ARTICLE IN PRESS

INTERNATIONAL JOURNAL OF HYDROGEN ENERGY XXX (2018) 1–10

Available online at www.sciencedirect.com

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

An experimental analysis of hydrogen enrichment on combustion characteristics of a gasoline Wankel engine at full load and lean burn regime

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ARTICLE INFO

Article history:
Received 13 July 2018
Received in revised form
13 August 2018
Accepted 17 August 2018
Available online xxx

Keywords:
Lean burn Wankel rotary engine
Hydrogen-enriched gasoline
Reduced combustion duration
Engine economy

ABSTRACT

In this paper, a gasoline Wankel engine was modified and equipped with self-developed hybrid electronic control unit to experimentally investigate the effect of hydrogen-enrichment level on combustion characteristics of a gasoline Wankel engine at wild open throttle position and lean burn regime. Testing were carried out under constant engine speed of 3000 rpm and the lean operating limit of the original gasoline engine. The spark timing was set at 15 °BTDC. The hydrogen energy fraction in the intake was gradually increased from 0% to 10%. The results showed that hydrogen enrichment was effective on improving the combustion process through the shortened of the flame development and the flame propagation periods, advancing the central heat release, increasing the HRRmax and reducing the cyclic variation proportionally to the amount of hydrogen added to the air fuel mixture. Furthermore, increasing hydrogen fraction in the intake improves the engine economy by reducing the cooling loss.

Introduction

The Wankel rotary engine, which is a potential alternative to reciprocating engine [1,2], is recognized as a low cost engine with a simple design and fewer components and so on [2–4]. However, the main interest of the Wankel engine is its power density that is higher than that of comparable reciprocating piston engine [4–6]. This characteristic may offer a benefit if used for extending the range of electric vehicles [7–9] as well as in hybrid vehicle power [10]. In fact, the development of electric and hybrid vehicle technologies, these last few years, has raised the interest in the Wankel engine [11–14]. This has well established the Wankel rotary engine importance in the future automotive applications.

The Wankel rotary engine uses a triangular rotor that turns inside an elliptical combustion chamber [15–17]. Consequently, the combustion chamber has a large surface to volume ratio that is not favorable to the spread of the flame front [17–21], which expands the quenching area and causes high heat transfer rates [22,23]. As a result, the combustion in the rotary Wankel engine is slower and less efficient than in the piston engine. This makes the rotary engine facing challenges such as a weak engine economy and high hydrocarbon emissions at the exhaust [15,24–28]. Additionally, the geometry of the trochoid and the rotor divide the combustion

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https://doi.org/10.1016/j.ijhydene.2018.08.110

Please cite this article in press as: Amrouche F, et al., An experimental analysis of hydrogen enrichment on combustion characteristics of a gasoline Wankel engine at full load and lean burn regime, International Journal of Hydrogen Energy (2018), https://doi.org/10.1016/j.ijhydene.2018.08.110

chamber into two sides, while the rotor is rotating, the squish flow that is moving from the trailing to the leading side of the combustion chamber accelerates the flame propagation faster in the leading direction. Therefore, the remaining combustion as the trailing side is squished, is quenched by the cool housing walls, which further reduces combustion efficiency and increases unburnt hydrocarbons emissions. This events is the most implicated factor to the low efficiency and high unburned hydrocarbon emissions of the Wankel rotary engine [3]. Lean burn is one of the basic technique used for improving engine efficiency and reducing emissions [4,6,29,30]. In fact, when appropriate lean mixture is burnt, there is plentiful oxygen offered to the fuel to be completely burnt, accordingly, CO and HC emissions are reduced [31,32]. Moreover, the increased excess air, will decreases the combustion temperature, resulting in reduced NOx emissions and dropped cooling losses that help to improve the engine thermal efficiency [29]. Therefore, lean burn can be a way to offset the Wankel engine's drawbacks.

In the spark ignition internal combustion engines, the lean burn is limited by Lean Operating Limit (LOL). The LOL is the upper limit at which combustion stability is achieved [33]. Over leaning out an air −fuel mixture may lead to engine instability, misfire [34], and finally, it will make the ignition impossible to occur [35]. The LOL is mainly dependent on characteristics of the fuel used, such as the fuel flammability and flame rate. In fact, a slow flame speed will result in combustion instability, decreasing heat release, and increasing HC emissions [36]. Thus, the lean combustion limit is a key parameter indicating the capability of engine lean operating [37].

In the other hand, because of the burning characteristics of the Wankel engine, the property of the fuel used within that engine directly affects the quality of the combustion, and this parameter is much more important while lean burn strategy is applied. Gasoline is the most common liquid fuel used within spark-ignition rotary engine. Unfortunately, the narrow flammability, low flame speed and the lengthy quenching distance of gasoline make pure gasoline-fueled SI engines undergo slow and incomplete combustion, high cyclic variation and even misfire at the lean-burn conditions. Resulting in reduced engine thermal efficiency and increased carbon-related emissions [14]. In the meantime, the elongated and irregular combustion chamber shape and the squish flow resulting at high speed make gasoline difficult to vaporize which make homogeneous air-gasoline lean mixtures difficult to form and then to ignite. This is why applying lean burn technology to the Wankel engine, more than for reciprocating engine, involves the use of a fuel which has a high flame speed, high flammability, high diffusivity and short quenching distance to speed up the combustion. These are the distinctive characteristics of Hydrogen. Physicochemical and combustion capability of gasoline can also be improved with hydrogen enrichment, and accordingly, mitigate the challenges due to the Wankel engine combustion chamber shape [11]. Moreover, the lean burn limit of hydrogen is reached at the excess air ratio of 10 [29], which is much wider than that of gasoline. This will also help gasoline Wankel engine operates smoothly under further diluent conditions and thus gaining better performance at lean burn conditions.

Hydrogen is a renewable and clean energy sources that is characterized by a wide flammability and low ignition energy, a high diffusion rate and a significantly fast flame rate [12,38,39]. All of these characteristics are helpful to reduce the combustion duration, drop cooling losses and decrease the cycle-by cycle variations within the internal combustion engine [3,39–42]. It has already been proven that the increase of hydrogen fraction in air-fuel mixture can help to increase the flame speed of the mixture [43–45]. Moreover, burning hydrogen in Wankel engine is well suited, this is because the local separation of intake, compression, power and exhaust stroke reduces the combustion anomalies episodes that typically happens in spark ignition reciprocating engine while high amounts of hydrogen are used.

Ji et al. [28] have investigated the effect of hydrogen addition on combustion and emissions performance of a gasoline rotary engine at part load and stoichiometric conditions. For their experimental study, the authors have added different volume fractions of hydrogen with a maximum of 5% to gasoline at an engine speed of 3000 rpm and a fixed spark timing of 25°CA BTDC. The results have demonstrated that the addition of hydrogen, at part load and stoichiometric conditions, was able to enhance the gasoline rotary engine combustion through the improvement of the thermal efficiency, the shortening of the flame development and propagation durations and the reducing of the HC, CO and CO_2 emissions. Thereafter, Su et al. [14], have investigated the combustion and emissions characteristics of a hydrogen-blended gasoline rotary engine at a part load and lean conditions. For this purpose, hydrogen volume fractions of 0%, 3% and 6% and an engine speed of 4500 rpm were used. The authors found out that the flame propagation period is reduced with hydrogen addition, thus, indicates the possibility of extending the lean burn limit of gasoline rotary engine with hydrogen addition. They also found that hydrocarbons emissions and the energy losses of the rotary engine were reduced with hydrogen addition. Instead, at full load condition, Amrouche et al. [20] experimentally investigated the capability of hydrogen to extend the lean burn limit and thus reducing the fuel consumption and NOx emissions of a gasoline Wankel engine. The tests were carried out by using 0%, 3% and 6% of hydrogen energy fractions and an engine speed of 3000 rpm. According to this study, hydrogen enrichment is an effective strategy that is used to reduce NOx emissions through extending the lean burn limit of gasoline Wankel engine at full load condition. Besides, Amrouche et al. [12] have investigated the effect of hydrogen addition on gasoline Wankel engine performance and emissions at low lean limit and full load conditions. Different hydrogen energy fractions with a maximum of 10% and an engine speed of 3000 rpm were used. As results, a proportional increasing thermal efficiency and reducing specific HC, CO and CO_2 emissions with an important rise in NOx specific emissions were observed. However, this investigation, has focused only on some issues based on efficiency and emissions.

Although a great number of research papers, a few investigations have been done on extending the lean operation limit of gasoline SI engine by hydrogen enrichment [20,29]. However, a very few papers were focused on the effect of hydrogen addition level on the performance and emissions of

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