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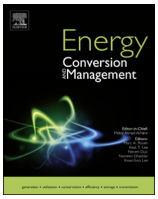

Numerical study of hydrogen direct injection strategy on mixture formation and combustion process in a partially premixed gasoline Wankel rotary engine

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ABSTRACT

In Wankel rotary engine (WRE), high mainstream velocity in combustion chamber blocks flame propagating to the end of combustion chamber, which causes high emissions and low combustion efficiency due to unburned mixtures. To solve this problem, a three-dimensional dynamic simulation model of a hydrogen-gasoline blends fueled WRE is built and validated. The in-cylinder mixture formation and combustion process are investigated under different hydrogen injection timing (HIT) and duration (HID) conditions. The study results show that the concentration of hydrogen distributed between the spark plug region and rear combustion chamber increases with retarded HIT and extended HID. Faster flame speeds are obtained for HIT of 110 °CA BTDC and HID of 40 °CA. At a fixed HID of 20 °CA, compared with HITs of 210 and 160 °CA BTDC, the peak in-cylinder pressures for HIT of 110 °CA BTDC are increased by 14.3% and 6.8%, respectively. At a fixed HIT of 110 °CA BTDC, the peak in-cylinder pressure in HID of 40 °CA is 52.3% and 9.21% higher than HIDs of 20 and 30 °CA. The highest in-cylinder pressure is achieved with the hydrogen injection strategy that HIT of 110 °CA BTDC, HID of 40 °CA. However, as the temperature increases with pressure, nitrogen oxide emissions are also increased with retarded HIT and extended HID obviously. Considering the lowest carbon monoxide is achieved and the unburned zone in the rear region of combustion chamber is eliminated in HIT of 110 °CA BTDC, HID of 40 °CA. The hydrogen direct injection strategy that HIT of 110 °CA BTDC, HID of 40 °CA acquires the best engine performance in this research.

1. Introduction

Compared with reciprocating engine, the operation mode of rotating piston makes the Wankel rotary engine (WRE) obtain higher running speed and better motion stability, which could effectively improve the engine output power and reduce noise [1,2]. Meanwhile, the simple structure of WRE also significantly reduces the engine total mass and volume, so that the power to weight ratio is higher than that of the traditional reciprocating engine [3]. Therefore, the WRE is more suitable for application in mobile electricity generator, plug-in hybrid vehicle and small aircraft [4,5]. However, as the high surface to volume ratio increases the quenching effect and the flattened combustion chamber impedes the fast and complete combustion of fuel-air mixtures, the WRE always suffers the high emissions, poor fuel economy and low thermal efficiency [6,7]. Especially when the WRE is fueled with gasoline. Although gasoline is one of the most widely applied fuels in spark-ignition engine due to the ability and safety of fuel transport, the long quenching distance aggravates the emissions. Meanwhile, the relatively low flame speed of gasoline makes it hard for flame spread to the rear region of combustion chamber before the exhaust valve open [8,9]. As a result, when the WRE is fueled with gasoline, the fuel economy and emissions characteristics are further deteriorated [10]. Consequently, improving WRE performance has attracted many attentions from engineers and scholars [11,12].

Several technologies have been used in WRE, such as turbo system [13], double spark plug ignition system [14], heat pipe assisted cooling system [15], etc., which could effectively enhance the combustion process and increase the thermal efficiency. Besides, hydrogen enrichment is another feasible way to promote the engine performance [16,17] due to the shortest quenching distance, the lowest ignition energy and the highest flame speed of hydrogen. Sun et al. [18,19] experimentally studied the flame propagation characteristic of

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hydrogen in a spherical closed vessel. The peak value of hydrogen unstretched laminar flame speed is near 300 cm/s under normal temperature and pressure conditions, which is almost 10 times to that of gasoline. In turbulent ambience, turbulence further accelerates the propagation velocity of combustion wave, which also reduces heat loss [20]. They also conducted a series of experiments to investigate turbulent explosion characteristics of syngas with different hydrogen volume fractions [21,22]. The test results indicate that increasing hydrogen volume fraction could raise the maximum pressure and the maximum rate of pressure rise, and increasing turbulent intensity could obtain similar results. Huang et al. [23,24] investigated the influences of hydrogen enrichment on the flame propagation characteristics of natural gas in a constant volume vessel. The test results show that hydrogen enrichment increases the flame speed of fuel-air mixtures by improving the activity of chemical reaction for the raised concentration of O, H and OH radicals. Meanwhile, they also studied the effects of hydrogen addition on the combustion and emissions performances in a natural gas engine [25–27]. Results show that hydrogen addition decreases the engine cycle-by-cycle variations, shortens the total combustion duration and reduces carbon emissions. Besides, advancement of ignition timing also promote combustion performance for hydrogen addition due to the increase of flame speed [28–31]. Therefore, the hydrogen enrichment is a promising approach to improve the combustion and emissions performance of WRE [32,33]. Amrouche et al. [34–37] experimentally investigated the performance of hydrogen-enriched ethanol and gasoline rotary engine at ultra lean and full load conditions. Their researches show that the accelerated combustion speed after hydrogen enrichment shortens the flame development and propagation periods, which contributes to increase thermal efficiency and reduce post combustion. After hydrogen enrichment, the lean operation limit is extended and the engine stability is improved under ultra lean conditions. Thus, the hydrogen-enriched rotary engine obtains a better fuel economy. Meanwhile, hydrogen enrichment also decreases the hydrocarbon and carbon monoxide emissions effectively. Although the nitrogen oxide emissions increases with hydrogen addition, these could be controlled by lean combustion strategies. Therefore, the hydrogen-enriched rotary engine achieves a better emissions performance. The similar conclusions were also acquired in the researches of Pan et al. [38] and Ji et al. [39,40]. In the computational fluid dynamics (CFD) investigations of Pan et al., hydrogen enrichment increases the peak pressure of natural gas fueled rotary engine by 29%. In the experimentally studies of Ji et al., A higher brake mean effective pressure and thermal efficiency are obtained in the gasoline rotary engine after hydrogen enrichment. During the process of hydrogen volume fractions rise from 0% to 5.2%, hydrocarbon emissions are reduced by 44.8%. Consequently, hydrogen enrichment is confirmed to be a feasible way to improve the WRE performance. However, the hydrogen supply method in the above mentioned researches is port injection enrichment, which reduces the engine volumetric and combustion efficiencies due to the decreased intake air volume [41,42]. Besides, the fuel-air mixtures in the rear region of combustion chamber fail to be burnt due to high bulk flow velocity could hardly be solved by homogeneous hydrogen enrichment [43].

As the hydrogen direct injection enrichment does not occupy the volume of air in the intake port, nevertheless, could increase the combustion rate by controlling the in-cylinder fuel distribution, the shortcoming of engine with hydrogen port injection enrichment could be overcome [44–46]. Meanwhile, the engine performance are also affected by the hydrogen injection strategies significantly. Huang et al. [47–50] investigated the combustion characteristics of a natural gas-hydrogen blended fuel direct-injection engine under different fuel-injection timing conditions. With advanced fuel-injection timing, brake thermal efficiency shows an increasing and then decreasing trend, and the maximum value is obtained at injection timing of 270 °CA BTDC. Yu et al. [51] studied the influences of hydrogen direct injection strategies on the hydrogen-enriched gasoline engine performance. The test results indicate that when the hydrogen is injected during the compression stroke, a stratification mixture is formed around the spark plug region, which benefits the formation of stable flame kernel. Fan et al. [52,53] numerically investigated the effects of hydrogen direct injection strategies on the mixtures formation and combustion process in a hydrogen direct injection plus natural gas port injecting rotary engine. At a fixed hydrogen injection duration (HID) of 24 °CA, with retarded hydrogen injection timing (HIT), the stratification phenomenon of hydrogen becomes obvious increasingly. At a fixed HIT of 210 °CA BTDC, with the extension in HID, the accumulation area of hydrogen reduces significantly. The fastest combustion speed is acquired with the hydrogen injection strategy which have a HIT of 210 °CA BTDC and HID of 40 °CA. Compared with the case which had a HIT of 390 °CA BTDC and HID of 24 °CA, the combustion rate increases by 11.7%.

In conclusion, the hydrogen injection strategy is a key factor affecting the performance of engine with hydrogen direct injection enrichment. The HIT and HID could not only influence the hydrogen distribution and fuel-air mixtures formation by affecting the in-cylinder flow field, but also affect the mixtures composition and combustion characteristics. Therefore, a CFD model is built to study the mixture formation and combustion process in a gasoline WRE with hydrogen direct injection enrichment under different HITs and HIDs.

2. The CFD analysis

2.1. Geometric model generation

The engine adopted in this study is Z160F WRE, which is a side-ported and gasoline-fueled rotary engine. The specifications of the tested engine are listed in Table 1. Based on this WRE, the geometric model is built with CATIA software. To investigate the influences of hydrogen direct injection strategies on mixture formation and combustion process in the hydrogen-enriched gasoline WRE using HDI, a hydrogen nozzle is set on the position located at the intersection between the major axis of the WRE and cylinder form line. The position of hydrogen nozzle and the schematic diagram of WRE are shown in Fig. 1. The radius of the hydrogen injection nozzle is 1.5 mm. The three dimensional dynamic simulation model is established with CONVERGE software. The simulation starts from the exhaust valve closing timing to the exhaust valve opening timing without considering the valve overlap process and the residual gases.

2.2. Boundary and initial conditions

The simulations are performed under the intake port pressure (MAP) and engine speed of 35 kPa and 4500 rpm, respectively. The volume fraction of hydrogen in the hydrogen-air mixtures is defined as hydrogen additional volume fraction (α_{H2}), which is fixed at 3%. In the present study, the global Φ of gasoline-air-hydrogen is constant at 0.8. To ensure the value of global Φ is invariable, the gasoline-air mixtures are set as homogeneous and Φ is set as 0.75 in the intake port. A fixed spark timing of 25 °CA BTDC for all computations. In order to investigate the combined influences of HIT and HID on the WRE

Table 1
Specifications of testing WRE.

Specifications	Value
Generating radius/mm	69
Width of rotor/mm	40
Displacement/L	0.16
Compression ratio	8.0
Eccentricity/mm	11
Power output	3.8 kW/4000 rpm
Intake timing/(°CA)	75 ATDC, 61 ABDC
Exhaust timing/(°CA)	62 BBDC, 70 ATDC