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The influence of injection strategy on mixture formation and combustion process in a direct injection natural gas rotary engine

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HIGHLIGHTS

- The fuel movement was affected by the impact angle and the intensity of vortex.
- With retarded injection timing, the motion trend of fuel at ignition timing was obtained.
- The ideal fuel distribution at ignition timing for high combustion rate was studied.
- The optimal injection strategy had a high increase in the peak pressure.
- The drawback of the optimal injection strategy was a certain increase in NO emissions.

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ABSTRACT

The application of direct injection (DI) technology is considered as an effective way to improve the performance of the rotary engine. This work seeks to numerically dissect the influence of injection strategy on mixture formation and combustion process in a DI natural gas rotary engine. A 3D dynamic simulation model established in our previous work was used to acquire some critical information which was difficult to obtain through experimental investigations. These were the flow field, the fuel distribution, the temperature field and some intermediate concentration fields in the combustion chamber. Simulation results showed that for mixture formation, the motion mechanism of the fuel varies with the injection position. The mass of fuel located at the back of the combustion chamber for injection nozzles A, B and C, was determined by the intensity of vortex I, the coupling function between the value of the impact angle and the intensity of vortex I, and the value of the impact angle respectively. In addition, with retarded injection timing, the accumulation area of fuel for all injection nozzle positions moved from the back to the front of the combustion chamber at ignition timing. For combustion process, the overall combustion rate for the injection strategy (case A4) whose nozzle was 50 mm apart along the engine major axis and whose injection timing was 360°CA (BTDC), was the fastest. Compared with the out-cylinder premixed gas-filling method (case premix method), the improved combustion rate of case A4 had a 29.7% increase in peak pressure, but also a certain increase in NO emissions.

1. Introduction

The rotary engine is widely used in the military and civil area for its advantages, which includes multi-fuel capacity, simple and compact design and small noise level [1–3]. In particular, the development of plug-in hybrid electric vehicle (PHEV) and small unmanned aerial vehicle (UAV) desperately needs a kind of power equipment with high power-to-weight ratio. As the rotary engine is able to satisfy the demand excellently, it has wide application prospects [4]. For example, the combination of a compact rotary engine and a small generator dynamo is considered as one of the most promising power generation modes for PHEV [5]. For the above reasons, more attention has been paid to the research of rotary engines by many countries and research institutes.

Currently, various fuels such as gasoline, diesel, aviation kerosene, natural gas and hydrogen have been successfully applied to rotary engines. However, the disadvantages of the rotary engine fueled with diesel and aviation kerosene, such as high fuel consumption and high emissions, seriously restrict its development [6]. There are two reasons for this phenomenon. One reason is that the long and narrow combustion chamber shape of the rotary engine makes it hard for the low volatility liquid fuel to atomize

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[7]. The other reason is that, the main flow pattern in the combustion chamber is unidirectional at ignition timing [8]. The general direction of the unidirectional flow comes from the back to the front of the combustion chamber, which results in the different flame propagation in the front and the back of the combustion chamber. Along with the direction of the flow, it is easy for the flame to propagate towards the front of the combustion chamber, which makes the fuel in the front of combustion chamber burn out without delay. However, against the direction of the flow, it is difficult for the flame to propagate towards the back of the combustion chamber, which leaves a lot of unburnt fuel in the back of the combustion chamber [9,10]. Relatively speaking, gaseous fuel like natural gas and hydrogen, is easy to form combustible mixture in the cylinder, compared to diesel, aviation kerosene and other traditional liquid fuel. That is, the rotary engine fueled with gas can greatly overcome the poor fuel vaporization of the rotary engine fueled with liquid fuel [8]. In addition, natural gas is applied extensively as a kind of high quality clean energy, which is put forward by many governments [11]. Therefore, the natural gas rotary engine is considered a new clean and promising energy system. However, it cannot be neglected in truth that the combustion rate of the natural gas in the back of the combustion chamber is still in a low level. Moreover, when the out-cylinder premixed gas-filling method (premixed-charge) is used, the above problem is further exacerbated. This is chiefly because the gas mixture is evenly distributed in the combustion chamber for the premixed-charge rotary engine, which results in lots of gas mixture distributed in the back of the combustion chamber. That is, the low combustion rate in the back of the combustion chamber still forms a barrier to further improve the performance of the rotary engine fueled with natural gas. Therefore, the question of how to improve the combustion efficiency of the rotary engine has been a major issue. In recent years, some new technical methods have been applied. For example, new apex seals were designed for a rotary engine to improve sealing and increase volumetric coefficient [12]. Hydrogen was added to increase the combustion rate of gasoline in a rotary engine [13]. Direct injection (DI) technology was used to organize the fuel distribution, so as to improve combustion process in a rotary engine [14]. A pilot flame ignition system was added to a direct injection stratified charge rotary engine, to find the possibility of simultaneous reductions of fuel consumption rate and HC exhaust gas emissions [15]. Among them, the application of DI technology is considered as a very effective way of solving the problem enumerated above [14]. This is mostly because the combustion rate can be increased by controlling the fuel distribution. When the fuel is only distributed at the middle and the front of the combustion chamber, the ideal fuel distribution can fundamentally avoid the problem of the unburnt fuel in the back of the combustion chamber [8]. To achieve the ideal fuel distribution and high combustion efficiency, it is imperative to study the realization mechanism of different stratified mixture and its effect on flame propagation in DI rotary engine. Generally, mixture formation and combustion process in DI engines (DI reciprocating engine or DI rotary engine) are mainly determined by the in-cylinder flow field, the injection strategy and the combustion chamber geometry [16,17]. For the reciprocating engine, Krishna et al. [18] used particle image velocimetry (PIV) and computational fluid dynamics (CFD) to analyze the in-cylinder flow field in a two-stroke engine under motoring conditions. They found that the turbulent kinetic energy and tumble ratio decreased by about 13% and 26% respectively, when the compression ratio was increased from 7 to 8. Wang et al. [19] described the optimization of the combustion chamber geometry to improve the combustion efficiency and reduce the HC and CO emissions in a natural gas engine with diesel micro-pilot-induced ignition (MPII). Keskinen et al. [20] investigated the effect of injection pressure and injection timing on mixture formation process in a DI engine. They found that mixing rate was highly sensitive to injection timing, and only slightly influenced by injection pressure. Ma et al. [21] studied the influence of diesel injection strategy on gasoline/diesel dual-fuel combustion mode. The research results showed that in controlling combustion, the earlier the diesel fuel was injected, the larger role the mixture reactivity played. The later the diesel fuel was injected, the larger role the mixture stratification played. Park et al. [22] studied the influence of multiple-injection strategies on an engine performance fueled with biodiesel fuel. It was found that compared with the single-injection mode, the multiple-injection mode showed a higher indicated mean effective pressure and a decrease of soot, HC, and CO emissions. Agarwal et al. [23] investigated the effects of fuel injection pressure on spray characteristics in a DI engine. Their investigation results showed that compared with lower fuel injection pressure, higher fuel injection pressure led to a longer spray tip penetration and larger spray area.

As seen above, previous works suggested that, reasonable flow organization, injection strategy and combustion chamber geometry, can improve mixture formation and combustion efficiency in the reciprocating engine. However, the research on the realization mechanism of different stratified mixture and its effect on flame propagation in the DI rotary engine is still inadequate. In terms of experimental research, Maki et al. [24] conducted an experiment to measure a 2D flow field on the rotor housing central plane (RHCP) of a side ported rotary engine. Hasegawa et al. [25] made an experimental visualization study on the air-fuel mixture formation inside a low-pressure DI stratified charge rotary engine. The flow field and the fuel vapor distribution on the RHCP of the rotary engine, were visualized with the laser light sheet method and the schlieren method. The motion pictures showed that the vortices which gave major features to the flow field, played a key role in the air-fuel mixture formation process. Tabata and Kagawa [14] investigated the jet characteristics of the hydrogen gas injector in a constant volume vessel using high speed photograph method. Moreover, the combustion flame propagation on the RHCP of the hydrogen rotary engine was visualized by high-speed camera system. Experimental results showed that the jet penetration of the low-density gas was weak and the flame propagation was fast in the hydrogen combustion. Kawahara et al. [26] made cycle-resolved measurements to investigate the effects of the fuel concentration near the spark plug on the combustion characteristics in a rotary engine. Experimental results showed that there was a strong correlation between the fuel concentration measured with the spark plug sensor and the combustion characteristics during the initial combustion period, which occurred faster when conditions were slightly richer than stoichiometric near the spark plug. Nizar et al. [9] used a high-speed camera to acquire combustion pictures on the RHCP of an optical premixed-charge hydrogen-fueled rotary engine. Experiments with optical and real rotary engines proved that turbulence effectively increased mass burning rate in front of the combustion chamber. Karatsu et al. [10] used two high-speed cameras to observe the combustion process in bottom view and side view simultaneously. Experimental results once again demonstrated that the flame was easily propagated towards the front of the combustion chamber, but difficult to propagate towards the back of the combustion chamber. From the above mentioned experimental works, it can be seen that the flow field, the mixture formation and the combustion process on the RHCP of rotary engine has been measured. However, the 3D flow field, the mixture formation and the combustion process inside the combustion chamber could not be obtained, due to limitation of the experimental set-up. Moreover, fuel reaction rate which affects the engine performance predominantly cannot be realized from the measurement [27]. However, their meaningful work offered valuable experimental data, which could be used for validating the simulation.