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# Numerical investigation on the mixture formation and combustion processes of a gasoline rotary engine with direct injected hydrogen enrichment

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## HIGHLIGHTS

- A CFD model was established and validated for $H_2$-gasoline fueled rotary engine.
- $H_2$ was direct injected in the combustion chamber at three injection positions.
- The mixtures formation and combustion processes were investigated.
- Proper $H_2$ distribution burned the mixtures in the rear region of chamber.

## ARTICLE INFO

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## ABSTRACT

The present study established a computational fluid dynamics model and numerically investigated the mixture formation and combustion processes of a gasoline rotary engine enriched by the direct injected hydrogen at three injection positions. It is found that the special flow field inside rotary engine combustion chamber has strong interactions with the hydrogen jet-flow, and the hydrogen distribution could further influence the charge combustion. At the end stage of compression stroke, the mainstream field whose direction same to rotor movement is formed, and a vortex with high vorticity existed in the front of combustion chamber. With the influences of mainstream field and vortex, the hydrogen almost fills half of combustion chamber and properly rich hydrogen region distribution is obtained near the spark plug with the injection position close to the spark plug. In addition, proper equivalence ratio distribution could enhance the flame propagation and mixtures combustion completeness in rear region of combustion chamber. Compared with injection position far away from the spark plug, the peak in-cylinder pressure of the injection position close to the spark plug increases by 18.3%, and carbon monoxide emission is decreased obviously, but nitrogen monoxide emission increases due to higher in-cylinder temperature.

## 1. Introduction

Rotary engine possesses high operating speed, simple design [1], low noise level and high power to weight ratio [2], it is able to satisfy the power demand of plug-in hybrid vehicle and small-unmanned aerial vehicle. Therefore, the rotary engine is widely used in both the military [3] and civil area [4]. However, the flattened combustion chamber structure, high surface to volume ratio and linear sealing method make rotary engine always suffer low thermal efficiency [5], high fuel consumption [6] and high emissions [7]. Several new technologies have been applied in rotary engine, such as turbo system [8], direct-injection stratified-charge system [9], heat pipe assisted cooling system [10] and laser ignition system [11], which have effectively improve rotary engine performance. Meanwhile, fuel property is another key factor for internal combustion engine (ICE) performance. Considering the ability and safety of fuel transport in extended-range electric vehicles and mobile power generation device, gasoline is one of the most widely used fuels in spark-ignition rotary engine. Nevertheless, the homogeneous gasoline-air mixtures are difficult to be formed in the flattened combustion chamber under high operating speed condition. Besides, the fast and complete burning is also restricted by the long and narrow combustion chamber. Therefore, the fuel economy and emissions performance of the gasoline rotary engine are further deteriorated. Generally, a fuel with high flame speed and diffusion speed is more suitable for the rotary engine.

Comparatively, hydrogen is a renewable and green fuel [12], which

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can be produced from water [13] and biomass [14] by microbe [15,16] and solar [17,18]. Meanwhile, hydrogen also has high flame speed [19], high diffusive speed [20], wide flammability and so on and it is a promising green alternative fuel for spark-ignition engines, [21] including rotary engine [22]. According to the researches of Huang et al. on fundamental combustion devices and spark ignition engines, hydrogen enrichment could promote the formations of O, H and OH radicals [23] in nature gas combustion processes. Meanwhile, the flame speed [24] and combustion stability [25] increased effectively. The engine cyclic variability decreased after hydrogen addition [26]. Consequently, the hydrogen enrichment is a promising approach to improve the combustion performance of ICE [27,28]. Kacem et al. [29] numerical and experimental investigated the effect of hydrogen enrichment on LPG fuelled reciprocating engine. The results showed that the brake torque produced by 20% hydrogen enrichment increased by 20% compared to the pure LPG under high engine speed. Navarro et al. [30] developed a zero-dimensional model to predict hydrogen-enriched methane engine's performance and carbon dioxide ($CO_2$) emissions. With the increase of hydrogen proportion, the maximum pressure and indicated work increased, $CO_2$ emissions dropped. Amrouche et al. experimentally studied the effects of hydrogen enrichment on ethanol and gasoline rotary engine performance at lean and wide open throttle conditions. The test results confirmed that hydrogen enrichment increased the thermal efficiency [31], extended the lean operation limit and decreased the hydrocarbon (HC) and carbon monoxide (CO) emissions [32]. Ji et al. conducted a series of researches to investigate the combustion and emissions characteristics of a hydrogen blended gasoline rotary engine under various operating conditions. Their researches indicated that the cyclic variation, fuel energy flow rate, HC, CO and $CO_2$ emissions were reduced after hydrogen blending [33]. Meanwhile, peak chamber temperature, pressure and heat release were enhanced by hydrogen addition [34]. Pan et al. [35] also numerical studied the influence of hydrogen enrichment on combustion process of a natural-gas-fueled rotary engine. The results showed that the peak pressure increased by 29% with hydrogen enrichment. Therefore, hydrogen enrichment is a feasible way to improve the rotary engine performances. However, hydrogen port injection occupies the volume of intake air and reduces the inhaled mass of main fuel, which decreases the volumetric and combustion efficiencies of the engine.

As the combustion rate could be increased by controlling the fuel distribution in the combustion chamber [36], the drawback of hydrogen port injection could also be overcome by direct injection (DI) [37]. Especially for the rotary engine, according to the special mechanical design and operation mode, a mainstream flow field whose movement direction same to the rotor is formed in the combustion chamber. With the effect of mainstream flow, the flame propagation direction is deflected to the rotor movement direction and the center of the burned zone moves in same direction. Therefore, an unburned zone exists in the rear combustion chamber until the exhaust valve opened [38]. If the unburned mixtures in rear region of the combustion chamber can be ignited by the ideal distributed hydrogen, the fuel economy and emissions performances of the rotary engine could be effectively improved. Consequently, the application of DI is an effective method to enhance the rotary engine performance. To achieve a high combustion efficiency, it is important to study the effects of hydrogen distribution on flame propagation in gasoline rotary engine. Generally, taking full advantages of DI fuel property contributes the improvement of engine performance.

For the conventional reciprocating engine, Huang et al. numerical and experimental investigated the combustion and emissions performance of an ethanol direct injection (EDI) plus gasoline port injection (GPI) engine. The test results indicated that EDI contributed to increase the pressure rise rate [39] and maximum in-cylinder pressure [40], which resulted in greater power output and thermal efficiency. Although CO and HC emissions increased with EDI, these issues could be controlled by EDI heating [41]. Zhuang et al. [42] also studied the effect of EDI on knock mitigation in a GPI engine. The test results showed that EDI plus GPI could effectively mitigated engine knock and permitted more advanced spark timing. In the ethanol energy ratio range from 15% to 35%, every 2% or 3% increment of ethanol energy ratio permitted about 2 °CA advance of knock limited spark advance. Biffiger et al. [43] experimental compared the three different injection strategies: pure port injection of methane, pure port injection of hydrogen-enriched methane and a combination of port injected methane and direct injected methane or hydrogen. The test results showed that the extension of lean limits of engine operation with hydrogen direct injection and methane port injection increased compared to the premixed combustion of pure methane and similar to that of premixed hydrogen-enriched methane. Yu et al. conducted a series of studies on combustion and emissions characteristics of a gasoline engine with hydrogen DI. Their researches showed that flame development and propagation durations were reduced after hydrogen DI. Meanwhile, the engine performed higher heat release rate with the rise of hydrogen fraction as well as the effective thermal efficiency [44]. Cyclical variation was decreased and lean-burn limit was extended. Besides, HC and CO productions were reduced, but nitric oxide ($NO_x$) generations increase [45].

For the rotary engine, Hasegawa et al. [46] experimental studied the fuel–air mixtures formation process in a DI rotary engine. The test results indicated that the vortexes in the combustion chamber played a key role in the mixtures formation process. Pan et al. numerically investigated the effect of injection timing (IT), injection angle (IA) and injector position in the mixture formation and combustion process in a DI natural gas rotary engine. Simulation results showed that the combustion rate was improved by small IA with IT at early stages of intake stroke, as well as big IA with IT at early compression stages [47]. Besides, compared with the fuel port injection, the injector position installed at 50 mm apart along the engine major axis and IT fixed at 360 °CA BTDC (Crank Angle Before Top Dead Center) obtained a 29.7% increase in the peak pressure [48].

As discussed above, the advantages of hydrogen could be fully revealed on promoting the combustion process with hydrogen DI. Different from gaseous fuels, the mixture formation and combustion processes of liquid gasoline in rotary are more complex. The position of hydrogen DI enrichment could not only influence the mixtures formation and distribution characteristics by affecting the charge motion and flow field within the combustion chamber, but also affect the charge composition and combustion characteristics. Therefore, a computational fluid dynamics (CFD) model is established to study the mixture formation and combustion processes in a gasoline rotary engine with enriched by DI hydrogen under different injection position.

## 2. Models and validation

### 2.1. Geometric model generation and boundary conditions

The geometric model is established based on a side-ported Z160F rotary engine. The schematic diagram is shown in Fig. 1 and the main engine specifications are listed in Table 1.

To study the grid independence, three different basic grid sizes of combustion chamber are chosen, which are 1, 2 and 3 mm, respectively. Meanwhile, 2 mm basic grid size with adaptive mesh refinement (AMR) case is also listed here. AMR can automatically refine the grid size to 0.5 mm in velocity, temperature and species fluctuating domains. The predicted mean in-cylinder pressures under different grid size are displayed in Fig. 2. The pressure curve of 2 mm grid size adopted AMR is almost overlapped with that 1 mm. To balance the calculation accuracy and time cost, the 2 mm grid size with AMR case is selected as the setting in following cases.

Three different nozzle positions of A, B and C which symbolize the direct hydrogen injection at the rear, middle and front of the combustion chamber as shown in Fig. 3 are chosen in this study. The position of