A single cylinder research engine for investigating combustion of direct ethanol injection and port gasoline injection

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Abstract

Ethanol has been used as a renewable fuel in internal combustion (IC) engines. However, the existing method of blending gasoline and ethanol fuels does not take the advantages of ethanol fuel, such as its high Octane number and great latent heat of vaporization, to increase the engine compression ratio and consequently the thermal efficiency. Ethanol direct injection plus gasoline port injection (EDI+GPI) is a new technology for using ethanol fuel more effectively and efficiently in IC engine. To experimentally investigate this new technique, a research engine has been developed by modifying a commercial product representing the cylinder capacity of a down sized passenger car engine. In the development of this research engine, two major tasks were addressed: the two separate fuel systems and the electronic control unit (ECU). The operation of both fuel systems including the high pressure pump and the common rail fuel pressure are electronically controlled. The ECU also controls the throttle position and fuel flow rates in an open loop to provide the flexibility of manual adjustments of engine speed, load and lambda. Sample results are reported to show that the developed engine system has met the basic requirements of experiments in this investigation.

Introduction

The new strategy of separately fuelling the ethanol and gasoline/Diesel fuels have been in development for promoting the application of ethanol fuel to IC engines. This is because that this new strategy can take the advantages of ethanol fuel such as its great Octane number and latent heat for protecting engine from knock, which allow a higher compression ratio and consequently the increase of thermal efficiency and reduction of CO_2.

Motivated by the potential of ethanol fuel, different research engines are required to meet the special aims in experimental investigation in different projects. Multi-cylinder commercial engines have played an important role in presenting a quick demonstration of new techniques. Aiming to assess the concept of direct injection of ethanol fuel which was first proposed by Cohen et al [1], Stein et al [2] modified a Ford engine, 3.5L turbocharged direct injection 'EcoBoost', with a port fuel injection (PFI) system outfitted for port injection of 91 RON gasoline. The original direct injection (DI) system was used to inject E85 into the combustion chamber as required at high engine load conditions. The compression ratio was increased from 9.8:1 to 12:1 by modifying the piston. Their experimental results verified the prediction of the E85's role [1] by finding that E85 DI was extremely effective in suppressing engine knock during high load operation conditions. To investigate the best engine performance achievable, a Toyota V-6 3.5-liter gasoline engine (2GR-FSE) was used with two fuel injectors in each cylinder [3]. One of the two injectors was a direct injection injector generating a dual-fan-shaped spray with wide dispersion, and the other was a port injector. With this dual injection system, the engine achieved maximum power and minimum emission levels for production engines of this displacement.

Single cylinder engines have also been used to provide a more independent and flexible way for experimental investigation. To investigate the combustion characteristics of spark ignition (SI) engine with gasoline and ethanol dual-fuelled, a three-valve 0.675L single-cylinder engine was built based on a PFI 5.4L V8 engine [4]. The engine was equipped with a conventional PFI and a Visteon's low pressure direct injection fuel system. The injection pressure for PFI was fixed at 3.5 Bar. The direct fuel injector was side mounted on the top of cylinder head to inject fuel at a constant rail pressure of 20 Bar. In that research a relative air fuel ratio (AFR) meter and a universal exhaust gas oxygen sensor were installed to measure and control the AFR value. However, the calculation of the AFR value in terms of the ratio of gasoline and ethanol (E85) fuel was not reported. Wu et al investigated dual fuel combustion using a 0.566L 4-stroke SI engine equipped with a high pressure (15MPa) spray-guided DI and a low pressure (0.3MPa) PFI system [5]. The air/fuel ratio was maintained at stoichiometric ratio throughout the study by applying the cross-over theory. The engine was controlled by an in-house LabView program.

As a new strategy for using ethanol fuel in SI engines more effectively and efficiently, EDI+GPI will require substantial research before it is turned to reality. Developing a research engine to meet the aims of experimental investigation is crucial and challenging. This paper reports our work on developing a research engine system for investigating EDI+GPI, including engine modification and development of the fuel systems and control strategies.

The research engine

Design Principles

The project has two major objectives. One is to investigate the leveraging effect of EDI+GPI on engine power output, fuel consumption and exhaust gas emissions. The other is to study the effect of ethanol direction injection on engine knocks suppression. To reach these objectives, a research engine which meets the following requirements is needed.

1. The engine structure should be simple and robust so that it can accommodate a fuel injector in cylinder head and allows modifications to increase compassion ratio.

2. The engine should represent the cylinder capacity, compression ratio and other parameters of a typical modern light duty passenger vehicle.

3. Parameters affecting engine performance, like the spark timing, air/fuel ratio, fuel injection timing etc. should be individually controllable.

4. The high pressure fuel supply system for ethanol direct injection should be able to provide the required fuel pressure in stable operation. The injection timing and fuel quantity should be adjustable.

5. The ethanol/gasoline ratio should be adjustable in a full range of 0% to 100%.
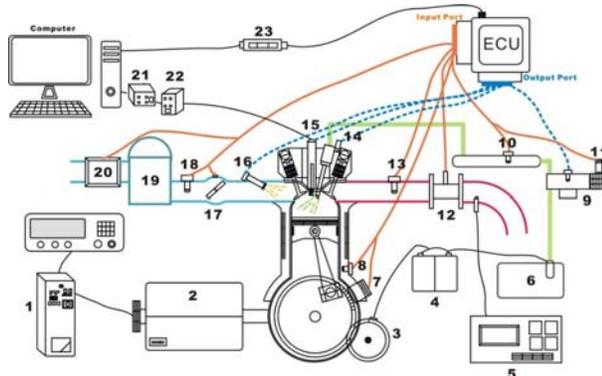
1. Dynamometer controller 2. Dynamometer 3. Start motor 4. Battery 5. Horiba MXEA-584L gas analyser 6. Ethanol fuel tank 7. Encoder on crankshaft 8. Temperature sensor 9. High pressure fuel pump 10. Common rail pressure sensor 11. Encoder on high pressure pump shaft 12. Bosch wide-band lambda sensor 13. Temperature Sensor 14. Direct fuel injector 15. Kistler spark plug pressure transducer 16. Port fuel injector 17. Throttle valve position sensor and driving motor 18. Temperature sensor 19. Inlet air regulator 20. Air flow meter 21. Combustion analyser 22. Charge amplifier 23. CAN Communication module

Figure 1- Schematic of the engine system

To meet the above requirements, the research engine system should consist of three major parts: control and monitoring panel, the engine and the electronic control unit (ECU). Figure 1 illustrates the components and their links. As shown in the figure, the engine system is equipped with sensors (8, 10, 12, 13, 15, 18 20) and actuators (2, 14, 16, 17) for measurements and control. It has a high pressure fuel system including a high pressure fuel pump (11), a common rail and a high pressure fuel injector (9) for direct injection of ethanol fuel. The engine is coupled to a DC dynamometer (2) to maintain certain speed and/or torque. The solid lines link all the sensors and the dashed lines connect all the actuators. All signals from the sensors and to actuators are sent to or by the ECU. They can be displayed by a software program on a computer which is connected to the ECU via the CAN communication module (23). A Horiba MEXA-584L gas analyser (5) is used to measure the exhaust gas emissions. Exhaust gas samples are taken from the exhaust pipe at a position 0.4 meter to the exhaust valve and before the three-way catalyst converter. In order to investigate the anti-knocking ability of EDI+GPI, a compressor will be used to simulate the inlet pressure increased by turbocharging.

Engine Modification

A four-stroke single-cylinder gasoline engine powering the Yamaha YBR250 Motorcycle was selected as the baseline engine in this study. It is air-cooled and has a displacement of 250cc. The original YBR250 engine was equipped with port fuel injection, a three-way catalyst converter and an onboard ECU for controlling the engine speed and port fuel injection. The port fuel injection pressure was 250 kPa in the original engine. Table 1 lists its specifications.

Engine type	Single cylinder, air cooled, 4-stroke, SOHC.
Displacement	249.0 cc
Bore × stroke	74.0mm x 58.0 mm
Compression ratio	9.8:1
Lubrication system	Wet sump
Maxim power	15.4KW at 7500 RPM

Table 1 - Specifications of Yamaha YBR250 engine

To achieve the ethanol direct injection, the cylinder head was modified with a high pressure fuel injector installed. Figure 2 illustrates the relative position of the fuel injector in the cylinder head. The injector was mounted on the same side with the spark plug, opposite the sprocket of the camshaft to avoid any interference with it. The position of the injector was selected due to the structure constraint in the cylinder head. It was installed with an angle of 15 degrees from the horizontal surface (the interior surface of the cylinder head was defined as horizontal surface) and 12 degrees from the vertical surface. The tip of the injector was placed between the intake valve seat and the spark plug. In this way, the tumble flow may be used to form richer mixture adjacent to the spark plug. Thus lean combustion may be achieved and investigated with this engine.
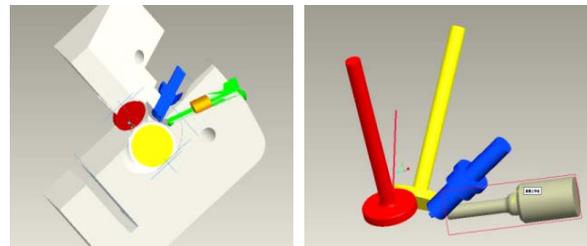
Figure 2 - Relative position of direct fuel injector in cylinder head (exterior view). The exhaust valve is shown on the left hand side in red colour. The inlet valve is shown on the right hand side in yellow colour. The spark plug is shown in the middle in blue colour.

High pressure ethanol direct injection system

A high pressure fuel injection system was developed to inject ethanol fuel directly into the combustion chamber. The high pressure fuel injection system consists of an injector, a common rail, a pressure sensor, a decompression valve, a low pressure fuel pump, a high pressure fuel pump, an electrical drive motor and an encoder. Figure 3 is a schematic diagram of the high pressure fuel system for ethanol fuel direct injection.
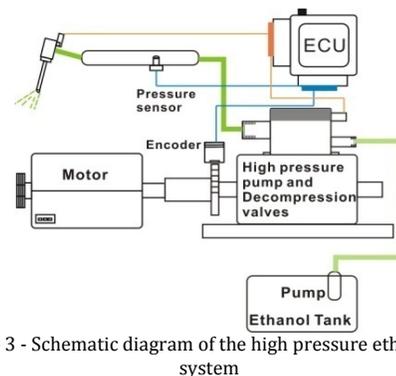
Figure 3 - Schematic diagram of the high pressure ethanol fuel system

The high pressure pump and the injector were adopted from the turbo charged direct injection engine equipped on Volkswagen EA888. The pump is an electronic unit pump with a safety valve

opening at pressure of 140 Bar. It provides steady fuel pressure in a range of 30 Bar to 130 Bar. The common rail pressure is controlled through a high speed electronic on/off solenoid valve which is actuated by the control unit to allow or stop the ethanol fuel delivered to the common rail. An encoder was used in this high pressure fuel system for the control unit to decide the phase of the valve's opening and closing. In Volkswagen EA888, the fuel pump for direct injection was driven by the overhead camshaft. In the present fuel system, the fuel pump is driven by a camshaft linked to an electrical motor operated at a constant speed of 1500 RPM.

The high pressure injector has six orifices to produce six spray plumes in a ¾ moon pattern. The spray has an angle of 60° with a 5° bent axis. The injector was side-mounted next to the intake valve, aimed to form rich mixture around the spark plug with the aid of cross flow. Its six orifices have different angles to direct fuel to different areas of the combustion chamber. In the present research, as described above and shown in Figures 2, the injector was installed with a certain angle from the vertical surface so that part of the fuel could be injected into the area adjacent to the spark plug.

Control unit

The ECU was developed based on a Freescale's MC9S12XPE100 16-bit high performance MCU, a product specifically designed for automotive electronics. It replaced the original ECU of the YBR250 engine to meet the special requirements of the current project. It controls the high pressure fuel system and engine operation conditions. Figure 4 shows the input and output signals of the ECU.
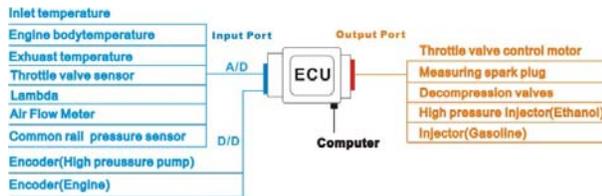
Figure 4–Inputs and outputs of ECU

The ECU has 16 analogue inputs and 12 digital inputs. As shown in Figure 5, seven of the analogue and two of the digital inputs are used for acquiring signals of inlet temperature, engine body temperature, exhaust temperature, throttle position, lambda, air mass flow rate, common rail pressure, and signals from the encoders. Signals from the sensors and transducers are processed by the control unit which in turn decides the output signals to drive the actuator for controlling the throttle opening angle, the spark timing, injection timing and pulse widths of two fuel injectors. A H-bridge driving circuit was used to drive the throttle valve stepper motor. Two low level current switches are used to control the gasoline fuel injection and the decompression valve on the high pressure fuel supply system. A high level current switch is used for controlling the high pressure ethanol direct injection.

Control strategies were developed and implemented in the research engine to minimize the time and other resources for conducting the experiments. Figure 5 illustrates the basic control strategy. During the experiment, the engine load is provided by the dynamometer and the engine speed is kept constant. The control unit allows manual adjustments to provide sufficient flexibility for people conducting the experiments to achieve the engine testing conditions in a wide range and multiple combinations. The input quantities of both fuels and the throttle position can be manually adjusted to achieve the targeted engine speed, torque and lambda.

Lambda control

A Bosch wide-band lambda sensor was installed in the exhaust pipe of the tested engine. However, it was designed for measuring the lambda for the engine with a single fuel and could not be used directly in the dual fuel case. In the present study, the fuel injectors were calibrated and the flow rates of the ethanol and gasoline fuels were calculated with the calibration equations and the input of the required fuels to the control unit. Therefore a real-time air/fuel ratio was obtained from the calculated fuel flow rates and the measured air flow rate.

Data acquisition

The test data are acquired through the control unit and by the measuring instruments. The data for engine operation and engine control are acquired through the ECU and real-time displayed on the computer screen through its built-in program and interface. The outputs of the rotary encoder and cylinder pressure transducer are acquired by a combustion analyser and the acquired data are used to calculate the mass burnt factor (MBF) and the heat release rate.
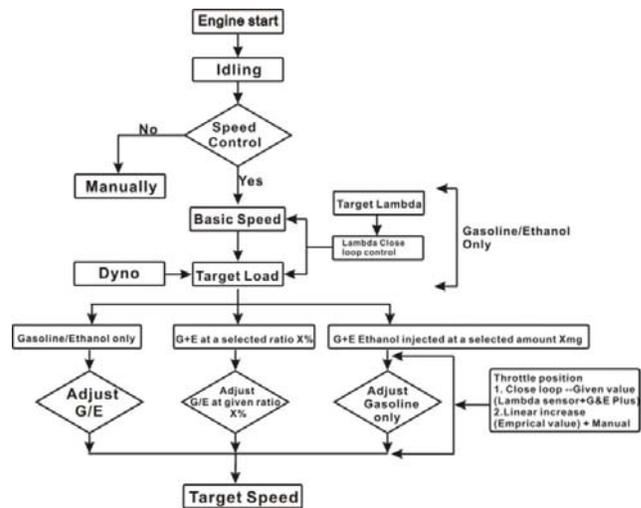
Figure 5 - Basic control strategy

Preliminary sample results

Using the developed research engine system, experiments were conducted in a preliminary investigation to EDI+GPI. Sample results are presented to show the effect of varying ethanol/gasoline volumetric percentage on engine performance, combustion and emissions. During the experiments, the total energy input of both ethanol and gasoline fuels were kept unchanged, while the percentage of ethanol/gasoline (volume based) was varied in a certain range. Figure 6 shows the engine BMEP varying with the ethanol/gasoline volumetric percentage at three engine speeds of 3500rpm, 4000rpm and 4500rpm. The engine spark timing and ethanol fuel injection timing were fixed at 15 degrees before the top dead centre (BTDC) and 300 degrees BTDC respectively during the tests. As shown in Figure 6, at all three engine speeds, the BMEP increases with the increase of ethanol/gasoline volumetric percentage. This preliminarily shows the leveraged effect of using ethanol fuel on partially replacing gasoline fuel. This leveraged effect, as one of the major aims in this research, will be further investigated using the developed research engine system.

Figure 7 shows the variation of heat release rate (HHR) and mass burnt fraction (MBF) with ethanol/gasoline volumetric percentage at 3500rpm. As it can be seen, with the increase of

ethanol/gasoline volumetric percentage, the combustion completes earlier, due to faster heat release as shown by the HHR curves and the resulted shorter combustion period as shown by the MBF curves. Quicker combustion can reduce the combustion heat losses through the engine cylinder wall and increase the engine thermal efficiency.

Figure 8 illustrates the variation of brake specific nitric oxide (BSNO) and brake specific carbon dioxide ($BSCO_2$) with the ethanol/gasoline volumetric percentage at engine speeds of 3500rpm and 4000rpm. As shown in Figure 8, the BSNO and $BSCO_2$ decrease with the increase of ethanol/gasoline volumetric percentage except the $BSCO_2$ at 3500rpm at which $BSCO_2$ slightly increases with the increase of ethanol/gasoline volumetric percentage. As the NO emission is a result of high combustion temperature and lasting time, the decrease of BSNO proves the ethanol's potential in reducing the maximum and average combustion temperature. The decreased engine maximum in-cylinder temperature indicates the improved engine anti-knock ability and potentially the increase of engine compression ratio. In IC engines, the engine thermal efficiency is directly related to engine compression ratio, the increase of compression ratio will therefore lead to the improvement of engine thermal efficiency.
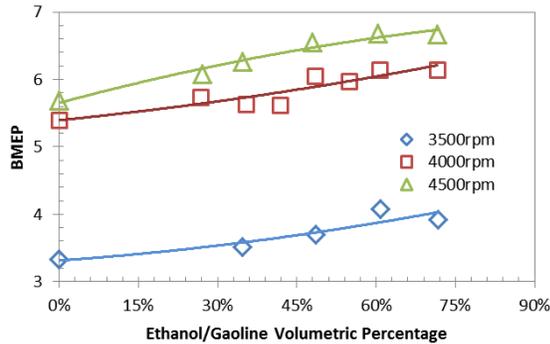
Figure 6 –Variation of BMEP with ethanol/gasoline volumetric percentage at engine speeds of 3500, 4000 and 4500 rpm.
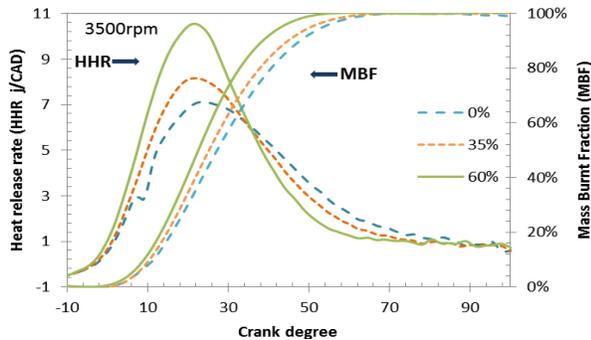
Figure 7 –Variation of heat release rate and mass burnt fraction with ethanol/gasoline volumetric percentage at 3500rpm.

Conclusions

1. To explore the potential of EDI+GPI, a single cylinder research engine system has been developed to facilitate the experimental investigation. The baseline engine selected was a single-cylinder 4-stroke engine with a displacement of 250cc, representing future car engines in a trend of reduced size.
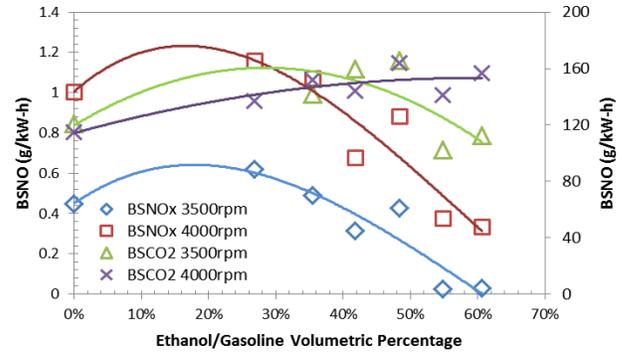
Figure – 8 Variation of BSNO and $BSCO_2$ with ethanol/gasoline volumetric percentage at 3500rpm and 4000rpm.

2. Design principles were set up in terms of the required conditions and functions to the research engine in order to meet the project's aims. Three major tasks have been addressed in the development of this research engine: engine modification, high pressure fuel system for ethanol fuel and control strategies.

3. The research engine system features controllability of the high pressure fuel pump to maintain a stable common rail pressure and flexibility of controlling the parameters affecting combustion and of manual adjustments of engine speed, load, lambda and the ratio of ethanol and gasoline fuels.

4. The preliminary results showed that this system met the basic requirements of the engine testing for achieving the objectives of the project.

Acknowledgments

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