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# Numerical investigation of mixture formation and combustion in a hydrogen direct injection plus natural gas port injection (HDI + NGPI) rotary engine

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ABSTRACT

Hydrogen direct injection (HDI) in cylinder is considered as an effective method to improve natural gas engine performance. The present study aims to bridge the gap on the HDI in rotary engine, and to investigate the effect of hydrogen injection timing (IT) and hydrogen injection duration (ID) on mixture formation and combustion process of a hydrogen direct injection plus natural gas port injection (HDI + NGPI) rotary engine. Numerical approach was used in this study for obtaining some critical information, which was difficult to obtain through experiment, such as flow field, fuel distribution and some intermediate concentration fields in cylinder. The research results showed that for mixture formation, the distribution law of the hydrogen and the natural gas at the late stages of the compression stroke (100°CA (BTDC)), was as follows: at a fixed ID of 24°CA, with retarded hydrogen IT, the stratification phenomenon of hydrogen became obvious increasingly, and the hydrogen distribution area moved towards the back of the combustion chamber continuously. At a fixed IT of 210°CA (BTDC), with the extension in ID, the accumulation area of hydrogen reduced significantly, and the hydrogen continued to gather in the middle of the combustion chamber. For combustion process, the overall combustion rate for the hydrogen injection strategy which had an IT of 210°CA (BTDC) and ID of 40°CA (case ID5), was the fastest. This was due to the fact that compared with the leading spark plug (LSP), the combustion condition around the trailing spark plug (TSP) has a great influence on the combustion process. For case ID5 at ignition timing, the hydrogen concentration near the TSP is high enough for the rapid formation of flame kernel. Compared with case IT1 which had an IT of 390°CA (BTDC) and an ID of 24°CA, the improved combustion rate of case ID5 had a 11.7% increase in peak pressure, and a 7% decrease in NO emissions.



## Introduction

As a replacement for the reciprocating piston engine, the Wankel rotary engine has its unique advantages, such as simple design, low noise and multi-fuel capability [1–5]. Due to the above-mentioned advantages, the rotary engine plays a significant role in some special fields, for instance, range extender (RE) in electric vehicle, small unmanned aerial vehicle

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(UAV) and high-performance racing car, etc. Among them, the range extender which uses the rotary engine as a power source, is considered one of the most promising electrical generator for electric vehicle [6–9]. Because of the widespread applications described above, many countries pay more and more attentions to the research on the rotary engine [10,11].

Currently, several common fuels have been applied to rotary engines, such as diesel, gasoline, ethanol, natural gas and hydrogen [12]. Among them, gas fuel is relatively suitable for combustion in rotary engines, such as natural gas and hydrogen. This is chiefly because that the gas fuel can overcome the defect of the poor liquid fuel atomization in the long and narrow combustion chamber of rotary engines. In addition, as a clean and great efficiency fuel, natural gas is widely used in power machines [13–15]. Therefore, the rotary engine fueled natural gas is considered as a new and promising engine. Unfortunately, the combustion efficiency of rotary engine still needs to be improved urgently. The reason for the low combustion efficiency is that, due to the unidirectional flow in combustion chamber, the fuel stayed at the rear of combustion chamber and cannot be burned in time [16]. Moreover, the low combustion speed of natural gas could also exacerbate the above drawback [17].

In recent years, many kinds of approaches have been used to improve the efficiency and reducing the emissions of rotary engine [18–27]. In general, these research approaches can be classified into two types. One type is hydrogen addition on the basic fuel, which is used to improve mixture combustion quality. This is chiefly because that the high combustion speed of hydrogen could accelerate the combustion rate of the original fuel [28–30]. For example, Ji et al. [11,18] studied the effect of hydrogen addition on combustion process of a rotary engine fueled with gasoline. The results showed that the hydrogen addition could significantly improve the combustion characteristic at idle. Amrouche et al. [19] studied the effect of hydrogen addition on combustion performance of an ethanol rotary engine through experiment. The experimental data showed that the flame propagation periods and the cyclic variation were decreased by the hydrogen addition. An experiment was also conducted by Amrouche et al. [12] to study the effect of hydrogen addition on lean operation limit of a rotary engine fueled with gasoline. The results showed that the lean operation limit of the original engine was extended by the hydrogen addition by improving the combustion process. Fan et al. [20] studied the effect of hydrogen blending mode on the combustion process of a natural gas rotary engine by numerical simulation. The results showed that compared with the hydrogen port injection, higher combustion efficiency is acquired by the hydrogen direct injection. The other type is that the coupling function between the flow field and mixture formation in cylinder, is studied to improve the combustion efficiency of rotary engines. For example, Maki et al. [21] used particle image velocimetry (PIV) to acquire the 2D flow field on the rotor housing central plane (RHCP) of an optical rotary engine. The motion law of the vortexes on RHCP was thus obtained. Hasegawa et al. [22] used the schlieren method to study the mixture formation on the RHCP of a DI rotary engine. The result showed that the air-fuel mixture formation was largely controlled by the vortexes on RHCP. Tabata et al. [23] studied the combustion process on the RHCP in a rotary engine fueled with hydrogen, by using a high-speed camera system. The results showed that when hydrogen was used as the fuel in the rotary engine, the flame propagation was very fast. Nizar et al. [24] also acquired combustion pictures on the RHCP of a rotary engine fueled with hydrogen. The experimental results showed that the turbulence in the front of combustion chamber could improve the combustion rate effectively. Jeng et al. [25] used FLUENT software to make a 2D numerical simulation. This simulation was aimed to investigate the effect of the recess size on combustion process in rotary engine. Simulation results showed that the vortexes in cylinder which were important for mixture formation were induced by the rotation of the rotor at intake stroke. Harikrishnan et al. [26] made a 3D numerical simulation on STAR-CD software, to investigate the effect of recess shape on combustion process in a rotary engine. The results showed that compared to the region near the spark plug, the fuel located between the two spark plugs, has a lower combustion rate. Spreitzer et al. [27] described the ability of the CONVERGE software on the numerical study of rotary engines. Their results showed that, the air flow movement and combustion process in cylinder could be studied in an unprecedented analytical depth by numerical simulation method.

From the previous studies on rotary engine, it can be seen that the addition of hydrogen, the organization of flow field and the improvement of fuel distribution, can make the combustion rate increase appreciably. Therefore, many researchers tried to use hydrogen direct injection in cylinder to improve engine (reciprocating engine or rotary engine) performance [20,31]. This is mainly due to the fact that the method of hydrogen direct injection not only makes full use of the hydrogen properties, but also further organize a reasonable hydrogen distribution to increase combustion rate [32,33]. Generally, the mixture formation process and combustion characteristics in port injection and direct injection engines are mainly determined by the injection strategy, such as injection timing (IT) and injection duration (ID) [34,35]. In recent years, scholars have done a lot of research on the injection strategy in the reciprocating engine using hydrogen direct injection. For example, Biffiger et al. [31] studied the effect of split port/direct injection of methane and hydrogen in a spark ignition engine. The results showed that late fuel injection towards the spark plug could produce a significant advantage due to increased turbulence or charge stratification. Du et al. [36] conducted an experimental investigation on combustion and emission characteristics of a lean burn gasoline engine with hydrogen DI. Their results showed that the addition of hydrogen made stable combustion at 1.5 excessive air coefficient possible. Shi et al. [37] also studied the effect of ignition timing on the combustion and emissions of a hydrogen-enhanced gasoline engine. Their results showed that when the hydrogen IT was 110°CA (BTDC), a higher mixture concentration was acquired around the spark plug, which is helpful to ignition and the formation of flame kernel. Sun et al. [38] studied the effect of hydrogen DI on particle number emissions from a lean burn gasoline engine. The results indicated that direct injection of hydrogen to SI engine could avoid the associated disadvantage of high particle number issue in the stratified combustion mode. Hamada et al. [39] made an experimental investigation to investigate the effect of IT on

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