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Numerical investigation of the effects of hydrogen enrichment on combustion and emissions formation processes in a gasoline rotary engine

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A B S T R A C T

The study aims to numerically investigate the combustion and emissions formation processes in a spark-ignition rotary engine fueled with hydrogen-gasoline blends. The Renormalization Group k-ε turbulence coupled with a skeletal primary reference fuel mechanism were adopted to simulate the engine working process under 0%, 2% and 4% hydrogen volume fractions in CONVERGE software. The flow field variation and detailed combustion processes were analyzed and discussed. Results showed that a mainstream flow field along with the rotor movement was formed during the compression stroke and sustained in the combustion chamber until the exhaust valve opening. The center of the burned zone would move in same direction with the mainstream flow. Meanwhile, due to the effect of the mainstream flow, the flame propagation in direction of the mainstream flow was expedited. While the flame propagation in contrary direction was retarded, consequently, the unburned mixtures at rear region of combustion chamber suffered incomplete combustion. The distributions of nitric oxide and carbon monoxide emissions were also dominantly affected by the flow field in the combustion chamber. After hydrogen addition, the increased OH, H and O radicals concentrations combined with the intense flow flied accelerated the combustion process, which resulted in the improvement and advancement of in-cylinder pressure and temperature. Compared with original gasoline case, the peak in-cylinder pressure was increased by 9.1% and 13.7% with 2% and 4% hydrogen blends, respectively. With hydrogen enrichment, the increased in-cylinder temperature promoted the formation of nitric oxide emission. Besides, Carbon monoxide emission was decreased with the increase of hydrogen addition fraction.

1. Introduction

Rotary engine is a potential alternative to the reciprocating engine and it is more suitable for hybrid electric vehicle as the power equipment of range extender [1,2]. Compared with the conventional reciprocating engine, the rotary engine has many advantages, such as high power to weight ratio from the high operating speed, compact and simple design due to the less moving parts, less vibration and noise resulting from non-reciprocating components, etc. [3]. For these reasons, the rotary engine is a promising energy system for mobile applications. The disadvantages of rotary engine, however, cannot be ignored. Generally, it includes high HC and CO emissions, poor fuel economy and low thermal efficiency [4]. These problems are basically caused by the following reasons: Firstly, fast and complete combustion of fuel/air mixtures is impeded by the flattened combustion chamber of rotary engine. Secondly, quenching effect is increased due to the high surface to volume ratio. Last but not the least, leakage problem is severe because of the linear sealing method. Therefore, a number of research interests are focusing on improving the fuel economy and emissions performance of the rotary engine. In the last three decades, several researchers have engaged in reducing the fuel consumption and exhaust emissions of the rotary engine [5–8]. Rose et al. [9] proposed a new design method of rotary engine base on the apex seal profile, which could improve sealing capability. Tashima et al. [10] developed a sequential twin turbo system for rotary engine to achieve a higher power output performance. Kagawa et al. [11] applied a direct-injection stratified-charge system (DISC) to a rotary engine. The application of the DISC improved the fuel economy, reduced exhaust emissions and increased thermal efficiency. Wu et al. [12] proposed a heat pipe assisted cooling system for rotary engine, which could eliminate the hot spots and reduce the temperature gradients on the wall of combustion chamber. Therefore, the temperature uniformity and durability of the rotary engine were improved. Shkolnik et al. [13] also developed a small rotary combustion engine with special construction, which could

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acquire 33% brake thermal efficiency for the compression ignition and 11% for the spark ignition rotary engine, respectively. Besides these researches in mechanical improvements, studies on fuel properties afford another method to enhance the rotary engine performance. Fuel property is a key factor for fuel economy and emissions performance [14,15]. Gasoline is one of the most widely used fuel in spark-ignition engines including the rotary engine. However, the flattened combustion chamber and the high operating speed make gasoline difficult to vaporize and form homogeneous gaseous mixtures. Meanwhile, the long quenching distance and low flame speed of gasoline are adverse for the fast and complete burning in the long and narrow combustion chamber. As a result, the fuel economy and emissions performance of the rotary engine fueled with gasoline are further deteriorated. Generally, a fuel with high flame speed, short quenching distance and high evaporability is more suitable for the rotary engine.

Comparatively, since it has a high flame speed, short quenching distance, high diffusive speed and wide flammability, etc., hydrogen can be seen as a promising green alternative fuel for internal combustion engines [16–19]. Huang et al. [20–23] investigated the effect of hydrogen enrichment on the combustion performance of nature gas in fundamental combustion devices and spark ignition engines. Their studies showed that hydrogen enrichment promoted the formations of O, H and OH radicals, which helped increasing the flame speed, improve the stability of flame structure and enhance the complete combustion of hydrocarbon fuels. Consequently, the hydrogen enrichment is a potential approach to overcome drawbacks in rotary engine by improving homogeneity and burning velocity of fuel-air mixtures. Amrouche et al. [24,25] experimentally studied the performance of a hydrogen-enriched ethanol rotary engine at ultra-lean and full load conditions. The test results showed that hydrogen enrichment shortened the flame development and propagation periods, which contributed to concentrate heat release and reduce post combustion. Thus, hydrogen enrichment could improve the combustion process and increase thermal efficiency of the ethanol rotary engine. Meanwhile, hydrogen enrichment also extended the lean operation limit and enhanced the engine stability under ultra-lean conditions. These helped the engine gain better fuel economy and emissions performance. Ji et al. [26–29] investigated the effect of hydrogen enrichment on the combustion and emissions characteristics of a gasoline rotary engine at idle and part load conditions. The test results indicated that the brake mean effective pressure, in-cylinder temperature and thermal efficiency were increased after the hydrogen enrichment. When the hydrogen volume fraction was raised from 0% to 5.2%, hydrocarbon emissions were decreased by 44.8%. Amrouche et al. [30,31] also conducted a series of researches to study the combustion and emissions characteristics of a hydrogen-enriched gasoline rotary engine at high speed and wide open throttle conditions. Their investigations confirmed that hydrogen enrichment could improve the power output, decrease the hydrocarbon and carbon monoxide emissions. Nevertheless, the nitrogen oxide emissions were increased with the increase of hydrogen fraction, which could be potentially controlled by using lean combustion operation. Thus, hydrogen enrichment is demonstrated to be a feasible way to improve the rotary engine performance. However, due to limitations of the experimental testing measures, it is hard to insight details of the flow field, flame development and propagation processes, emissions forming processes and distributions in combustion chamber by experiment.

With the great improvement of computing technologies, the CFD models have been widely used not only in understanding the relationship between turbulent flow and combustion process, but also in investigating the multi-fuel engine performances. Huang et al. [32,33] based on the presumed Probability Density Function look-up tables studied the dual-fuel spray combustion process in an ethanol direct injection plus gasoline port injection (EDI + GPI) reciprocating engine. The results indicate that the application of EDI + GPI can increase the power output and thermal efficiency. Ji et al. [34] applied the extended coherent flame model (ECFM) and a self-developed laminar flame speed correlation to capture the combustion process in a reciprocating engine fueled with hydrogen-gasoline blends. The results illustrated that the hydrogen enrichment increasing the flame propagation speed and enhancing the degree of flame wrinkling. Knop et al. [35] modified the ECFM combustion model and the extended Zeldovitch model to investigate the combustion and NO formation processes in the hydrogen-fueled reciprocating engines. The calculation results demonstrate that the charge homogeneity was a key parameter to control the flame propagation and NO formation. Fan et al. [36] established a three-dimensional dynamic simulation model for a rotary engine using a multi-dimensional software. Based on Reynolds-Averaged Navier-Stoke (RANS) turbulence model, the developed model was used to investigate the flow field, volume coefficient and average turbulent kinetic energy of the rotary engine under different engine speeds, manifolds absolute pressures (MAP) and intake angles. in addition, based on the eddy-dissipation concept model, they [37–40] also systematically studied the influence of pocket shapes, injection strategies, ignition positions and timings on mixture formation, combustion process and emissions characteristics of a natural-gas-fueled rotary engine with and without hydrogen addition. According to their computed results, the optimal pocket shape, injection and ignition strategies were obtained. Besides, they also found that the peak pressure of natural-gas-fueled rotary engine could be increased by 29% with hydrogen enrichment.

These numerical studies are very helpful for understanding the intrinsic characteristics of rotary engine, however, few of them coupled reasonable turbulent model with chemical reaction mechanism to explore the flow filed, combustion process and emissions distribution of the hydrogen-enriched gasoline rotary engine. The adoption of chemical mechanisms could accurately perform the in-cylinder reactions and flame structures [41,42]. Current investigation established a three-dimensional dynamic simulation model for the hydrogen-enriched gasoline rotary engine. Models for the dynamic grid, turbulence and combustion were built using the computational fluid dynamics code CONVERGE. The model accuracy was validated with the experimental results under different hydrogen enrichment levels. The turbulent combustion process and emissions distribution characteristics of the hydrogen-enriched gasoline rotary engine were explored and discussed.

2. Mathematical model establishment and validation

2.1. Computational mesh and boundary conditions

The three-dimensional dynamic simulation model was built based on a side-ported and gasoline-fueled Z160F rotary engine. The schematic diagram and specifications of testing engine are shown in Fig. 1 and Table 1, respectively. The grid independence study was conduct by

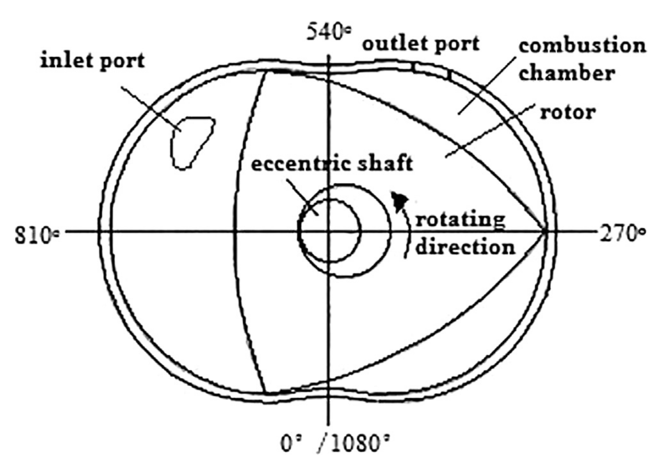

Fig. 1. Schematic of the tested rotary engine.