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Investigation on combustion and emissions characteristics of a hydrogen-blended n-butanol rotary engine

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ABSTRACT

In this paper, a rotary engine equipped with an n-butanol and hydrogen port-injection system was developed to investigate the combustion and emissions characteristics of a hydrogen-blended n-butanol rotary engine at part load and stoichiometric conditions. A self-developed hybrid electronic control unit was adopted to adjust the injection durations of n-butanol and hydrogen. The rotary engine was run under the conditions of 4000 rpm, a manifold absolute pressure of 35 kPa and a fixed spark timing of 45 °CA before the top dead center during the whole testing operation. The hydrogen volumetric fraction in the total intake was varied from 0% to 6.30%. The test results manifested that the brake thermal efficiency and chamber temperature were simultaneously increased with hydrogen addition. The hydrogen supplement obviously shortened flame development and propagation periods. Both chamber pressure integral heat release fraction versus crank angle were increased when the hydrogen fraction was enhanced. HC emissions were reduced by 54.5% when hydrogen volume fraction was raised from 0% to 6.30%, CO and CO_2 emissions were also reduced after increasing hydrogen blending fraction. NOx emissions were mildly elevated due to the improved chamber temperature.

Introduction

With the depletion of fossil fuel resources and the serious combustion pollution of conventional fossil fuels, researchers have promoted investigations on searching new alternative fuels for vehicle engines, such as natural gas [1–3], alcohols [4–7], dimethyl ether [8–10] and so on. It has been demonstrated that the n-butanol is a feasible fuel substitution, which has four isomers of n-butanol, iso-butanol, sec-butanol and tert-butanol [11–13]. N-butanol could be produced from biomass, which could be combusted as mono fuel for spark-ignition (SI) engines or blended with other fuels for SI and compression-ignition (CI) engines [7,14]. In views of practical application and combustion, n-butanol has some superior characteristics compared with other alcohol fuels, such as low corrosive, high stoichiometric air-to-fuel ratio and low prone to water contamination [15,16]. As its fuel properties are very close to gasoline, less modifications on the engine are required for applying n-butanol as the main fuel [17,18]. Knowing from the

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published literature, blending n-butanol to the gasoline engine could gain less emissions [19–22] and elevated engine indicated mean effective pressure (IMEP) [23]. Meanwhile, some researches are also focusing on further improving the butanol engine combustion and emission performances [24–27].

The rotary engine is deemed as a promising alternative to the reciprocating engines [28–30] and is suitable for automotive applications [31,32], especially serving as the range extender for battery electric vehicles [33–35], due to its preponderant advantages of higher power-weight density, more compact and less vibration compared with the reciprocating engines [36–42]. In addition, the rotary engine possesses multifuel capability [35,43]. Unfortunately, the rotary engine generally suffers low engine efficiency and high pollutant emissions [44]. This result mainly comes from the long and narrow combustion chamber [16], which has a high surface to volume (S/V) ratio that increases the heat transfer from the burning mixture to the rotors and walls [45]. This is not effective to produce output during the expansion stroke, which decreases engine efficiency. Furthermore, the combustion efficiency inside the chamber is dropped due to "quenching effect" induced by the large S/V of the combustion chamber walls [46]. Unburned hydrocarbons are also increased when the quenching effect is strengthened. Additionally, within the combustion chamber of the rotary engine, the trochoid housing divides the combustion chamber into two sides, a relatively strong squish flow from the trailing to the leading side is produced because of the rotational movement of the rotors. This can make the flame spread faster in the leading direction than in the trailing direction. As a result, the rest of burning gases is quenched by the cool housing wall when the trailing side is squished, which further deteriorate engine efficiency and emissions. Conclusively, unburned combustion in the trailing edge within the working chamber is the main contribution to the low efficiency and high unburned hydrocarbons formation.

Unfortunately, rotary engine performance could be worsened when fed with n-butanol. This is because as a liquid fuel, n-butanol have to be vaporized to form homogeneous gaseous mixture before the combustion event. However, the long-narrow combustion chamber and the winding admission passage of rotary engine make it difficult to form homogeneous mixture. Meanwhile, the relatively low flame velocity of n-butanol could cause the incomplete combustion losses. Moreover, the relatively long quenching distance of n-butanol also prevent the flame from reaching the narrow and limited areas, such as the rotor ends and walls of the flattened working chamber.

Finding a feasible way to heighten the engine efficiency and drop emissions of the rotary engine has interested researchers [17–26]. Knowing from the published literature, direct-injection, stratified charge [47,48] and turbocharged systems [49,50] have been used to improve the rotary engine performance. Except for these, some others were stimulated by using alternatives of the traditional fuels possessed specific properties which could improve the combustion process, such as hydrogen-gasoline blends [29–32], hydrogen-ethanol blends [35], natural gas-hydrogen blends [38] and hydrogen [51–53]. Since hydrogen has a wide flammable-range, high diffusion coefficient and fast burning velocity, hydrogen supplement could improve the combustion of original fuel [54,55]. Specifically speaking, owning a high diffusion speed, blending hydrogen could improve the homogeneity and combustion completeness of original mixture [56–59]. Besides, the low ignition energy of hydrogen could ease the ignition process of original mixture [60]. Due to the high flame speed of hydrogen, adding hydrogen could elevate the mixture burning velocity [59,60]. Therefore, the reduced exhaust losses and increased engine thermal efficiency are obtained. Investigations conducted by Huang et al. [61,62] showed that the laminar flame speed of hydrogen was much higher than that of butanol, and the addition of hydrogen could be effective on elevating the flame speed of hydrocarbon fuels. Generally, increasing the flame speed of in-cylinder mixture avails the combustion to be taken place much closer to the top dead center, which is helpful for reducing the cooling and exhaust losses. Brady et al. [63] experimentally and computationally studied the counter-flow ignition of the n-butanol/hydrogen mixture at atmospheric and elevated pressures. They found that the hydrogen-blended mixture was easily to be ignited. Namely, hydrogen addition resulted in a decrease in ignition temperatures. Raviteja et al. [6] researched the hydrogen enrichment on the performance and emission parameters of a butanol-blended gasoline engine. The results indicated that the efficiency of the engine improved upon hydrogen enrichment. HC and CO emissions showed about 60% reduction with 10% hydrogen enrichment, whereas NOx emissions almost doubled itself. The combustion analysis showed reduced delay periods, shortened combustion durations, elevated cylinder pressures, heightened temperatures and improved combustion after hydrogen supplying.

Now, hydrogen has been added into rotary engine to improve the performance of original engine. Among these works, Ji et al. [29–32] investigated the performance of a hydrogen-blended gasoline rotary engine at partial load and stoichiometric, idle and various excess air ratios, and different spark timings. The experimental results showed that the combustion pressure and engine economy were simultaneously increased by hydrogen blending. HC and CO emissions were reduced with the increase of hydrogen volume fraction. The similar conclusions were given by Amrouche et al. [34,35] from a Wankel rotary engine fueled with hydrogen enriched gasoline and ethanol. In addition, Fan and Pan et al. [38] studied the performance of a natural gas/hydrogen rotary engine. The experiment outcomes revealed that the combustion rate, the intermediate OH and the peak pressure were improved with hydrogen induction for the natural gas/rotary engine.

Although many literature and publications have shown the impact of hydrogen addition on rotary engine fueled with gasoline, natural gas and ethanol, paper aiming the performance of a hydrogen/n-butanol rotary engine is still inadequate. As fuel with proper characteristics differently influences the engine performance, there is a desired need to quantitatively study the effect of hydrogen addition on performance of the n-butanol rotary engine. This paper introduced an experimental study on the effect of hydrogen addition on combustion and emissions characteristics of an n-