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Short communication

Performance comparison of 2-methylfuran and gasoline on a spark-ignition engine with cooled exhaust gas recirculation

Mingzhang Pan, Gequn Shu, Jiaying Pan, Haiqiao Wei *, Dengquan Feng, Yubin Guo, Youcai Liang

State Key Laboratory of Engines, Tianjin University, 92 Weijin Road, Tianjin 300072, China

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ABSTRACT

In the present study, the impact of exhaust gas recirculation (EGR) rates, from 0% to 15%, and compression ratio (CR) of 8, 9, and 10 on the combustion characteristics and emission performance of 2-methylfuran (MF) and gasoline were studied. Experiments were carried out on a Ricardo E6 single-cylinder spark-ignition (SI) research engine, under stoichiometric conditions, MF could produce higher cylinder pressure, knocking intensity, combustion temperature, and nitrogen oxides ($NO_{x)}$ emissions than gasoline at higher CRs. However, an appropriate level of cool EGR improved the combustion and emissions, particularly through knock suppression and reduced NO_x emissions. When the cooled EGR rate reached 15%, the NO_x emissions from the gasoline at a compression ratio of 10 was reduced by about 20.6 g/kW h (>72.5%) compared with 0% EGR. With a low EGR rate, there was only a slight improvement in the indicated thermal efficiency; however, when the EGR reaches 15%, the MF results in 31.2% higher indicated thermal efficiency when compared to gasoline with a CR of 10. This work further advances the knowledge of how to improve the overall performance of MF as an alternative fuel for internal combustion engines.

1. Introduction

Energy security and environmental protection have become two major global concerns in the 21st century. With the increasing scarcity of inexpensive energy sources and environmental pollution from the use of fossil fuels, alternative energy sources have attracted great attention to help achieve economic and environmental sustainability [1]. Compared with carbon-free fuel, biofuels, for example, ethanol in particular, has shown great potential for the supply of renewable energy to reduce the dependence on mineral oil. However, significant research effort has been devoted recently to the production of biofuels from cellulosic biomass as opposed to its production from edible sugars and starches [2,3].

Due to technological breakthroughs in manufacturing, 2-methylfuran (MF) is believed to be one of the strongest biofuel candidates as an alternative to gasoline in the near future [4–6]. As an alternative biofuel, MF presents several attractive features. Firstly, it has an approximately 40% higher energy density than ethanol and it is insoluble in water [7]. Secondly, it has a relatively high octane number compared with gasoline, which indicates better knock resistance. Furthermore, the production of MF only uses one third of the energy need for ethanol fermentation [8]. Such benefits have helped attract attention to MF as a potential gasoline alternative.

Recently, preliminary laboratory research has compared 2-methylfuran and 2,5-dimethylfuran with ethanol as gasoline alternatives by evaluating their characteristics including laminar burning velocity [9–11], spray and evaporation properties [12], combustion and emission characteristics [13,14], and knock resistance [15,16]. Daniel et al. [17] carried out spark timing and load experiments in a direct-injection spark-ignition (DISI) engine fueled with gasoline, ethanol, and DMF. The results indicated that DMF presented comparable combustion efficiency and emissions qualities to gasoline and was able to surpass ethanol in some cases. In another DISI engine experiment by Zhong et al. [13], DMF showed similar combustion properties to gasoline; however, its emissions of nitrogen oxides were relatively high due to its higher combustion temperature. David et al. [16] carried out research on the knocking propensity of different volume concentration blends of 2,5-dimethylfuran–gasoline and ethanol–gasoline. Their work demonstrated that blending small amounts of oxygenates with gasoline can significantly improve auto-ignition resistance due to the mixture's chemical composition and anti-knock properties.

Although these discoveries further support MF as a promising substitute for petroleum-based fuels, more detailed research is needed to further understand about its combustion mechanism and emissions characteristics before it can be used in commercial

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* Corresponding author. Tel./fax: +86 022 27891285.
E-mail address: whq@tju.edu.cn (H. Wei).

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applications. Previous experiments have mainly focused on DISI engines, leaving information on DMF performance in port fuel injection (PFI) engines incomplete [18]. Previous experimental results have shown that the nitrogen oxides (NO_x) emissions from SI engines fueled with DMF were higher than those of gasoline and ethanol; however, little published work has investigated the influence of exhaust gas recirculation (EGR) on the emissions performance. This is especially relevant to NO_x reduction, since EGR is the most important route by which these emissions can be reduced in stoichiometric combustion systems. Moreover, the knock propensity of MF combined with EGR technology requires additional study [19].

Despite the advantages of using the EGR technique related to improved fuel economy, combustion, and emissions performance [20–22], little is known about the behavior of MF combined with EGR in SI engines. To our knowledge, the present study is the first investigation about the impact of externally cooled EGR on the combustion and emissions characteristics of MF using a single-cylinder SI engine with variable compression ratios. The results were compared to those obtained from the use of gasoline.

2. Experimental setup

2.1. Workbench and instruments

All experiments were performed on a modified Ricardo E6 single-cylinder SI research engine. The engine included a PFI system assisted by a MOTEC M400 engine control unit (ECU). Four installation holes at the 2-valve cylinder head could be utilized to install the spark plug, pressure transducer, and transient temperature sensor. The primary parameters of the research engine are shown in Table 1.

The engine was coupled to a DC dynamometer to maintain a constant speed of 1500 rpm (±5 rpm) under full load. The cylinder pressure was measured with a Kistler 6041A pressure transducer, which was flush-mounted in the combustion chamber. Pressure signals were passed from the transducer to a Kistler 5018 charge amplifier and finally recorded by a national instruments data acquisition card, and the pressure trace was used to infer the combustion durations. The maximum cylinder combustion temperature was measured by a fast-response thermocouple. It is an eroding type made by NANMAC corporation, transient temperature sensors with response times of less than 20 μs and the maximum of temperature more than 2580 K. Which was flush-mounted at the sidewall of the cylinder head. Crankshaft position signals were obtained through an optical–electrical encoder with a sampling frequency of 720 Hz. Coolant and oil temperatures were controlled at 75 °C and 85 °C (±5 °C), respectively, using a Proportional Integral Differential controller. All temperatures were measured with K-type thermocouples. Inlet pressure were controlled at 0.1 MPa. All data acquisition and analysis were controlled by the LabVIEW program.

2.2. Emissions measurement and EGR control

A Horiba MEXA-7100DEGR gas tower was utilized to measure the concentrations of gaseous hydrocarbons (HC), carbon monoxide (CO), and NO_x contained in the exhaust. Exhaust samples were pumped from the exhaust pipe via a line heated to 190 °C to the analyzer. The analyzer was calibrated before every engine test.

Table 1
Specifications of the SI research engine.

Items	Description	Items	Description
Engine type	PFI engine	Compressible ratio	Variable
Engine cycle	Four stroke	Engine speed	1500 rpm
Bore × stroke	80 × 100 mm	Ignition timing	Variable
Connecting rod	185 mm	IVO/IVC	−370/−110 CAD
Displacement	0.5 L	EVO/EVC	213/377 CAD

For the cooled external EGR system, an EGR control valve was combined with a heat exchanger and intake supercharger to steer the flow of fresh air and re-circulated exhaust gases. Fig. 1 shows the schematic of the emissions measurement system and EGR control setup. The EGR rate was measured by UEGO sensors in both the exhaust and intake pipes. Oxygen concentration was also measured in both pipes by an ECM 5220 analyzer with an accuracy of 0.5%. For each test cycle, experimental data was measured only after the temperature and flow rate of the EGR had reached a steady state. Herein, the EGR ratio was defined as in Eq. (1) [23,24]:

$$\mathrm{EGR}\% = \frac{x_{O_2,\mathrm{amb}} - x^{\bullet}_{O_2,\mathrm{man}}}{x_{O_2,\mathrm{amb}} - x^{\bullet}_{O_2,\mathrm{exh}}} \tag{1}$$

where $x_{O_2,\mathrm{amb}}$ is the ambient oxygen concentration, $x^{\bullet}_{O_2,\mathrm{man}}$ represents the oxygen concentration in the mixture of fresh intake air and recirculated exhaust gas, and $x^{\bullet}_{O_2,\mathrm{exh}}$ is the oxygen concentration of the exhaust gas in the exhaust pipe.

2.3. Fuel testing procedure

The MF used in this experiment was benchmarked against commercial 97# gasoline. The fuel properties are shown in Table 2.

The impact of the external EGR on the combustion characteristics and emissions performance were researched with a fixed engine speed of 1500 rpm and 100% engine load.

Fuel consumption was determined based on an average value over a period of 60 s using the volumetric air flow rate measured using an air flow meter and oxygen transducers. The M400 ECU could also determine the actual air–fuel ratios (AFRs) based on the oxygen content in both intake and exhaust gases. All tests were performed at a stoichiometric air–fuel ratio with a fixed fuel injection timing of 280 CAD. Experimental data were collected from 200 consecutive cycles with a sampling frequency of 0.2 CAD using the LabVIEW program.

Between fuel tests, the high pressure fuel system was purged using gaseous nitrogen until it became clean. The Lambda Aim Value settings of the MOTEC M400 were also changed constantly to maintain the stoichiometric AFR for each fuel during the tests. Spark timing was set at 24 CA before top dead center (BTDC) in the whole work except spark timing of knock text set at 26 BTDC. Ambient temperature was measured during all tests to ensure the environment was maintained at 20 ± 3 °C.

3. Results and discussion

3.1. Cylinder pressure, heat release, and combustion temperature

Cylinder pressure is the most important indicator in a combustion chamber. Cylinder pressure curves for engine tests using MF and gasoline were collected under EGR rates from 0% to 15% and engine CRs from 8 to 10. The data collected at a CR of 9 are shown in Fig. 2 and are similar to the data at CRs of 8 and 10.

For a given EGR rate, both of the rates of the pressure increase and peak cylinder pressure were higher for the MF than for gasoline. Under test conditions without EGR, the peak cylinder pressure for MF was 3.75 MPa while that for gasoline was only 3.40 MPa, indicating that engines fueled with MF can produce higher cylinder pressures under stoichiometric conditions. Upon introducing and increasing the rate of external EGR, peak cylinder pressure and the rate of pressure increase both decreased rapidly for both fuels. However, the downward trend in the curves was more evident for