Improvement of Spark-Ignition (SI) Engine Combustion and Emission during Cold Start, Fueled with Methanol/Gasoline Blends

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Improvement of Spark-Ignition (SI) Engine Combustion and Emission during Cold Start, Fueled with Methanol/Gasoline Blends

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A three-cylinder, with a bore of 68.5 mm port fuel injection, engine was adopted to study the combustion and emission characteristics of a methanol/gasoline-fueled engine during cold start and warm up. The cylinder pressure analysis indicates that engine combustion is improved with the methanol addition into gasoline. With the increase of the methanol fraction, the flame developing period and the fast burning period are shortened and the indicated mean effective pressures become higher during the first 50 cycles. Meanwhile, a novel quasi-instantaneous measurement system was designed to measure engine emissions during this process. With the increase of the methanol fraction (below 30%), the unburned hydrocarbon and carbon monoxide (CO) are decreased obviously. The measured results show that the hydrocarbon is reduced about 40% at 5 °C and 30% at 15 °C during the cold-start and warm-up period; CO is reduced nearly 70% when the engine is fueled with M30 (30% methanol in volume), and a higher difference in the exhaust gas temperature of about 140 °C is achieved at 200 s after starting than fueled with gasoline.

1. Introduction

Many efforts are being made to reduce air pollution originating from automotives. Noxious emissions, such as carbon monoxide (CO), unburned hydrocarbon (UHC), and oxides of nitrogen (NO_x), in the exhaust of gasoline-powered engines are effectively controlled by the adoption of a three-way catalytic converter (TWC), whereby they are oxidized or reduced to harmless carbon dioxide (CO_2), nitrogen (N_2), and water vapor (H_2O). Today, the TWC has become a common feature for the port fuel injection gasoline engines with closed loop λ feedback control. However, the catalytic converter will not be able to function effectively until it reaches the light-off/operating temperature, although TWCs used in motor vehicles nowadays are able to achieve the reductions of CO, UHC, and NO_x by up to 95% when they are fully warmed up.[1] Recent research has revealed that ∼60−80% of the UHC and CO are emitted from a motor vehicle equipped with a TWC within the first few minutes following engine cold start.[2] As a result, most of the tailpipe hydrocarbon (HC) measured during the U.S. 1975 Federal Test Procedure (FTP 75), Economic Commission for Europe (ECE), and New European Driving Cycle (NEDC) has been found to be from the cold-start operation of the tests at ambient temperatures of 20−30 °C, before the catalytic converter is warmed up.[3] Especially, the recent Euro III and Euro IV emission standards have included a subambient cold-start test at a temperature of −7 °C, during the first 780 s of the urban cycle, limiting HC and CO tailpipe emissions in such conditions. This peculiarity offers scope for the reduction of overall spark-ignition (SI) engine emissions.

As world energy consumption continues to grow, with the primary resources being the fossil fuels, the search for cleaner alternative fuels for automobiles has been extended during the last few decades. Methanol (CH_3OH) has several advantages that distinguish it as an attractive alternative fuel over petroleum fuels. The first is low price. Methanol can be produced from synthesis gas (mixture of CO and hydrogen) that is formed by steam reforming of natural gas, gasification of coal, or from biomass, all of which are available in abundance or regeneration. At present, the price of methanol production is about $350 U.S./ton in China, which is nearly half of that of petroleum fuels. Even though the value is compared in the equivalence energy, it is still a little lower than that of petroleum fuels. The second is low emission. The lower boiling point (65 °C) makes them evaporate more easily, which is beneficial for combustion, resulting in lower HC emissions. Moreover, its high oxygen content (50 wt %) and simple chemical structure that can lead to lower CO enhance its appeal as an alternative fuel or additive to gasoline in SI engines.

Because the implementation of methanol as an automotive fuel is limited by the cold-start problems as a result of the low vapor pressure and high latent heat. Many research approaches have been taken, such as intake air heating, fuel heating, fuel reforming, supplementary fuel, and blend fuel, etc.[4−6] When the SI engine was fueled with blend fuel, little modifications to the engine were taken. Therefore, it is a simpler practical

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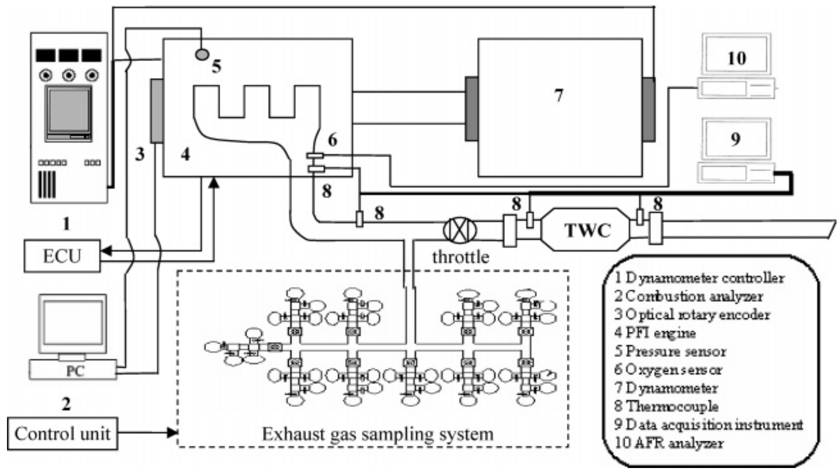

Figure 1. Schematic diagram of the PFI engine test bench setup.

Table 1. Specifications of the Engine

type	bore (mm)	stroke (mm)	displacement (cm^3)	compression ratio
JL368Q3	68.5	72	796	9.4

approach for the application of methanol in the internal combustion engine. Different mixtures of methanol−gasoline are widely studied now, and the performance, combustion, and emission characteristics under normal working conditions are already well-known but little attention is focused on the cold-start and warm-up stage.

In this paper, three kinds of methanol−gasoline (10, 20, and 30% methanol) blends were prepared to fuel a SI engine, a quasi-instantaneous sample system was developed, and the combustion and emission characteristics were investigated during the cold-start and warm-up process.

2. Experimental Section

A three-cylinder, port fuel injection (PFI), four-stroke, electronic control SI engine was used for the investigation. The engine specifications are listed in Table 1. Figure 1 shows the schematic diagram of the test bench of the PFI engine.

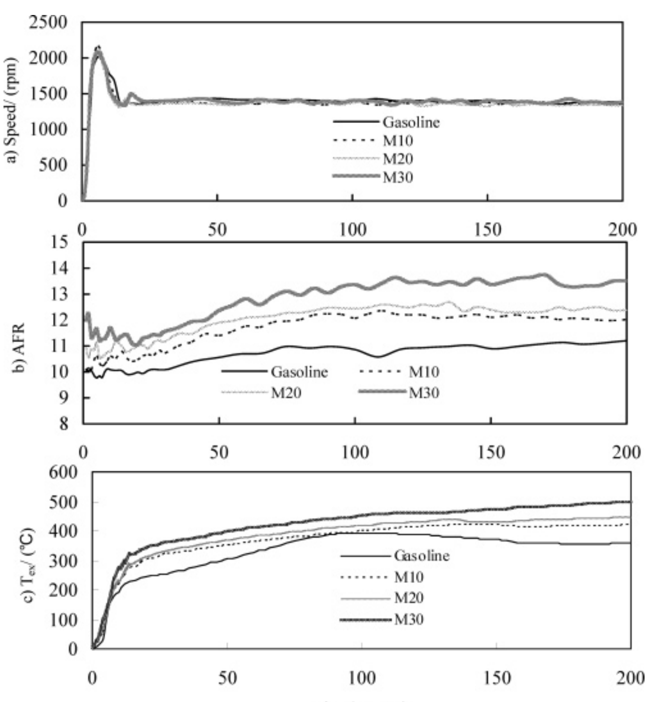

Figure 2. Effect of blend fuels on speed, AFR, and T_{ex} during the cold-start and warm-up process (engine is started at 5 °C).

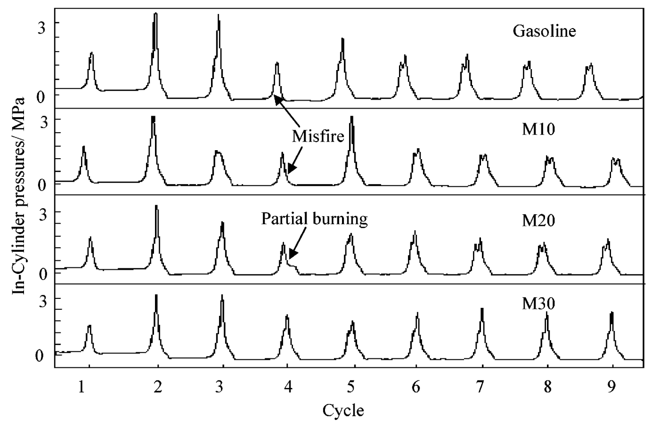

Figure 3. In-cylinder pressures of the initial cycles during cold starting.

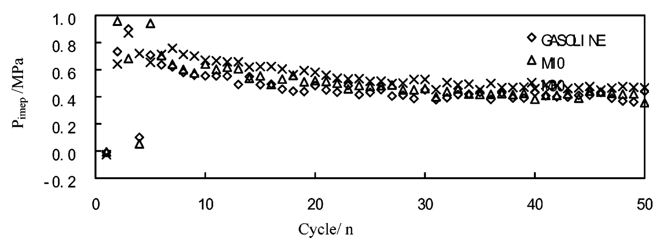

Figure 4. IMEP of the first 50 cycles during cold start.

During the transient phases of cold start and warm up, the engine speed and air/fuel (A/F) ratio (AFR) change with time, as well as the engine-out emissions of HC and CO. Because there is no fast measuring system, a quasi-instantaneous measurement system was designed in this study. It consists of three processes; they are the bag-sampling process, constant temperature heating process, and stable analyzing process.

The bag-sampling system is made of solenoids, bags (3 L), and a control unit. An 8-bite programmable microprocessor produced by the ATMEL company was used in the control unit. A section control program is prestored in the microprocessor to control electromagnetic valves that are connected with the sampling bags. The bag-sampling system is triggered at the same time of engine key-on. The whole measurement duration is divided into three stage (∼0−10, ∼10−30, and ∼30−200 s), including 40 sampling points. The period of sampling is 1, 2, and 8 s for the three stages (the exhaust gas concentrations change quickly in the beginning; therefore, a higher sampling frequency is used), respectively. The flow rate of charge is regulated with the throttle valve on the exhaust pipe. During every sampling period, the exhaust gas is trapped in the bag. In other words, the exhaust gas was divided into 40

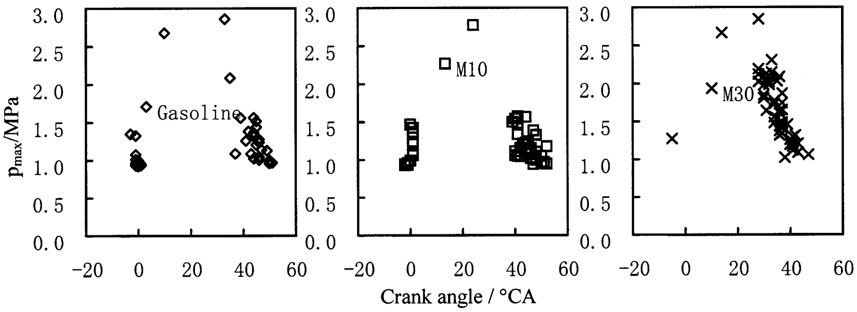

Figure 5. Maximum cylinder pressures versus occurring crank angle of the first 50 cycles.

segments along the time and trapped in 40 different bags for the following analyses.

After sampling, the bags will be heated to a temperature of 120 °C in a constant temperature system for 15 min, which can promote the evaporation of unburned fuel and water and make the sampled gas mix homogeneously quickly for measuring. Then, the concentrations of HC and CO in bags are analyzed one by one with an emission analyzer (MEXA-324J). Moreover, the cylinder pressure is also sampled and analyzed by the AVL system (INDIMETER 619) from engine start. The AFR is measured with a heating type universal exhaust gas oxygen (UEGO) AFR analyzer (Horiba Mexa-700λ), and the exhaust gas temperature (T_{ex}) is recorded with data acquisition (YOKOGAWA DL750).

3. Results and Discussion

3.1. Cold-Start Engine Performance. In this research, little modifications were made to the engine, and it was under the same electronic control unit (ECU) control strategy fueled with different fuels, and it was an open loop control without λ feedback during cold start.

Figure 2a shows the variation of the engine speed. It can be seen that the engine goes though the same start process with all of the fuels, and no evidence of a start problem was found because of the application of blend fuels. It can be concluded from the UEGO A/F ratios (Figure 2b) that the mixtures become leaner with the increase of the methanol fraction. It is under the same injection MAP, but methanol contains 50% oxygen and can supply oxygen by itself during combustion. Figure 2c gives the exhaust temperatures with various fuels. The T_{ex} fueled with M30 is about 140 °C higher than that of gasoline at a time of 200 s. The higher exhaust temperature demonstrates the improvement of combustion in the cylinder, which can also shorten the light-off time of the TWC.

3.2. Cold-Start Combustion Characteristics. Figure 3 compares the in-cylinder pressures of the first several cycles during the cold-start process. After one nonfiring (motoring) cycle, the first firing cycle occurs with a relatively high pressure. The cylinder pressure diagrams show the same behaviors for the four fuel cases. The intake manifold pressure is at atmospheric pressure and starts to decrease rapidly as the engine utilizes the air in it. It is clear that the initial one or two firing cycles have a very high maximum pressure because of the high intake pressure and large fuel injection. There is an obvious misfire cycle following the firing cycles when the engine runs on gasoline and M10, a partial burning cycle of M20. For M30, there is no misfiring operation. The pressure data of the subsequent cycles in Figure 3 show that engine combustion cyclic variation changes better with the increase of methanol in gasoline, which proves the improvement of combustion during the cold-start and warm-up process. The slow combustion during cold start forms another peak cylinder pressure after top dead center because the throttle is nearly closed and the volumetric efficiency in the cylinder is very lower.

Figure 4 shows the comparison of the indicated mean effective pressure (IMEP) of gasoline, M10, and M30 with the first 50 cycles. Methanol has a higher Reid vapor pressure and lower boiling temperature than gasoline;[5] therefore, methanol can change the volatilization characteristic of blend fuels and make the premixed mixture prepared better than gasoline. Moreover, methanol has a faster flame propagation speed than gasoline that can accelerate the combustion of blend fuels in the cylinder.[5] IMEP increases with more methanols added into gasoline because of the improvement of combustion during cold start. The IMEP fueled with M30 is nearly 0.15 MPa higher than fueled with gasoline for every cycle.

Figure 5 gives the maximum pressures in the cylinder versus the occurring crank angle of the first 50 cycles, and Figure 6 gives the flame development and fast burning duration of them. It can be seen from the figures that the flame development and fast burning durations are shortened when blend fuels contain more methanol. As a result, the combustion fueled with M30 finishes earliest among three fuels and the maximum pressures in the cylinder are higher than the maximum compression pressures occurring after top dead center (ATDC), ∼20−40° CA. For other fuels, the combustion finishes later than ATDC, 40° CA, and in these cases, only some of the maximum pressures in the cylinder are higher than the maximum compression pressures and more statistical data of the maximum pressures are substituted by the maximum compression pressure occurring around 0° CA.

3.3. Cold-Start Emission Characteristics. Because the engine is in cold state, the stoichiometric mixture is hard to prepare. To start the engine easily, more fuel is injected into the intake manifold accordingly. As a result, a significant part of the spray is spread on the intake port surface and valve backs forming a thin film.[7] Fuel inducted into the cylinder is comprised of vapor and liquid. The liquid droplets strike the cylinder wall and piston crown. During the compression stroke, fuel is carried into the clearance gap around the piston by blow-by, and as the piston rises, surface fuel on the liner will be swept into the piston land and ring grooves.[8,9] All of the above descriptions strongly contribute to the emission of HC during cold starting. There is a general agreement that the main sources of engine-out HC emissions during cold starting and warm up are[10−12]

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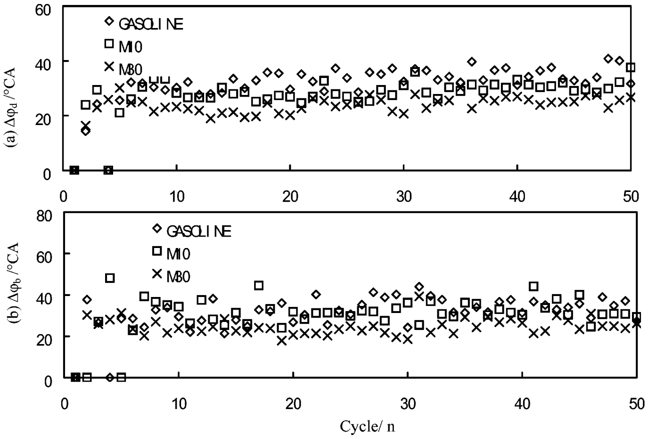

Figure 6. Flame development and fast burning phase of the first 50 cycles during cold start.

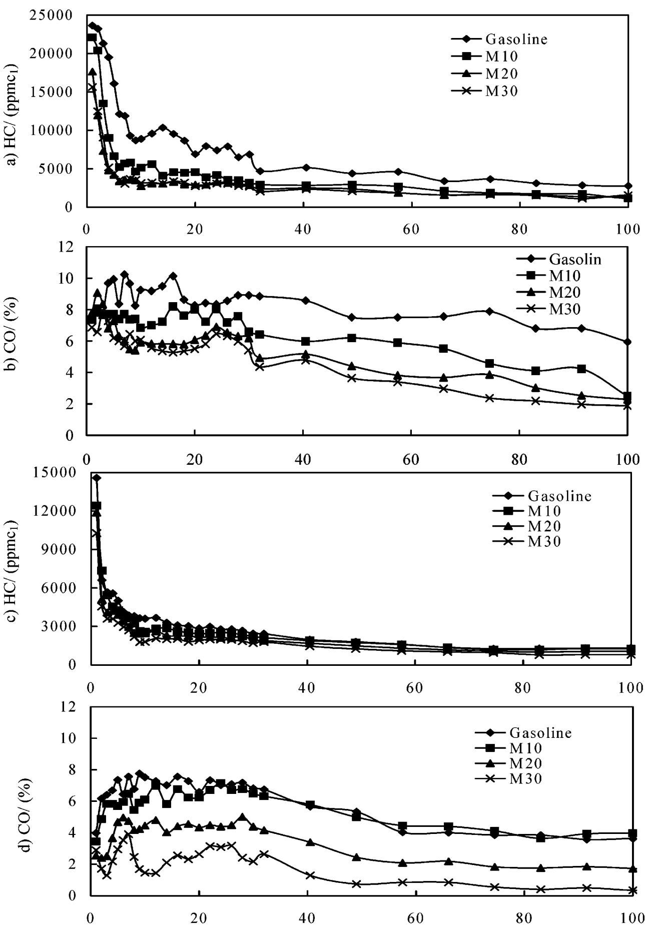

Figure 7. Effect of blend fuels on the concentration of emissions during cold start and warm up (engine is started at 5 °C for a and b and at 15 °C for c and d).

(1) misfiring or partial burning (incomplete flame propagation), (2) wall wetting and quenching, (3) crevice storage of the fuel−air charge and its release, and (4) adsorption and desorption of fuel vapor in the lubricating oil film. Figure 7 shows the measured HC and CO emissions during the initial 100 s. Figure 8 shows the average measured HC and CO emissions during the next 100 s. The engine test conditions are maximum brake torque (MBT) timing before top dead center (BTDC), 7 °CA, for gasoline at the environment temperature of 5 and 15 °C, respectively. The engine was soaked in the room for 10 h before each test. The measurement process is a spontaneous engine

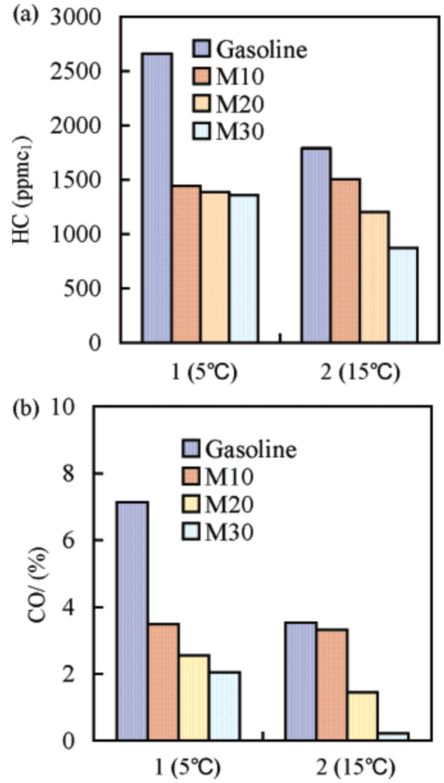

Figure 8. Average HC and CO emissions from 100 to 200 s after cold start.

start process originating from the ECU control MAP. The throttle is nearly closed, and no load is added on the engine.

At 5 °C, the highest HC emission is about 24 000 ppm, after 35 s; HC emission gradually descends to 2800 ppm. When methanol−gasoline fuel blends are used, HC decreases more than 40% and is stabilized around 1500 ppm. However, the percentage of methanol in gasoline seems to have little effect. At 15 °C, except the difference at the beginning few seconds, HC emission characteristics are similar to the 5 °C test. HC emissions fall to 1200 ppm, and the differences among fuels become smaller. During the time from 100 to 200 s, HC emission steps down as shown in Figure 8a.

It is known that CO emissions from internal combustion engines are controlled primarily by the A/F equivalence ratio. As shown in Figures 7 and 8, both temperature and fuel blends have a significant effect on CO emissions. For example, at 5 °C, the CO emission of gasoline cold start is more than 6%, while the CO emission of M30 cold start, at 15 °C, is only 0.5%. The reduction of CO emissions with M30 is approximate to 70% at 5 °C and 90% at 15 °C. This may be due to the higher oxygen contained in blend fuels and better mixing obtained under high temperatures. As shown in Figure 2b, M30 has an almost stoichiometric mixture and it is the leanest.

4. Conclusions

The conclusions from this work can be summarized as follows: (1) There was no evidence of engine malfunction, and the engine is started easily with the test fuels at 5 °C, when the methanol percentage in the methanol−gasoline mixtures was increased. (2) With the increase of the methanol fraction, the flame developing period ($\Delta\varphi_d$) and the fast burning period ($\Delta\varphi_b$) are shortened and the IMEP becomes higher during the first 50 cycles. When the methanol percentage in blend fuels increases to 30%, the combustion is improved. Misfire or partial burning disappears during cold start. (3) With the increase of the methanol percentage in gasoline, the CO emission is reduced remarkably, which is approximate to 70% at 5 °C and 90% at 15 °C, when engine is fueled with M30. The HC emission is reduced to 40% and minimally affected by the methanol percentage at 5 °C. At 15 °C, more HC emission is decreased with the increase of the methanol addition. (4) A higher T_{ex} is achieved with the increase of the methanol percentage in gasoline, which can accelerate the lighting off of the TWC.

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Nomenclature

A/F or AFR = air/fuel ratio

TWC = three-way catalytic converter

ATDC = after top dead center

T_{ex} = exhaust gas temperature

CO = carbon monoxide

UEGO = universal exhaust gas oxygen

ECU = electronic control unit

$\Delta\varphi_d$ = flame developing period

HC = hydrocarbon

$\Delta\varphi_b$ = fast burning period

IMEP or P_{imep} = indicated mean effective pressure

PFI = port fuel injection

P_{max} = maximum in-cylinder pressure

SI = spark ignition

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