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Effect of hydrogen addition on the combustion and emission of a diesel free-piston engine

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ABSTRACT

The free-piston engine (FPE) is a new crankless engine, which operates with variable compression ratio, flexible fuel applicability and low pollution potential. A numerical model which couples with dynamic, combustion and gas exchange was established and verified by experiment to simulate the effects of different hydrogen addition on the combustion and emission of a diesel FPE. Results indicate that a small amount of hydrogen addition has a little effect on the combustion process of the FPE. However, when the ratio of hydrogen addition (R_{H2}) is more than 0.1, the R_{H2} gives a positive effect on the peak in-cylinder gas pressure, temperature, and nitric oxide emission of the FPE, while soot emission decreases with the increase of hydrogen addition. Moreover, the larger R_{H2} induces a longer ignition delay, shorter rapid combustion period, weaker post-combustion effect, greater heat release rate, and earlier peak heat release rate for the FPE. Nevertheless, the released heat in rapid combustion period is significantly enhanced by the increase of R_{H2}.

Introduction

In the context of severe energy shortage and serious environmental pollution, the conventional engine with low efficiency and high emission has been unable to meet the strong demand of energy saving and emission reduction [1,2]. The free-piston engine (FPE) comes into being under this background [3]. The new engine abandons the crank connecting rod mechanism of conventional engines, thus reducing the friction loss, improving the thermal efficiency, and moving with a variable compression ratio, which provides flexible fuel applicability and possibility of new clean combustion modes [4–6]. These potential advantages of FPE bring broad application fields. It can be used not only as a driving system for hybrid electric vehicles or electric vehicles, but also as an auxiliary power for electromechanical device.

In recent years, the FPE has attracted considerable research interests, and a great deal of research work has been done by scholars and research institutions around the world. Kosaka et al. made a significant contribution to the development of a single-piston FPE [7–9], including the fundamental characteristics of the FPE, the control system for generator and the control method of linear generator to improve the efficiency and stability. Roskilly [10] mainly used a computational fluid dynamics model to investigate the gas motion, combustion process and the formation mechanism of nitrogen oxides of a diesel FPE. They found that the FPE produces a stronger radial

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flow near the top dead center (TDC) than a conventional engine, but it has little effect on the combustion process. Lim et al. [11] studied the effects of key parameters such as equivalent ratio, ignition time and spring stiffness on the operation characteristics and performance of a spark-ignition FPE by means of numerical simulation. The results showed that reducing the ignition advance angle or increasing the spring stiffness can significantly improve the dynamic of piston, electric power output and the engine performance. Kim et al. [12] mainly studied the influence of air flow rate and alternator load on the operation characteristics of a liquefied petroleum gas FPE. Their results showed that piston dynamics are the main factors affecting indicated mean effective pressure (IMEP) when the conductance changes. They also found that the motion stroke and frequency are negatively related to the air flow rate, but the IMEP and electric output increase as the air flow rate increases. Yuan et al. [13] studied the combustion characteristics of a two-stroke FPE by a coupling simulation. They analyzed the influence of special piston motion on the combustion process of the FPE and compared the simulation results with a conventional engine. The results showed that the FPE has a faster piston motion and longer combustion duration than those of the conventional engine. Meanwhile, they found that the maximum in-cylinder pressure and temperature of FPE are lower than those of the conventional engine.

The emission characteristics of FPE have been studied, some researches indicated that the FPE has the advantages of variable compression ratio, wide adaptability of fuel, and less nitric oxide (NO) emission, but some deficiencies were also found, such as high soot emission [14]. As is known to all, hydrogen fuel has the advantages of low ignition energy, fast flame propagation speed, large lean operation limit, and low hydrocarbon (HC) and carbon monoxide (CO) emissions, which is considered as an ideal alternative fuel for internal combustion engines [15,16]. There are many studies on hydrogen engines at present. Park et al. [17] investigated the effects of lean fuel and exhaust gas recirculation (EGR) on the combustion and emission performance of a heavy-duty engine with natural gas-hydrogen dual fuels. The results showed that the engine can reduce the emission and improve the efficiency by expanding the lean operation limit. Du et al. [18] studied the effect of addition of hydrogen and exhaust gas recirculation on combustion characteristics of a gasoline engine. The results found that with increase of hydrogen addition, the NO emission increases. Barrios et al. [19] experimentally studied the influence of hydrogen addition on combustion characteristics and particle number size distribution emissions of a diesel engine. Through the research they indicated that with hydrogen injection, the number of nucleation mode particles decreases in direct proportion to the total particle number, and the carbon dioxide (CO_2) emissions decrease when hydrogen is injected. Jhang et al. [20] investigated experimentally the effect of hydrogen addition on the emissions of a heavy-duty diesel engine under constant speed from the low to high engine load. Their experimental results showed that the brake thermal efficiency increases with an increasing amount of hydrogen, and the hydrogen addition can reduce the emissions of CO_2 and CO. At the high operation load, the reduction in emissions was the most significant.

From the above researches, it is known that adding hydrogen fuel to natural gas engines or diesel engines can improve the thermal efficiency and economy, meanwhile reduce some harmful emissions. While the FPE is a special power engine, which abandons the conventional crank-connecting rod mechanism, making the law of piston movement is different from that of the conventional engine. Some researches indicated that the FPE has higher movement speed and acceleration in late compression stroke, which brings about different ignition, fuel spray, evaporation, air-fuel mixing, heat transfer, and combustion characteristics for the FPE, compared with conventional engines [21–24]. So adding some hydrogen to the diesel FPE may have a particular effect on combustion process and emission characteristics due to the special piston motion law and variable compression ratio. However, there are few researches on hydrogen addition of the FPE. In this study, some hydrogen fuel is added to a diesel FPE, and the influence of different hydrogen addition ratios on the combustion and emission characteristics of the FPE was investigated and revealed.

Fundamental and method

FPE prototype

The FPE prototype presented for this study is shown in Fig. 1, which adopts a dual piston opposed structure. The FPE is composed of two free piston combustion cylinders arranged horizontally, with a linear generator arranged in the middle, and the piston rod assembly is coaxially connected with the mover of the linear generator. The engine uses a two-stroke, compression ignition work cycle. The gas exchange of the FPE is regulated by a looping scavenging way. The diesel fuel is injected directly into the cylinder at the appropriate time, and the hydrogen fuel is premixed with air. In starting process, the linear generator is used as an electric motor to initialize the engine. After starting, the motor is immediately converted into a generator. The converted electric energy can be stored or utilized directly. The main parameters of this FPE are listed in Table 1, and more information can be seen in elsewhere [22,24,25].

Simulation method

Unlike conventional engines, the FPE abandons the crank-link mechanism, so the piston is “free”. Although the piston

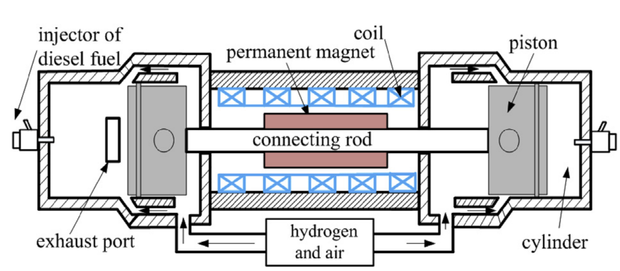

Fig. 1 – The basic structure of the FPE.

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