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An experimental evaluation of ultra-lean burn capability of a hydrogen-enriched ethanol-fuelled Wankel engine at full load condition

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ABSTRACT

This paper experimentally investigates the effect of hydrogen addition on the lean burn capability of an ethanol-fuelled Wankel rotary engine at Wide Open Throttle (WOT) operating conditions in order to observe the resultant engine economy and the hydrocarbon emissions. During the tests, a monorotor Wankel engine operating at 3000 rpm was modified to run on an ethanol–hydrogen blend with 0% and 5% hydrogen energy fractions in the intake. The excess air ratio was varied from 1.7 to the Ultra-Lean Operating Limit (ULOL) of a specified hydrogen–ethanol mixture. With hydrogen addition, the test results show that the ultra-lean operation limit of pure ethanol fuelled Wankel engine was extended and the engine stability was enhanced. Moreover, the engine fuel economy was increased and Hydrocarbons (HC), Carbon Monoxide (CO) and Carbon Dioxide (CO_2) emissions were reduced after hydrogen addition.

Introduction

The Wankel rotary engine is an interesting alternative to the reciprocating engine [1–4]. Since the Wankel engine has higher power density than the same power reciprocating engine [4,5], it can potentially be used in hybrid vehicles [6] or as range extender for battery electric vehicles [7,8]. Growing concerns with regards to fossil energy depletion and environment degradation have led to active investigation of renewable and clean alternative fuels in internal combustion engines. Renewable ethanol has been proven to be one of the most promising alternative fuels used in spark ignition engines [9–11]. Ethanol is a non-toxic substance that can be produced from various agricultural crops [11–13]. Furthermore, ethanol has higher adiabatic flame speed, heat of vaporization and octane number than gasoline which improve the anti-knock characteristics of the ethanol engine and potentially allows a larger compression ratio to be used. These characteristics are helpful to enhance the thermal efficiency and potentially increase the power output of the ethanol engine as compared to those fueled by gasoline [14–17]. Moreover, the ethanol hydroxyl group benefits a complete combustion that avails improved engine efficiency and reduced CO and HC emissions from ethanol engines [9,18]. Using ethanol in a Wankel rotary engine could be an interesting option to ease specific drawbacks of the Wankel engine, which are reduced thermal efficiency and high levels of hydrocarbons emissions [19]. These detriments are the results of the overall geometry in the Wankel engine. However, since ethanol has lower stoichiometric air/fuel ratio and smaller mass and volumetric Lower Heating Value (LHV) [14],

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the volumetric fuel consumption of ethanol Wankel engine will likely be higher than that of gasoline fueled engines. A possible solution to this problem could be to run the ethanol Wankel engines lean or with dilute combustion regimes. Lean or dilute combustion is effective at improving the engine economy and reducing the exhaust emissions of the reciprocating engine [20]. Extending the internal combustion engine lean burn capability is a way to extend the benefits of lean combustion. Experience gained through the years has proven that hydrogen enrichment effectively extends the lean limit of the fuel and enables high dilution combustion regimes [9,21,22].

Hydrogen is characterized by the highest mass energy density and the highest stoichiometric air/fuel ratio of any fuel. Therefore, hydrogen addition may reduce the specific fuel consumption of the ethanol engine [23,24]. Moreover, hydrogen has a wider flammability range, a low ignition energy and high adiabatic flame temperature and diffusion rates that could help to improve the homogeneity of the fuel-air mixture, enhance the flame stability and reduce the quenching effect in the Wankel engine [25,26]. Therefore, hydrogen addition should be helpful to reduce unburned hydrocarbons emissions [27,28] and increase thermal efficiency of Wankel rotary engine [28]. Indeed, Amrouche et al. [1] have experimentally studied the performance and emissions of different hydrogen energy fractions in an enriched ethanol fueled Wankel engine, at Wide Open Throttle (WOT) and a lean equivalence ratio of about $\Phi = 0.47$ operating conditions. Their study demonstrated that the addition of hydrogen was effective for enhancing the brake thermal efficiency and thus decreasing the Brake Specific Energy Consumption (BSEC). Moreover, hydrogen enrichment reduces the CO, HC and CO_2 emissions.

Hydrogen enrichment has been successfully used with different fuels in reciprocating SI engines to enable lean or dilute combustion regimes to improve engine combustion performance and reduce the exhaust emissions [9,13,19,20]. Furthermore, extending the LOL of reciprocating engine using hydrogen has been used as strategy to reduce NOx emissions to very low levels [13,21]. Zhang et al. [9] have investigated the performance of an SI reciprocating engine fueled with ethanol–hydrogen mixtures ($1<\lambda < 1.5$) at unthrottled, 1400 rpm and MBT conditions. They found out that combustion duration was shortened and HC and CO emissions were decreased with the addition of 3% hydrogen volume fraction in the intake. Additionally, hydrogen addition helped extend the engine lean limit, which remarkably lowers NOx emissions of the engine. For the Wankel engine, Amrouche et al. [2] have experimentally investigated hydrogen enrichment capability to extend the lean limit of the gasoline Wankel engine at a WOT condition. This study demonstrated that hydrogen addition could effectively extend the Lower Operating Limit (LOL) of the gasoline Wankel engine and reduce the engine cyclic variation proportionally to the fraction of hydrogen added in the intake. Moreover, the extension of the LOL of the Wankel engine with hydrogen addition results in better fuel economy of the engine and reduced carbon based emissions such as HC, CO, CO_2 while the NOx emissions were reduced to very low levels that meet the Best Available Control Technology (BACT) standard, without being treated by a three-way catalytic converter.

Through the literature, we observed that published papers on experimental investigation of Wankel engine are limited. Furthermore, none of these studies investigated the effect of hydrogen enrichment on ultra-lean burn capability of the ethanol fuelled Wankel engine under WOT operation condition. Indeed, improving the engine efficiency by reducing the pumping loss is possible though running an engine at WOT condition and adjusting its load by controlling the excess air ratio [9]. However, the strong turbulent flow of the Wankel engine [4] especially at unthrottled condition associated with the narrow flammability and high latent heat of vaporization of ethanol could make the Wankel engine running under the unthrottled and ultra-lean condition difficult. However, the unique characteristics of hydrogen may improve the combustion stability of ethanol Wankel engine under these conditions.

Thus, this paper presents the experimental results of combustion and emissions performances of both pure ethanol and ethanol enriched at 5% energy fraction with hydrogen in a mono rotor Wankel engine under full load and at the ultra-lean operating regime. The main purpose of this study is to enhance the engine economic efficiency and reduce the unburnt hydrocarbons emissions while extending the ethanol Wankel rotary engine ULOL.

Experimental setup and procedure

The engine used for this research is 0.530L single rotor, air cooled Wankel engine with a single spark plug. This engine was manufactured by Outboard Marine Corporation (OMC), USA. A Telma CC100 eddy current dynamometer was coupled to the engine to control and measure the engine speed and output torque. Fig. 1, displays a schematic diagram of the experimental set up.

To achieve real time control over the air/fuel mixture preparation as well as hydrogen addition, two fuel injection systems were implemented within the OMC Wankel engine, one for ethanol and the other for hydrogen. A calibrated Micromotion CMF010M Coriolis flow meter with an accuracy of 0.10% of rate for flow rates of 0–23 g/s was used to meter the fuel flow of ethanol. The ethanol used in this study is a 100% pure Ethanol, 200 proof (100%). The hydrogen used was Bottled industrial hydrogen (99.95% purity) that is regulated down to 35 PSIG and metered via a calibrated GFC 47 Aalborg differential pressure mass flow controller, with an accuracy of ±3% (0–20% full scale), and ±1.5% (20–100% full scale).

A hybrid electronic control unit (HECU) was developed in the laboratory. The HECU uses the original electromotive ECU and calibration computers to control in a real time the spark timings, injection timings and injection durations of ethanol and hydrogen according to the desired air to fuel ratio and the specified hydrogen energy fractions in the intake.

A calibrated Kistler 6051B high temperature piezoelectric pressure transducer was used to capture working chamber pressure data (sensitivity 20.5 pC/bar). The crank angle signal was synchronized with pressure trace. Working chamber