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Effect of injection strategy on fuel-air mixing and combustion process in a direct injection diesel rotary engine (DI-DRE)

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ABSTRACT

This paper aims at improving the combustion efficiency of direct injection diesel rotary engine (DI-DRE) by adjusting the injection strategy. An experimental validated 3D-dynamic simulation model coupled with chemical kinetics mechanism was established. A high-pressure direct injection mode was used to investigate the effect of diesel fuel injection timing (IT) and injection angle (IA) on fuel-air mixing and combustion process in a DI-DRE with spark ignition. Results showed that increasing IA changed the fuel distribution position from front to back of the combustion chamber, delayed IT and the fuel distribution area also became narrower and more concentrated. For combustion process, the fuel concentrated at partial central position towards the back of the combustion chamber was better for ignition. The distribution of more continuous mixture between the two spark plugs and concentration of more fuel near the trailing spark plug (TSP) was conducive to the improvement of combustion efficiency. The preferable combustion rate and emission performance were obtained when the IT was 80°CA (BTDC) and IA was 90°. Compared to the original scheme, maximum combustion pressure increased by16.82% while crank angle for maximum combustion pressure reduced by 8.19%. Soot and CO emissions reduced by 41.48% and 32.87% respectively. However, NO and CO_2 emissions increased slightly.

1. Introduction

The rotary engine (RE) has the advantages of simple structure, high power density, low noise and low vibration [1,2]. These innate features have attracted considerable attention since its inception. Due to its small size, lightweight, multi-fuel and high-speed performance, RE has been widely used in many areas, especially in aerospace and automotive field. For aerospace field, RE is mainly used in unmanned aerial vehicle (UAV) and helicopters. UAV Engines Ltd, a UAV manufacturer in England, is famous for its “AR” series RE [3]. Switzerland Mistral Engines Ltd has been developing and producing multi-cylinder RE [4]. For the automotive field, RE is mainly used as vehicle power and range extender power. It is well known that the most successful company to use RE for automotive power is Mazda Motor Company in Japan. And also it has developed the “RX” series RE which is able to burn hydrogen and gasoline [5]. Austrian AVL company has carried out researches on RE as the expander power [6]. Although RE has been widely used in many areas, some shortcomings restrict the further expansion of its application. For example, the most prominent problem is the incomplete combustion in the back of the combustion chamber, which leads to higher fuel consumption and poor emissions. Currently, many new technologies have been used to improve the economic performance and emission performance of RE, such as installing the turbocharger to improve the volumetric efficiency [7], optimizing the design of apex and corner seals to improve the gas sealing performance [8], using the DI technology to rationally organize the mixture distribution [9], burning gas fuel such as, hydrogen [10] and natural gas [11] and blending hydrogen [12–14] to improve the flame propagation speed. Among them, the DI technology is deemed to be an effective solution to the above-mentioned problem whether be it burning of gas fuel or liquid fuel [9]. This is because the DI technology can precisely control the fuel injection parameters, such as injection timing (IT) and injection angle (IA), to optimize the injection strategy and realize the fuel stratified distribution. It should be noted that, since the compression ratio of RE is relatively low, the compression ignition is not feasible and the spark ignition method is generally used. Accordingly, this special rationale will bring more challenges to the improvement of combustion process in the RE. Therefore, by optimizing the injection parameters to ensure that the mixture distributes near the spark plug and can be ignited reliably are quite important in a direct injection rotary engine (DIRE).

Nowadays, DI technology has had matured advancement application in reciprocating piston engine, which provides valuable experience for its application in RE. However, due to the rotational movement of

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Nomenclature

DI	direct injection
RE	rotary engine
DIRE	direct injection rotary engine
UAV	unmanned aerial vehicle
DI-DRE	direct injection diesel rotary engine
IT	injection timing
IA	injection angle
TSP	trailing spark plug
LSP	leading spark plug
TDC	top dead center
BTDC	before top dead center
ATDC	after top dead center
CFD	computational fluid dynamics
EDC	Eddy-dissipation concept
DPM	discrete phase model
KH-RT	Kelvin-Helmholtz and Rayleigh-Taylor
PIV	particle image velocimetry
P_{max}	maximum combustion pressure
φ_{max}	crank angle for maximum combustion pressure
T_{max}	maximum combustion temperature

the triangular rotor, the air movement pattern in RE is very different from that of the reciprocating piston engine. This brings many challenges to reasonably organizing the mixing formation and the combustion process in DIRE. Therefore, some scholars have carried out researches on the fuel-air mixing and combustion process of DIRE. Earlier, Nguyen et al. [15] built a DIRE assembly. Then based on the measured pressure data, they evaluated the performance and combustion efficiency of a diesel RE under different working conditions. The results showed that when the injection parameters remain unchanged, the burning rate was improved with a proper advanced ignition timing, and the peak pressure and average temperature were also improved. Hamady et al. [16] studied the fuel spray-air mixing flow characteristics of kerosene/air in a DIRE by using the visualization technology and high-speed cameras. Their results indicated that the formation of vortices during compression process had a significant effect on the turbulence intensity in the combustion chamber during the early combustion stage. They also pointed out that injection parameters were critical because large fuel droplets could lead to incomplete or late combustion. Morita et al. [17] used a high-speed flow visualization technique to study the spray characteristics and the mixing process in a DIRE. It was found that the airflow had an important effect on the mixing process after the injection process was completed. Moreover, injection pressure and IT had a significant effect on the spray characteristics. Specifically, at higher injection pressure, the jet mixing area was larger. At late IT it could lead to the fuel directly impinging on the rotary wall and reducing the fuel-air mixing. Eiermann et al. [18] designed a spark-assisted DIRE with heavy fuel. They discussed the influence of nozzle position and geometry on the combustion process. They found that the fuel IT and injection duration had an important effect on the performance of the engine, especially under low speed conditions. By increasing the nozzle diameter, the injection duration was shortened and it led to poor atomization. Hasegawa et al. [19] researched the DIRE by using gasoline under a low injection pressure, and analyzed the influence of IT on the mixture distribution. Their experimental data showed that an earlier IT is advantageous in obtaining the ideal mixture stratification at the front combustion chamber and vice versa at the back combustion chamber. The earlier literatures researched on different liquid fuels in the DIRE. They mainly focused on studying and evaluating the performance of the DIRE. Their researches found that the injection strategy was very important for the DIRE. Without doubt, the obtaining of the basic experimental data is very important, however, the key information during the fuel movement and combustion process in the combustion chamber are still not intuitively presented. Recently, there has been development of the gas fuel RE and the computational fluid dynamics (CFD) technology. This has made the research work on the DIRE focused on gas fuel and dynamics numerical simulation. Tabata et al. [20] adopted the visualization techniques to study the hydrogen/air injection process and combustion characteristics of DIRE. The experimental results indicated that the jet penetration of hydrogen in the combustion chamber was low. The fuel distribution in the direction of the injection axis was also irregular. Besides, the combustion propagation became fast and the flame propagation process moved from back to front of the combustion chamber. Votaw [21] explored the influence of the pilot injection parameters such as the IA, injection position and injection retraction distance on the combustion characteristics of the DIRE with heavy fuel by the numerical simulation method. Their results demonstrated that the engine could obtain the ideal combustion characteristics when the nozzle was set at the top dead center (TDC) position, the IA was 65° and the injection retraction distance was 6.6 mm. In addition, with an appropriate advanced IT and ignition timing it was better for the engine performance. Boretti et al. [22] changed the ignition method of RE to injection ignition method and established a simulation model of DIRE working process that could simultaneously ignite hydrogen and gasoline. Results showed that the improved engine combustion efficiency and torque output were better than those of premixed and port injection method. Currently, our research team has also done a series of research works on the DI technology and multi-fuel characteristics of RE [9,11,13]. In these researches, the injection strategy was systematically studied and the effect of the injection parameters on the fuel-air mixing, combustion process and emission characteristics in a DIRE was analyzed. The results indicated that, the fuel distribution in the combustion chamber, which was controlled by injection strategies, is very important for the combustion process. Also, using DI technology in a RE the combustion rate was significantly improved. However, these research works were only related to the gas fuel with low-pressure direct injection mode, but the liquid fuel with high-pressure direct injection mode has not been studied. Finally, in view of these literatures, it is found that the injection parameters have an important influence on the mixture formation and combustion process in DIRE. The CFD technology is a feasible and effective method to study the DIRE. However, the study of the DIRE is still not in-depth and comprehensive enough and the crucial information in the combustion chamber has not been fully presented. Especially, there is less literature focusing on the direct injection diesel rotary engine (DI-DRE) and almost no paper involved in 3D-dynamic simulation of a DI-DRE based on the chemical reaction kinetics.

For this purpose, a 3D-dynamic simulation model which is coupled with reduced n-heptane chemical kinetics mechanism was established and validated by experimental data. Then a high-pressure direct injection mode was used to numerically simulate the effect of diesel fuel injection parameters on mixture formation and combustion process in a DI-DRE with spark ignition. There is thus focus on presenting some key information during the DI-DRE working process, such as the temperature field, fuel concentration distribution and combustion intermediate concentration field. The influence of diesel fuel IT and IA on fuel-air mixing and combustion process was analyzed. The results could provide theoretical guidance for high-pressure DI technology application in RE, and also have some reference value in helping understudy some other liquid fuels for DIRE.