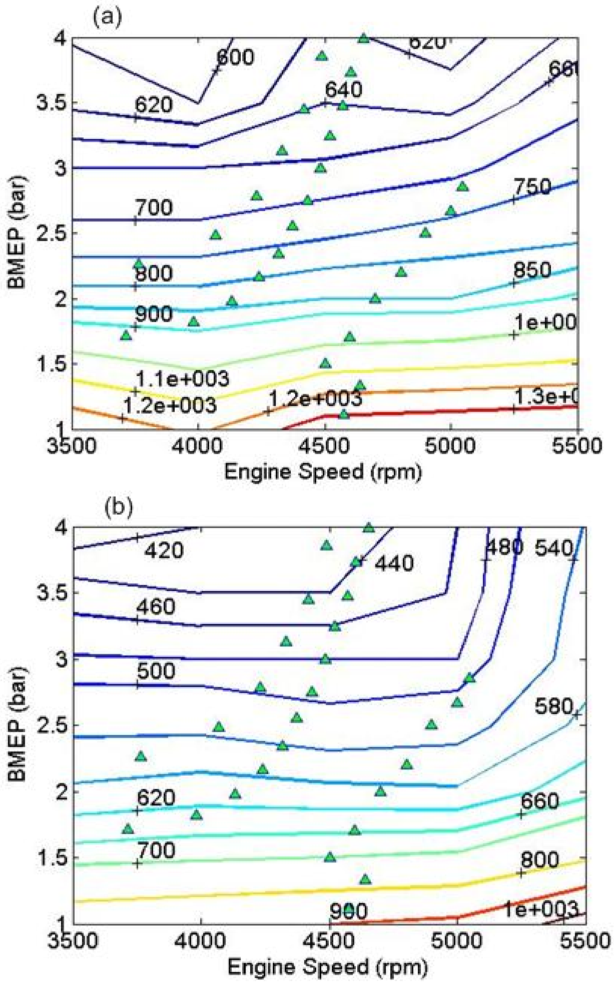

Fig. 7. Brake specific carbon dioxide (g/kW.h) maps and ECE-40 operating points (▲) in low-load region: (a) original gasoline engine, (b) SDI engine.

stratified mixture inside the cylinder, so it could reduce time and heat loss which would increase combustion efficiency (Yamamoto, 1999). Extending the lean limit of SDI engine to 1.7 of relative air/fuel ratio will reduce pumping loss, which is a key to friction loss in SI engine. That is the reason why SDI engine produces the lowest CO_2 emission (Khan *et al*., 2006; Guo *et al*., 2011).

Fig. 8 shows the BSCO maps of SDI engine and original gasoline engine in low loads. The BSCO of original engine is much higher than that of SDI. By taking the average of all testing points in the map, BSCO is reduced 94% for SDI compared with regular gasoline engine. The SDI engine is running at lean burn with relative air fuel ratio around 1.6 to 1.7, while the original gasoline engines are operated with a stoichiometric mixture (relative air/fuel ratio ≈ 1). So the CO emission of SDI engine must be lower than that of original gasoline engine (Khan *et al*., 2006). Carbon monoxide, which has been the focus of many environmental studies (Colbeck *et al*., 2011; Ma *et al*., 2011) is highly toxic to humans. The current study's reported results contribute greatly to reducing carbon monoxide in the atmosphere.

Fig. 9 shows the BSHC maps of SDI engine and original engine in low loads. BSHC of SDI engine is higher than that of original gasoline. By taking the average of all testing points in the map, the increase in BSHC is 4.57% for SDI, as compared with original gasoline engine. It could be explained that the HC emission is the consequence of incomplete combustion of hydrocarbon fuel, this might come from very lean regions at the periphery of the stratified charged fuel cloud (Håkan *et al*., 2000; James *et al*., 2003).

Fig. 10 shows the $BSNO_x$ maps of SDI engine and original gasoline engine in low loads. $BSNO_x$ of SDI engine is pretty low. By taking the average of all testing points in the map, the reduction of $BSNO_x$ for SDI is 47.0%, as compared with original gasoline engine. It could be explained that the principal source of NO_x is the oxidation of atmospheric nitrogen, which is temperature and oxygen concentration dependent (Lee *et al*., 2006; Wang *et al*., 2012). In homogeneous charge combustion, NOx emission increases tremendously because its air/fuel ratio is close to the peak value for NO_x emission production. In this research, however, the lean limit of SDI achieves 1.7 of relative air/fuel ratio, so the NO_x emission decreases further (Khan *et al*., 2006). Since NO_x is an important gas

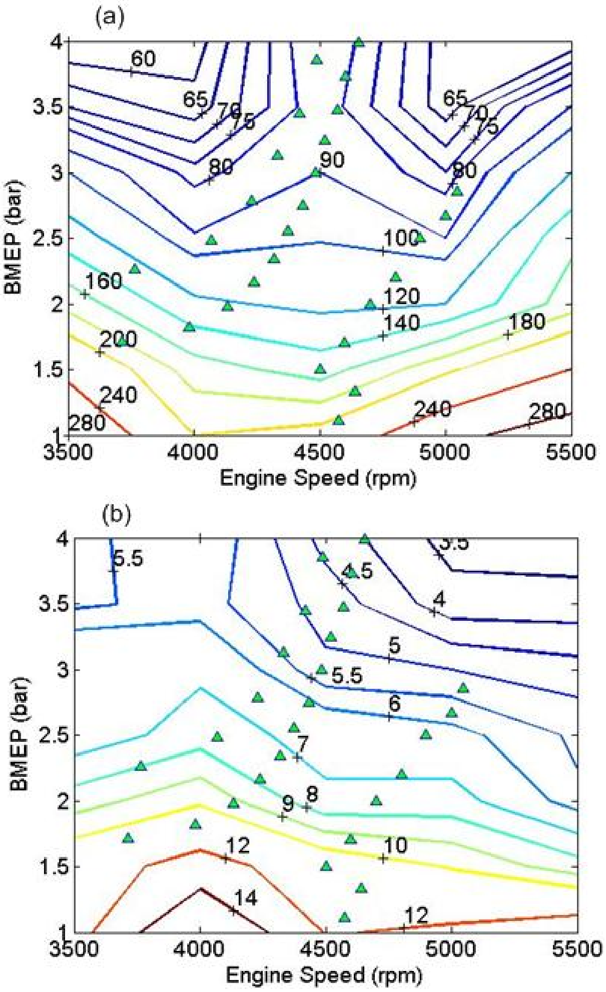

Fig. 8. Brake specific carbon monoxide (g/kW.h) maps and ECE-40 operating points (▲) in low-load region: (a) original gasoline engine, (b) SDI engine.

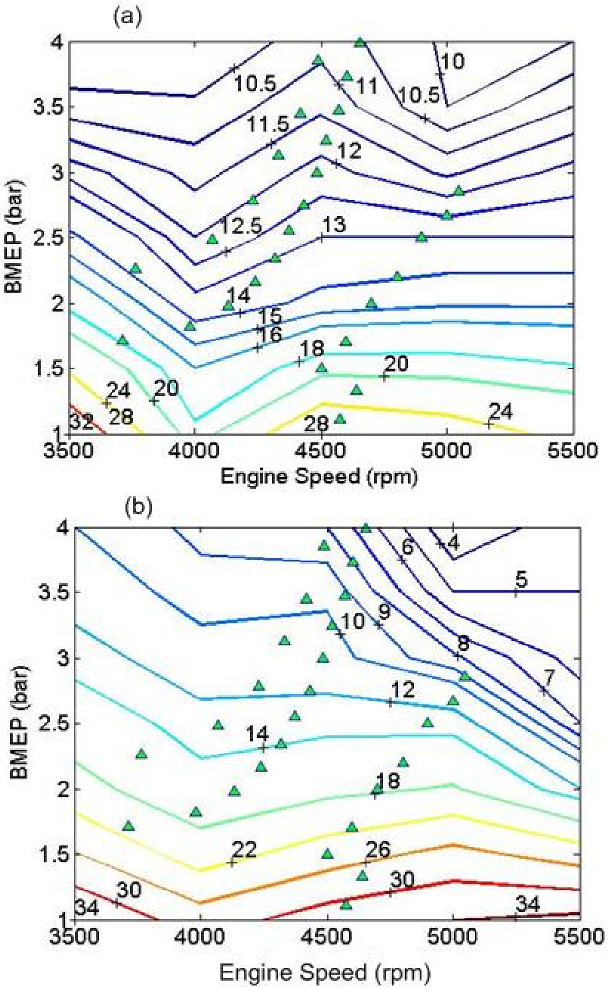

Fig. 9. Brake specific hydrocarbon (g/kW.h) maps and ECE-40 operating points (▲) in low-load region: (a) original gasoline engine, (b) SDI engine.

for formation of ozone and nitric acid (Kumar *et al*., 2008), that result is a good contribution to reducing motorcycle exhaust pollution and improve air quality.

CONCLUSIONS

A 125 cc 4-valve engine was retrofitted by designing a controllable plate to enhance the swirl of intake flow at low load. This design combined high swirl, injection during intake valve opening (Guo *et al*., 2011) and LPG gaseous phase to produce stratified charge, which is called semi-direct injection (SDI). The lean limit was extended to 1.7 of relative air/fuel ratio. The engine was tested at a low-load region which comprises most operating points of the ECE-40 driving cycle. A complete engine performance map under half-load operation was conducted for comparison between SDI and original gasoline engine. Measurements of various emissions characteristics on the target engine have led to the following conclusions:

(1) The new intake port design can be operated in both homogeneous and stratified modes with flow coefficient at homogeneous mode staying the same as the original intake port, while swirl ratio can reach 3.4 in stratified mode.
(2) Exhaust pollution is dependent on relative air/fuel ratio. Increasing relative air/fuel ratio will decrease CO and NO_x; however, original gasoline and LPG engines cannot achieve as high a lean limit compared to SDI engine, which can achieve a relative air/fuel ratio of 1.7, thus reducing both CO and NO_x significantly.
(3) Within a part-load region, which consists of most of the engine operating points of the ECE-40 driving cycle, SDI performs pretty well. By taking the average of all testing points in this region, the results of SDI compared with original gasoline engine are: BSEC and $BSCO_2$ are reduced by 19.2% and 27.0%, respectively. BSCO decreases tremendously by 94%, $BSNO_x$ decreases by 47%. However, BSHC increases by 4.5%.

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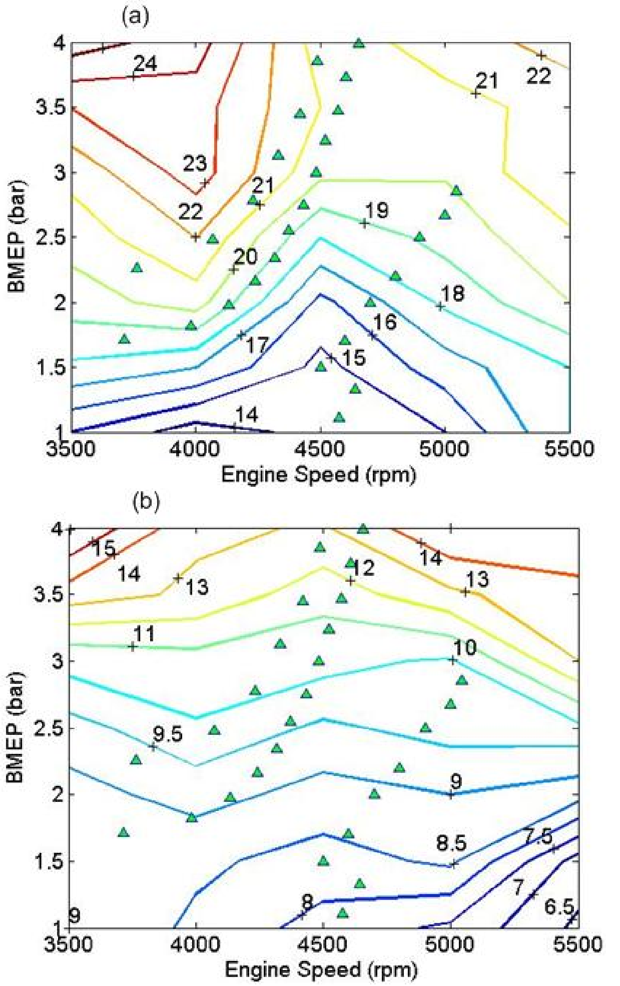

Fig. 10. Brake specific oxides nitrogen (g/kW.h) maps and ECE-40 operating points (▲) in low-load region: (a) original gasoline engine, (b) SDI engine.

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