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Investigation on performance of a hydrogen-gasoline rotary engine at part load and lean conditions

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HIGHLIGHTS

- This paper studied lean burn performance of a H_2-blended gasoline rotary engine.
- The p_{max}, Bmep, T_{max} and η_b increased after the H_2 blending.
- Both the CA0-10 and CA10-90 were shortened by the H_2 addition.
- The cooling loss and cyclic variation were reduced due to the H_2 enrichment.
- H_2 addition resulted in the reduced HC and CO emissions.

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ABSTRACT

Lean combustion is a promising method for getting ameliorate engine performance. However, due to the small flammability of gasoline and elongated combustion chamber of rotary engine, gasoline rotary engine tends to encounter partial burning and even misfire when mixtures are dilute. Hydrogen (H_2) occupies many advantages that may remit the aforementioned problems. For this motivation, a rotary engine installed gasoline-H_2 port-injection system was developed to explore the performance of rotary engine fueled with H_2-gasoline blends at part load and lean conditions. A speed of 4500 rpm, a manifold absolute pressure (MAP) of 35 kPa and a spark advance of 25 °CA were adopted for this research. Hydrogen volume fraction (α_{H2}) was kept at 0, 3% and 6%, respectively. Excess air ratio (λ) was gradually enlarged from 1.00 with a step of 0.05. For a given λ, when α_{H2} was increased, the results were showed subsequently. Peak chamber pressure was increased and its corresponding crank angle was advanced. Brake mean effective pressure, peak combustion temperature and brake thermal efficiency were simultaneously increased. Flame development and propagation periods, cooling loss and cyclic variation were reduced. HC and CO emissions were lessened whereas NOx emissions were heightened due to the raised combustion temperature.

1. Introduction

Possessing preponderant merits of superb power-to-weight ratio, more compact and smooth [1], rotary engine (RE) is promising to be applied in both civil [2] and military fields [3,4]. Besides, some automobile manufacturers [5], for example, Mazda, have developed RE for their commercial vehicles [6]. Moreover, with the global trend to achieve energy conservation [7] and emission reduction [8], today, the new target of almost all of automobile manufacturers is to develop more efficient and less polluting vehicles [9,10]. This situation helps raise the focus on emerging clean technologies such as fuel cell and electrical vehicles. However, compared to conventional vehicles equipped with engines, pure electric vehicles such as the battery electric vehicle suffer a significantly limited range because of the storage system [7,8]. Employing range extender is an expedient means to extend the electric vehicles range [11]. Since modern vehicles are generally compact and comfortable, the extender should be light, simple and high power-density. Because of the higher power density than the same power reciprocating engine, RE has been applied in hybrid vehicles power plant or prospectively as a range extender for pure electric vehicles [11]. Specifically, through previous studies, RE has given promising results while being used as a range extender by Ribaut et al. [12] and Varnhagen et al. [13] However, RE may suffer high fuel consumption and emissions [14]. In particular, HC and CO emissions are excessively high

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[15], due to quenching effect resulting from elongated and irregular combustion chamber shape of RE [16]. These hinder the expanded practical application of RE. Thus, reducing fuel consumption and emissions of RE is urgent for its extensive employment. Improving combustion process is a possible solution to surmount the shortcomings in fuel consumption and emissions, and certainly enhance the engine overall performance [17]. Lean combustion has been deemed to a feasible technology to remit fuel consumption and emissions of spark-ignited (SI) engines [17]. Specifically, a properly lean mixture combustion in a SI engine is one method to reduce NOx emissions and increase engine efficiency by decreasing the peak combustion temperature [18]. Unfortunately, the narrow flame range of gasoline may make gasoline engines suffer partial burning, severe combustion variation or misfire during lean-burn conditions [18], especially at high lean conditions. What's worse, when gasoline is combusted in RE at lean conditions, engine performance may deteriorate due to the irregular combustion chamber and high operating-speed of RE [14,15]. Therefore, physicochemical and combustion characteristics of gasoline need to be improved to help RE gain an ameliorative overall performance at lean conditions.

Since H_2 gains a wide flammability [19], high diffusive and flame propagation velocities [20], and small quenching distance [21], H_2 supplying could be feasible to help engines achieve better performance [22–25], especially at lean conditions [26]. Knowing from existing studies, H_2 could be employed as a promising substitute for traditional fossil fuels [27]. High diffusive speed of H_2 [28] could improve mixture homogeneity [29] and therefore enhance combustion completeness [30]. Besides, low ignition energy of H_2 helps mixtures to be easily ignited [31,32]. Due to high flame speed of H_2, H_2-supplied mixture burning velocity could be increased, which produces a dropped cooling loss and improved thermal efficiency [33]. As H_2 has an ultra-flame limit, H_2 addition could extend the relative excess air ratio of original mixtures at lean operation. However, high adiabatic-flame temperature of H_2 generally heightens the in-cylinder temperature of H_2-blended engines [34,35]. Thus, H_2 engines unexpectedly expel high NOx emissions [36]. Since H_2 is very light, volumetric energy density of H_2 is much lower than that of gasoline. This could lead to the decrescent power output of H_2 engines in comparison to gasoline engines. Moreover, combustion of pure H_2 could also be limited by difficulties in production, storage, and end-use [36].

Compared with pure H_2, adding a certain amount of H_2 into conventional fuel is considered to be another promising way for reducing the drawbacks of burning pure H_2 or pure gasoline and improving engine performance [36], especially at lean conditions [26]. Many researches about H_2 addition applied to conventional engines have been accomplished. Huang et al. [37–40] investigated the impact in combustion when H_2 was added into basic fuel. The consequences tell that combustion of LPG was improved after H_2 addition. Besides, natural gas SI engine performance was enhanced when H_2 was supplied into cylinder. Ji and Wang [30] performed a test focusing on lean performance of a H_2-gasoline engine. This investigation showed that engine performance was enhanced after H_2 addition. All in all, H_2 addition is effective on improving gasoline engines performance at lean conditions.

Except for utility of H_2 on conventional engines, publications also demonstrated that H_2 could serve as a substitute to fuel RE [41–43]. Since H_2 has a higher flame velocity than gasoline, H_2 rotary engine (HRE) could achieve better combustion and eased emissions in comparison to gasoline rotary engine (GRE). However, limited H_2 ancillary facility, unexpectedly increased NOx emissions and dropped power-output [17] prevent HRE from being applied widely at present.

H_2-blended RE consumes less H_2 and reduces power-output attenuation in comparison with HRE. Considering these points, Cichanowic et al. [43] tested a H_2-gasoline rotary engine (HGRE) equipped with a carburetor. It was found that enhanced thermal efficiency caused by H_2 supplement was found. Reductions in HC and CO emissions after H_2 blending were observed, although NOx emissions increased significantly. Amrouche et al. [44] probed the impact of H_2 addition on lean-burn performance of a GRE at wide open throttle (WOT). It was found that GRE gained a better performance when H_2 was supplied. Ji et al. [2] investigated the influence of various H_2 supplements on GRE performance of at the stoichiometric. The experiment showed that pressure, chamber temperature and brake thermal efficiency were simultaneously increased when H_2 supplying enlarged. H_2 enrichment also reduced combustion duration and emissions, including HC and CO.

Since RE could be applied as the range extender or power sources of removable electricity generator and unmanned aerial vehicles, to improve the RE performance, the combustion and emissions characteristics of hydrogen-enriched gasoline rotary engine have been investigated under WOT [44], idle [45] and stoichiometric part load conditions [2]. However, there is nearly no published papers that have been studied the performance of hydrogen-enriched gasoline rotary engine under lean and part load conditions. Different form WOT operation, the engine could meet weakened charge motion and high residual dilution under part load conditions. Besides, the temperature fields vary markedly from low to high loads, the effect of H_2 addition on improving engine performance might be different when the engine runs at part load conditions. Namely, H_2 adding could affect the GRE combustion process differently at part load and lean conditions. Furthermore, part load condition is more frequently-used than WOT condition. Thus, there is a desired need to study the effect of H_2 supplement on part load performance of GRE fueled with lean mixtures. This paper carried out experiments to explore the combustion and emissions characteristics of a HGRE at part load and lean conditions.

2. Experimental apparatus and procedure

2.1. Experimental apparatus

The experiment was conducted on a single-rotor, air-cooled and gasoline-fuelled RE, whose schematic diagram and specifications are demonstrated in Fig. 1 and Table 1, respectively. Some modifications are made for the original RE to realize the test operations. An electronic ignition module is newly developed for RE. A H_2-gasoline hybrid fuel management are mounted in the intake pipe, as it is shown in Fig. 2. A hybrid electronic control unit (HECU) is made to control H_2-gasoline injection as well as spark timing. The adoptive gasoline is mixed with 2% lubricant oil by volume fraction to lubricate the engine because the original RE has no individual lubricating system. Summary of test parameters (H_2 purity et al.) are given in Table 2.

Fig. 3 gives the schematic of test bench. The engine is loaded by an AC electrical dynamometer, which can govern and measure the speed and torque outputs of tested engine. A gasoline mass flow meter is used

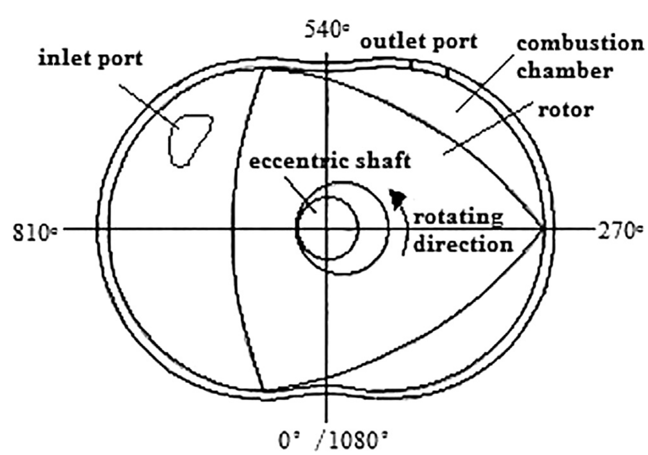

Fig. 1. Schematic of the tested rotary engine.