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Numerical investigation of the effect of injection strategy on mixture formation and combustion process in a port injection natural gas rotary engine

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ABSTRACT

This work aimed to numerically study the influence of injection strategy on mixture formation and combustion process in a port injection natural gas rotary engine. On the base of a 3D dynamic simulation model which was established in our previous work, some critical information was obtained, which was difficult to obtain through experiment, in terms of the flow field, the fuel distribution, the temperature field and the concentration fields of some intermediates. Simulation results showed that for mixture formation, the movements of fuel in injection stage were mainly controlled by the intensity of the vortex I for injection timing, and the value of jet flux for injection duration respectively. With retarded injection timing, the decreasing intensity of the vortex I resulted in less fuel moving toward the back of the combustion chamber. With the extension in injection duration, the decreasing value of jet flux resulted in more fuel staying at the back of the combustion chamber. For combustion process, the overall combustion rate for injection strategy which had an injection timing of 390 °CA (BTDC) and injection duration of 51.5 °CA (case ID4) was the fastest. This was mainly due to the fact that the accumulation area of fuel was at the middle and front of the combustion chamber. Meanwhile, fuel concentration near the leading and trailing spark plugs was conducive for the flame kernel formation. Compared with the injection strategy which had an injection timing of 450 °CA (BTDC) and an injection duration of 55 °CA (case IT1), the improved combustion rate of case ID4 had a 23% increase in the peak pressure, but also a certain increase in NO emissions.

1. Introduction

With energy crisis and environmental pollution occurring, energy saving and environmentally friendly electric vehicle (EV) in existence presents a great potential for the future [1,2]. However, the small range of electric vehicles is still one of the problems inhibiting the spread of these cars. Range extender (RE) in general is the realistic possibility to increase the range of plug-in hybrid electric vehicle (PHEV) in the near future without the need to improve the technology of the main battery storage. For improving the efficiency of entire vehicles, RE desperately needs a kind of power equipment with high-energy density and high power-to-weight ratio [3,4]. Compared with conventional reciprocating engine, the advantages of the rotary engine, like compact design, multi-fuel capability, low noise and low vibration levels, make it more suitable as the power equipment of RE [5]. For example, the combination of a compact rotary engine and a small generator dynamo is considered one of the most promising power generation modes for PHEV [6]. Therefore, for the wide application prospects described above, more attention is being given to the research on the performance and emission of rotary engine 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 [7]. Relatively speaking, gaseous fuels like natural gas and hydrogen, are more suitable to be used in rotary engines. This is mainly due to the fact that, gaseous fuel is easy to form combustible mixture in the cylinder as compared to diesel, aviation kerosene and other traditional liquid fuel. In addition, acting as an ecologically sensitive and efficient fuel, natural gas is often recognized as a promising option put forward by governments for a sustainable energy system [8]. Therefore, the natural

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gas-fueled rotary engine is considered to be a new and clean energy system. However, the question of how to improve the combustion efficiency of the rotary engine has been a major issue. This is because flow pattern in the combustion chamber is unidirectional flow at ignition timing. The general direction of the unidirectional flow is 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 toward 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 flow, it is difficult for the flame to propagate toward the back of the combustion chamber, which leaves a lot of unburned fuel in the rear of combustion chamber [9]. Moreover, when natural gas is used in rotary engine, its low burning speed could also exacerbate the above problem. Fortunately, the application of stratified combustion mode is considered as a key solution for these problems [10]. This is mostly because the combustion rate can be increased by controlling the fuel distribution, although the unidirectional flow pattern in the combustion chamber cannot be changed at ignition timing. Port injection and direct injection in cylinder are two ways of realizing stratified combustion. As compared to direct injection in cylinder, port injection is widely used in rotary engine, because of its low requirement on electronic fuel injection system [11]. Therefore, it is imperative to study the realization mechanism of different stratified mixture and its effect on flame propagation in the port injection natural gas rotary engine. Meanwhile, the injection strategy is one of the most influential factors for engine performance. The fuel-air mixing procedure significantly depends on the injection position, injection timing (IT), injection pressure and injection duration (ID) [12,13]. What is more, the mixture quality in the combustion chamber determines the combustion characteristics of the engine. At present, there are many studies on how to impact the combustion process by the injection strategy in reciprocating engines. For example, Yang et al. [14] experimentally studied the effects of natural gas port injection and diesel pilot injection on the combustion and emissions of a turbocharged common rail dual-fuel engine at low load. The results indicated that retarded natural gas injection timing achieved a stratified-like air-fuel mixture in cylinder under the different pilot injection conditions, which provided a method to improve the combustion performance and exhaust emissions at low load. Wang et al. [15] investigated the combustion and emission characteristics of a diesel engine with dimethyl ether (DME) as port premixing fuel under different injection timing. It was found that port premixing DME quantity played an important role in combustion and emission control. During low-temperature reaction phase, the peak value of heat-release rate (HRR) increased with a rise of port DME quantity because of relatively richer mixture concentration. Thangavel et al. [16] made experimental studies on simultaneous injection of ethanol-gasoline in the intake port of a four stroke spark ignition (SI) engine. It was found that the efficiency and torque were better at a mass ratio of 1:1 (50% of ethanol and 50% of gasoline) due to faster combustion as a result of better mixture preparation, as compared to conventional pre-blended injection of gasoline and ethanol. Lakshmanan et al. [17] made experimental studies at the optimized fixed injection duration of 90 °CA and injector opening time of 5 °CA (ATDC), to investigate the gas flow rate on the combustion, performance and emission of the engine. The experimental results show that the NO emission decreased with increase in gas flow rate, as compared to diesel fuel operating at full load. As seen above, despite previous works suggesting suitable injection parameters conducive to improve combustion efficiency, research about the effect of injection parameters on mixture formation and combustion processes in a port injection natural gas rotary engine are still rare. For example, as the air flow controls air-fuel mixture in rotary engine, particle image velocimetry (PIV) method was applied by Maki et al. [18] to measure the flow field in a rotary engine. However, due to the limitations of the experimental set-up, only the 2D flow field at low-speed was measured, that is, the 3D flow field under normal engine operating conditions could not be tested. Kawahara et al. [19] developed an optical spark-plug sensor with a double-pass measurement length using an infrared absorption technique for measuring hydrocarbon fuel concentrations. Cycle-resolved measurements were made to investigate the effects of the fuel concentration near the spark plug on the combustion characteristics of the commercial rotary engine. However, the distribution and movement of fuel in other positions of the cylinder could not be measured. Karatsu et al. [20] developed an optical rotary engine, and combustion in the combustion chamber was observed by bottom view and side view simultaneously using two high-speed cameras. Their work made significant contributions to the study of the flame propagation in the rotary engine. This once again demonstrated that it was easy to propagate the flame toward the front of the combustion chamber, but difficult to propagate the flame toward the rear of the combustion chamber by experimental research. However, further research on how to impact the combustion process by the fuel distribution is still needed. Spreitzer et al. [21] used the CONVERGE software to analyze the gas flow and the combustion processes in the three combustion chambers simultaneously. Although the mixture formation process was not discussed, their work showed that the rotary engine could be investigated in an unprecedented analysis depth through simulation. For example, Jeng et al. [22] used the FLUENT software to numerically investigate the influence of leakage through the apex seal, fuel type and recess size on the performance of a rotary engine. Their numerical results gave more insight into the effect of these parameters on the power output of a rotary engine.

This work seeks to bridge the gaps identified in literature, using numerical simulation to study the influence of injection strategy on mixture formation and combustion process in a port injection natural gas rotary engine. On the basis of the 3D dynamic simulation model which was established in our previous work [23,24], some critical information is obtained which is difficult to acquire through experiment. These are the flow field, the fuel distribution, the temperature field and some intermediate concentration fields. Our study also outlines a theoretical guide to determine the best injection strategy in the port injection natural gas rotary engine under different working conditions.

2. Geometric model generation and meshing

2.1. Computational domain

In the present study, the rotary engine has two spark plugs, leading spark plug (LSP) and trailing spark plug (TSP). A schematic diagram of the rotary engine is shown in Fig. 1(a). For convenience of discussion, the names of the components of the rotary engine are shown in Fig. 1(b). Technical specifications of the engine are listed in Table 1.

The simulations were performed at an engine speed of 3500 rpm and at wide open throttle. Natural gas was injected into the inlet port and all computations were made with excess air ratio of 1.5. The appropriate time window of the nozzle for fuel injection is from 470 °CA (BTDC) to 280 °CA (BTDC) for nozzle A. Therefore, at a fixed injection pressure, five different injection timings were used to study the effect of injection timing on mixture formation and combustion process in the engine. After that, at a fixed injection timing (390 °CA (BTDC)), eight different injection durations