Energy Conversion and Management 121 (2016) 272–280

Contents lists available at ScienceDirect

Energy Conversion and Management

journal homepage: www.elsevier.com/locate/enconman

Effect of hydrogen addition on combustion and emissions performance of a gasoline rotary engine at part load and stoichiometric conditions

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ARTICLE INFO

Article history:
Received 24 February 2016
Received in revised form 19 April 2016
Accepted 16 May 2016
Available online 21 May 2016

Keywords:
Hydrogen addition
Gasoline
Rotary engine
Combustion
Emissions

ABSTRACT

The rotary engines may encounter high fuel consumption and emissions due to its narrow and long combustion chamber design. The low ignition energy and high flame speed of hydrogen may help improve the combustion of rotary engines. In this paper, a gasoline rotary engine equipped with gasoline and hydrogen injectors was developed to investigate the combustion and emissions of hydrogen-blended gasoline rotary engines. The engine was run at 3000 rpm and a manifolds absolute pressure of 37.5 kPa with the stoichiometric excess air ratio. The spark timing was set to be 25°CA before the top dead center. The engine was first fueled with the pure gasoline and then blended with the hydrogen. The hydrogen volume fractions in the intake were gradually increased from 0% to 5.2%. The results showed that the combustion pressure, brake mean effective pressure, cylinder temperature and thermal efficiency were simultaneously increased after the hydrogen blending. The crank angle of peak pressure was advanced with the hydrogen addition. The hydrogen enrichment was effective on reducing flame development and propagation periods. HC emissions were reduced by 44.8% when the hydrogen volume fraction in the intake was raised from 0% to 5.2%, CO and CO_2 emissions were also reduced after the hydrogen blending.
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1. Introduction

As another type of internal combustion engines [1,2], the rotary engine possesses high power-weight density and high operating speed which is promising to be adopted in general aviation aircraft, vehicle, and various stationary and mobile applications [3–6]. In particularly, more than 2 million Mazda RX series sports cars equipped with the rotary engine have been manufactured and sold by Mazda Motor by 2000. The rotary engine plays as an important role in some special fields, such as removable electricity generation, military aircraft and high performance racing car, etc. [4–6]. Therefore, investigations on rotary engines have attracted many interests from academia, automotive industry and government. In general terms, compared to the conventional reciprocating engines, rotary engines have fewer components and parts, which could operate with less vibration and more compact structure [7,8]. The drawbacks of a rotary engine are generally including sealing problems, low power output at low speeds, poor brake thermal efficiency [9–11] and high CO and HC emissions [5,12–16]. The high toxic emissions of rotary engines could be resulted from several aspects. Firstly, the incomplete burned gas could be expelled from the combustion chamber as HC and CO emissions. Secondly, the quenching effect due to the large surface to volume ratio of the chambers results in high HC emissions. Thirdly, the unburned gas leakage from seals to the exhaust is also a source of HC and CO emissions [13–15]. Therefore, although the mechanical design of rotary engines makes it could gain higher power density and performance at high speeds, the shape of combustion chamber and sealing problems of the rotary engine make it may expel larger amounts of HC and CO emissions than the reciprocating engines. Therefore, improving the fuel economy and reducing the toxic emissions of the rotary engine is the key and challenge for its practical application.

Generally, the performance of rotary engine could be further deteriorated when it is fueled with liquid fuels, such as gasoline. This is because liquid fuels have to be vaporized to form homogeneous gaseous mixtures before combustion. However, the long and narrow combustion chamber and the high running speed of rotary engines reduce the time for forming homogeneous mixtures. Therefore, the combustion of liquid fuel–air mixtures is prone to be prolonged. Meanwhile, the relatively low flame speed of conventional liquid fuels, such as gasoline, could cause the incomplete combustion, since the flame has to travel a long distance in rotary engines. Moreover, the long quenching distance of gasoline also prevents the flame to reach narrow areas at the rotor ends and wall

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http://dx.doi.org/10.1016/j.enconman.2016.05.040
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Nomenclature

CA	crank angle
S/V	surface to volume ratio
MAP	manifolds absolute pressure (kPa)
TDC	top dead center
BTDC	before top dead center
HECU	hybrid electronic control unit
α_{H2}	hydrogen volume fraction (%)
λ	excess air ratio
V_{H2}	hydrogen volume flow rate (L/min)
V_{air}	air volume flow rate (L/min)
ρ_{H2}	density of hydrogen at standard state (g/L)
ρ_{air}	density of air at standard state (g/L)
$AF_{st,gas}$	stoichiometric air-to-fuel ratio of gasoline ($AF_{st,gas}$ = 14.6)
$AF_{st,H2}$	stoichiometric air-to-fuel ratio of hydrogen ($AF_{st,H2}$ = 34.3)
m_{gas}	gasoline mass flow rate (g/L)
ST	spark timing
p	chamber pressure (bar)
Bmep	brake mean effective pressure (bar)
η_b	brake thermal efficiency (%)
CA0-10	crank angle duration from spark discharge to 10% heat release of the total fuel (°CA)
CA10-90	crank angle duration from 10% to 90% heat release of the total fuel (°CA)
T	combustion temperature (K)
T_{max}	maximum combustion temperature (K)
CO_2	carbon dioxide
CO	carbon monoxide
HC	hydrocarbon
NOx	nitrogen oxide

of the flattened combustion chamber. Because of the quenching effect resulted from the excessively high surface to volume ratio (S/V) on the trailing area, more unburned HC emissions are formed in the wall of combustion chamber and other cold surfaces [17–20]. As a result, the rotary engine may easily encounter high fuel consumption and pollutant emissions when it is fueled with the gasoline, especially under low speed and load conditions [21,22]. The promising solution to overcome these drawbacks in fuel economy and toxic emissions is to improve the combustion process. Generally, the high operating speed and long combustion chamber of rotary engines require the fuel which has a high flame speed and easily to be vaporized. Therefore, improving fuel properties is a feasible approach for enhancing the performance of rotary engines.

The hydrogen is considered to be an alternative for internal combustion engines because it has many desirable properties [23], such as low ignition energy, high diffusivity, wide flammability, high flame velocity and short quenching distance [24–27]. Huang et al. [28–30] found that the flame propagation speed of natural gas-air mixture was accelerated after the hydrogen blending. Besides, through numerical simulation, they observed that the hydrogen blending to methane contributed to promoting the formation of OH, O, and H radicals in the flame, which could help stimulating the burning velocities of hydrogen-blended fuels. Moreover, the increase in flame temperature was also found for the premixed methane–hydrogen–air flames, which exerts an advantageous influence on improving the laminar burning velocity.

Several decades ago, the inspiration has been raised of adding hydrogen into conventional fuel for improving its combustion and emissions characteristics in reciprocating engines. In the previous literatures, effects of hydrogen enrichment on combustion and emissions characteristics of reciprocating spark ignition engines have been widely reported. Varde [31] experimentally investigated the hydrogen enhancement on performance a small spark-ignition gasoline engine. He found that the hydrogen addition could improve the engine thermal efficiency and reduce cyclic variations. Meanwhile, the decrease in combustion duration and the extension in lean limit were also observed after the hydrogen enhancement. Ivanic et al. [32] found that the hydrogen addition contributed to reducing the coefficient of variation in indicated mean effective pressure (IMEP) and speeding up the flame initiation phase of combustion. Yoshihito and Teruo [33] studied the performance of hydrogen and gasoline-mixed combustion in a spark ignition engine. They found that thermal efficiency of the engine operated with hydrogen supplemented mixtures was much higher than that with the pure gasoline. NOx emissions from the engine were almost reduced to zero when it was fueled with hydrogen-gasoline mixtures at lean conditions. Ji and Wang et al. [34–37] have accomplished many investigations on combustion and emissions characteristics of a hydrogen-blended gasoline engine under different operating conditions. According to these studies, the hydrogen addition was proved to be effective on improving the engine thermal efficiency, shortening the flame development and propagation periods and decreasing harmful emissions of the reciprocating gasoline engines.

Except for the application of hydrogen in reciprocating engines, some researchers also showed that the hydrogen could be used as an alternative for rotary engines [38–41]. Since the flame propagating speed of hydrogen is much higher than gasoline, the pure hydrogen-fueled rotary engines gain better efficiency and lower toxic emissions than gasoline rotary engines. However, in view of the limited hydrogen infrastructure distribution, the pure hydrogen rotary engine is also not likely to be widely applied at present.

Compared with the pure hydrogen-fueled rotary engines, the hydrogen-blended rotary engine consumes less hydrogen. This enables the hydrogen to be produced online by applying small hydrogen generators, which effectively alleviates concerns on hydrogen refilling and massive storage. Considering this point, Amrouche et al. [42] tested the effect of hydrogen addition on the performance of a gasoline rotary engine. They found that adding hydrogen to the gasoline rotary engine resulted in the improved thermal efficiency and power output. HC and CO emissions were reduced while NOx emissions were increased with the increase of hydrogen energy fractions at the wide open throttle condition with the original ignition timing.

However, experimental investigations, particularly the combustion and heat release analysis on the effect of hydrogen addition on combustion and emissions characteristics of a gasoline rotary engine are still inadequate. As the combustion and physicochemical characteristics of hydrogen are different from gasoline, the addition of hydrogen could affect the heat release and combustion process of gasoline rotary engines. And the improvement in heat release process is fundamental for the rotary engine to gain better efficiency and lower emissions. This paper conducted experiments on a rotary engine testing bench and explored the combustion and emissions characteristics of a hydrogen-enriched gasoline rotary engine.

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