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Experimental study of the spray characteristics of USLD, methanol and DME on the swirl nozzle of a Stirling engine

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ABSTRACT

The objective of this paper was to investigate the spray characteristics of methanol and dimethyl ether (DME) on the swirl nozzle of a Stirling engines by comparing with traditional ultralow sulfur diesel fuels (USLD) under different fuel injection rates and different surrounding back pressures in a constant volume pressure vessel. Under the test rig, the macroscopic and microscopic spray characteristics of the fuels were studied by a high speed camera and FAM Laser Particle Size Analyzer during the atomization process. The experimental results show that injection pressure and ambient pressure have a significant impact on the spray tip penetration and spray angles. Higher spray pressure makes the formation period of spray decrease and the penetration rate increase whereas higher back pressure inside the injection chamber leads to the shrinking of the spray angle. The atomization quality of DME under atmospheric back pressure is much better than that of methanol and ULSD while it becomes worse when ambient back pressure is higher than the saturated vapor pressure. Additionally, higher back pressure and a larger injection flow rate are beneficial to the atomization quality of ULSD, whereas those factors seem to have relatively small influence on the droplet size distribution of methanol.
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1. Introduction

To alleviate the pressure of energy shortage and environmental problems caused by fossil fuels, two approaches are generally adopted: one is to enhance the energy utilization efficiency of fossil fuels by improving the operating methods and combustion quality of engines; the other is to look for new alternatives of fossil fuels to reduce pollution. The Stirling engine is an external combustion engine and is famous for its high efficiency (up to 40%), quiet operation, and the ease with which it can use almost any heat sources. Its compatibility with alternative energy sources has become increasingly significant, with the concerns on the shortage of conventional fuels, environmental pollution and climate change due to the consumption of fossil fuels.

The Stirling engine has been used typically in the military field, especially as the power generator of the AIP (air independent propulsion) system. Because of its compatibility with alternative fuels and renewable energy resources, this engine is starting to be used for civilian purposes, especially as the core component of micro combined heat and power (CHP) units, in which it is more efficient and safer than a steam engine. Katsura et al. (2008) [1] developed a 55 kWe Stirling engine CHP system and studied its biomass combustion performance of pulverized wood powder, while Akio [2] studied the fuel properties and emissions characteristics of a Stirling engine operated with wood powder. Ahmad (2011) [3] presented a detailed description of the performance and efficiency of a biogas CHP system utilizing a Stirling engine. Amir et al. (2009) [4] experimentally examined the performance of a residential micro cogeneration system based on a Stirling engine fueled by diesel and biodiesel while, Nicolas et al. (2012) [5] examined the performance of a micro cogeneration system based on a Stirling engine fueled by diesel and ethanol.

Energy and environmental issues caused by fossil fuel combustion have prompted a growing number of researchers to explore the application of alternative fuels. Under this background, this paper experimentally studies the spray characteristics of the Stirling engine using methanol, and dimethyl ether (DME) by comparing them with the traditional fuel of ultra-low sulfur diesel (ULSD). Methanol and DME both have rich resources and can reduce emissions (CO, HC, NOX, and PM) [6–13] during the combustion process, and they are considered as promising alternative fuels. However, the densities of methanol and DME are less than that of low sulfur diesel. At room temperature (20 °C), the kinematic viscosities of methanol and DME are less than one tenth of that of ULSD. The saturation vapor pressure of DME under room temperature is much higher than atmospheric pressure [14]. All those physical properties have a great impact on fuel spray formation, atomization characteristics, combustion and emissions. Because the Stirling engine performs continuous combustion, it is crucial to ensure the power output in a stable range by keeping the stability of heat release during the combustion process. To optimize the

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combustion quality, it is important to improve the atomization quality of the Stirling engine. However, we will not comment on the combustion characteristics of fuels in this paper.

A practical pressure-swirl injector used in Stirling engines is operated here to study the spray characteristics of ULSD, methanol and DME. Very little information is available from literature on the penetration of diesel or biodiesel sprays from pressure-swirl injectors [15]. Wang et al. (1987) [16] only measured the mean drop size of diesel in pressure-swirl nozzles for different flow numbers and injection pressures. Wang et al. (2005) [17] measured the spray penetrations and cone angles of pressure-swirl injectors fueled with methanol and ethanol. Most investigations on spray characteristics of DME were conducted on a common-rail injection system with the injection pressure higher than 40 MPa [11,18,19]. Little information is about the flash-boiling sprays of volatile fuels (e.g. DME) actuated from the pressure-swirl injector with lower injection pressure (<10 MPa). Only the spray penetrations and cone angles of liquefied petroleum gas (LPG) at different back pressures were analyzed by Mesman et al. (2009) [20].

Above all, in this study, the macroscopic and microscopic spray characteristics of ultra low sulfur diesel (USLD), methanol and DME conducted on a pressure-swirl injector of a Stirling engine were investigated. The test rig is mainly composed of a constant-volume pressure vessel with a wide field of view, an oil supply system regulated by a high pressure cylinder, a high-speed video camera, a FAM laser particle size analyzer, image-processing software and a data acquisition system. The macroscopic spray characteristics including spray penetration, spray cone angle and spray tip penetration rate of three different fuels were measured by a high speed camera and analyzed based on their physico-chemical properties. The microscopic spray characteristics, such as droplet size distributions, were measured and analyzed by using a laser particle size analyzer.

2. Spray test system

2.1. Spray visualization experimental test rig

The schematic diagram of the Stirling engine spray test rig is shown in Fig. 1. The test rig is mainly composed of the constant-volume pressure vessel (Fig. 2) and the fuel injection system. The pressure vessel is made of stainless steel with the wall thickness of 60 mm to simulate the high-pressure condition inside the engine combustion chamber. It consists of three 100×150 mm transparent observation windows made of quartz and the designed maximum working pressure is 3.2 MPa. The injector is installed on the top of this vessel and a pressure sensor is installed on its top to monitor the pressure inside the vessel to monitor the real-time pressure of the container. The bottom of the pressure vessel is lined with barbed wire and a sponge to absorb fuel droplets within the vessel to prevent air flow from disturbing the spray formation.

Fig. 2. The high-pressure spray visualization chamber.

In the fuel injection system, a 40 L high pressure nitrogen cylinder is connected to provide constant injection pressure functioning in a similar way to the high-pressure injection system in internal combustion engines. A 10 L capacity nitrogen gas cylinder with a permitted pressure of 20 MPa is adopted as an oil tank, which is equipped with a pressure gauge and a pressure relief valve to display and control the gas pressure inside the tank. In practice, a 10 L nitrogen gas cylinder is connected to the high pressure nitrogen vessel as a pressure stabilizer to alleviate the

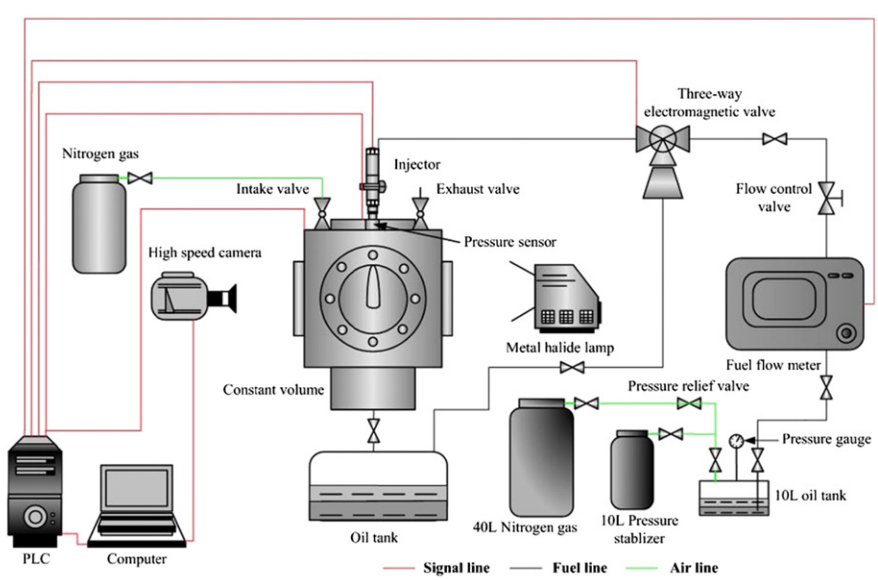

Fig. 1. Schematic diagram of the experimental setup.

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