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An experimental study of a hydrogen-enriched ethanol fueled Wankel rotary engine at ultra lean and full load conditions

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ABSTRACT

In this paper, the effect of hydrogen addition to ethanol in a monorotor Wankel engine at wide open throttle position and in an ultra-lean operating regime was experimentally investigated. For this aim, variation of hydrogen enrichment levels on the ethanol engine performance and emissions were considered. Experiments were carried out under a constant engine speed of 3000 rpm and fixed spark timing of 15 °BTDC. The test results showed that hydrogen enrichment improved the combustion process through shortening of the flame development and flame propagation periods and reducing the cyclic variation. Furthermore, the reduction of burn duration with the increase of hydrogen fraction enhances the thermal efficiency, reducing the brake-specific energy consumption, as well as reducing the unburned hydrocarbons emissions of the Wankel engine.

1. Introduction

The transportation sector is one of the major consumers of fossil fuels and a large contributor to environmental pollution. Ethanol fuel is considered a promising liquid alternative fuel for spark ignition engines [1–4]. This fuel is relatively nontoxic and can potentially be produced from different agricultural crops [2,5]. Ethanol has a high octane rating that promotes higher compression ratios engines with high efficiency [1]. In addition, the higher heat of vaporization and combustion velocity of ethanol as compared to gasoline potentially increases the power output [1,6–8] and it was proven that the combustion of alcohol fuels may generate less CO, HC and NOx emissions than gasoline [5,9]. However, according to Catapano et al., [1] since ethanol has a lower stoichiometric air/fuel ratio (about 9 vs. 14.6 of gasoline) and smaller LHV (about 26.9 MJ/kg vs. 43.5 MJ/kg for gasoline), the actual mass and volume fuel consumption of ethanol is higher than that of gasoline.

The Wankel rotary engine is a promising alternative to the reciprocating engine and is suitable for automotive applications. Rotary engine research has slown down for years, due to its poor efficiency compared to that of reciprocating piston engines. However, Mazda has sustained the development of the rotary engines for commercial automobile applications. Along with Mazda, a few aircraft and engineering companies are still developing a new generation of rotary engines. Most rotary engine research was accomplished from the 1980s to early 1990s by NASA. Since that time, the publication of technical research papers has reduced [10]. However, the development of electric and hybrid vehicle technologies has again raised interest in the Wankel engine [11–13].

The Wankel rotary engine is simpler and generates less vibration and noise than the conventional reciprocating piston engine due to non-reciprocating and fewer moving parts. In addition, the Wankel has a higher power-to-weight ratio (low specific weight and volume) [14,15] that may provide significant advantages in hybrid vehicle power or for use in extending the range of electric vehicles. For high speed operation, it also has a higher specific power output. Finally, Wankel engines have multi-fuel capability and can operate using SI or CI cycles. Unfortunately, in general, the Wankel engine has poor fuel efficiency and higher unburned hydrocarbons emissions as compared to reciprocating engines. The main contributor to these detriments is the Wankel engine's long and narrow combustion chamber [16] that has a high surface area/volume ratio, which increases heat transfer from the hot combustion gasses to the rotor and the rotor housing. During the expansion stroke, this dissipated heat is not effective to produce work, which lowers the engine's efficiency. Furthermore, the combustion efficiency within the Wankel engine is reduced due to quenching on the large surface area of the combustion chamber walls. This "quenching effect" also increases unburned hydrocarbons. Additionally, as the shape of the trochoid housing

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Nomenclature

$AF_{st,Eth}$	stoichiometric air-to-fuel ratio of ethanol ($AF_{st,Eth} = 9$)
AF_{st,H_2}	stoichiometric air-to-fuel ratio of hydrogen ($AF_{st,H_2} = 34.3$)
BSEC	brake specific energy consumption (MJ/kW h)
BTDC	before top dead center
BTE	brake thermal efficiency (%)
CA	crank angle
CA0-10	flame development, it is the crank angle duration from spark discharge to 10% heat release of the total fuel (°CA)
CA50	central heat release angle (°CA)
CA10-90	flame propagation, it is the crank angle duration from 10% to 90% heat release of the total fuel (°CA)
CI	compression ignition
CO	carbon monoxide
CO_2	carbon dioxide
COVimep	coefficient of variance of indicated mean effective pressure (%)
HC	hydrocarbon
HECU	hybrid electronic control unit
HRRmax	maximum heat release rate (J/°CA)
LHV_{Eth}	lower heating value of ethanol (MJ/kg)
LHV_{H_2}	lower heating value of hydrogen (MJ/kg)
IMEP	indicated mean effective pressure (bar)
LOL	lean operation limit
MFB	mass fraction burnt (%)
NOx	nitrogen oxide
OMC	outboard marine corporation
P_{max}	maximum working chamber pressure (bar)
Q_w	cooling loss (J/cycle)
rpm	rotation per minutes
SI	spark ignition
TDC	top dead center
T_{max}	maximum in-working chamber temperature (°C)
ULOL	ultra-lean operation limit
WOT	wide open throttle
θ	crank angle (°)
θ_s	crank angle of start of ignition (°)
$\Delta\theta$	total combustion duration (°)
λ	excess air ratio
Φ	equivalence ratio
$\%H_2$	hydrogen energy fraction (%)

divides the combustion chamber into two sides, a squish flow moving from the trailing to the leading side of the combustion chamber is produced through the spin of the rotor. In the working chamber, this squish flow accelerates the flame propagation faster in the leading direction than in the trailing direction. Therefore, as the trailing side is squished, the remaining combustion is quenched by the cool housing walls, which further reduces combustion efficiency and increases unburnt hydrocarbons emissions. Consequently, the slow and incomplete combustion at the trailing edge of the rotary engine is the most implicated factor to the low efficiency and higher unburned hydrocarbons emissions of the Wankel engine as compared to conventional reciprocating engines.

Finding a method to improve the efficiency and reduce the unburned hydrocarbons emissions of the Wankel engine has stimulated research interest [17–26]. Some studies focused on using different new technical methods such as Direct-injection, stratified charge [21] and turbocharged systems [22]. While others were dedicated to the improvement of combustion chamber shape and the flow field in the rotor housing [23–26]. Others were motivated by using alternative fuels with specific characteristics that can help to improve the combustion process. Among these works, we can cite Amrouche et al. [17], that fueled the Wankel engine with hydrogen enriched gasoline, Brown et al. [27], have used pure hydrogen within the engine and Fan et al. [28], that have studied the performance of a Wankel engine fueled with natural gas-hydrogen blends.

The knowledge of the rotary Wankel engine drawbacks and fuel characteristics can help to choose which fuel can achieve the best performance with that kind of engine. For higher thermal efficiency in the Wankel engine, it is effective to raise the burning speed such that a more isochoric combustion occurs [14]. Fueling the Wankel engine with ethanol may help to speed up the combustion and reduce quenching at the trailing edge of the chamber and thus reducing unburned hydrocarbons and improving thermal efficiency. However, due to its lower stoichiometric air/fuel ratio and smaller LHV compared to gasoline, using pure ethanol cannot resolve by itself the excessive fuel consumption of the Wankel engine even if the combustion efficiency within the engine could be improved. Thus, to further raise the burning speed and obtain stronger squish flow in the Wankel engine, hydrogen enrichment seems to offer improvements [17,29,30]. Hydrogen is characterized by having the highest mass energy density of any fuel (120.1 MJ/kg vs. 26.9 MJ/kg of ethanol) and the highest stoichiometric air/fuel ratio (34.3 vs. 9 of ethanol), so, hydrogen addition could potentially reduce the specific fuel consumption of the ethanol engine [29,31]. Moreover, hydrogen has a wider flammable mixture range and low ignition energy, a high diffusion rate and a significantly faster laminar burning velocity [17,30,32]. All of these characteristics are helpful to improve the combustion and reduce the quenching effect in the Wankel engine, [14,17,29,33]. In addition, hydrogen's combustion characteristics can improve the engine's lean burn capability [28–30,34]. Lean combustion is well known to reduce the rate of emission of unburned elements of CO, HC, NO_X, and is effective for improving thermal efficiency in the reciprocating engine [2,17,35], therefore, this kind of combustion could potentially help to resolve the Wankel engine's drawbacks [14,17].

While investigating the literature on internal combustion engines fueled with hydrogen–ethanol blends, we noticed that most published papers were focused on reciprocating piston engines [36–42]. Consequently, we had a strong motivation to investigate the effect of hydrogen addition to an ethanol-fueled Wankel engine at an ultra-lean condition, where the observed benefits in past literature could be even more significant for the Wankel engine.

2. Experimental methodology

2.1. Experimental setup

Fig. 1, displays a schematic diagram and photograph of the experimental set up. The engine used for this study is 0.530L single rotor, air cooled Wankel engine, using a single spark plug that was manufactured by Outboard Marine Corporation, USA. The engine technical specifications are listed in Table 1. A Telma CC100 eddy current dynamometer was coupled to the engine to control and measure the engine speed and torque output.

To achieve real time control over the air/fuel mixture preparation as well as hydrogen addition, two fuel injection systems were implemented instead of the carburetor initially built within the OMC Wankel engine. One system was used for ethanol in this