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Effects of hydrogen blending mode on combustion process of a rotary engine fueled with natural gas/hydrogen blends

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ABSTRACT

The highly advanced wankel rotary engine is a promising energy system because of its favorable energy to weight ratio, multi-fuel capability and large specific power output. This work aims to numerically study the performance, combustion and emission characteristics of a side-ported rotary engine fueled with natural gas/hydrogen blends under different hydrogen blending modes. Simulations were performed using multi-dimensional software FLUENT 14.0. On the basis of the software, a three-dimensional dynamic simulation model was established by writing dynamic mesh programs, choosing the RNG k-ε turbulent model, the eddy-dissipation concept (EDC) combustion model and a reduced reaction mechanism. The three-dimensional dynamic simulation model based on the chemical reaction kinetics was also validated by the experimental data. Meanwhile, further simulations were then conducted to investigate how to impact the combustion process by the coupling function between hydrogen distribution and the flow field inside the cylinder. Simulation results showed that in order to improve the combustion efficiency, the low-pressure early injection should be used as the hydrogen blending mode. The low-pressure early injection, not only allowed the hydrogen in the combustion chamber to be distributed evenly, but also resulted in the high concentration areas of hydrogen located at the front of the trialing spark plug, which can be used to increase the combustion rate. For the hydrogen low-pressure early injection, the improved combustion rate made in-cylinder pressure and the intermediate OH increase significantly. Compared with no hydrogen induction, it shows a 29% increase in the peak pressures. Meanwhile, the drawback is the increase in NO emissions.

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Introduction

The highly advanced Wankel rotary engine is a promising energy system. The advantages of the Wankel rotary engine over a conventional reciprocating engine include a high power-to-weight ratio, a large specific power output from a high allowable engine speed, a simple and compact design resulting from less moving parts, multi-fuel capability, as well as low noise and vibration levels attributed to non-reciprocating components [1]. There are two main types of rotary engines, based on the different ways of intake: side ported rotary engines and peripheral ported rotary engines. The side-ported rotary engine not only inherits the advantages of the peripheral-ported rotary engine, but also is more likely to be a potential alternative to the reciprocating engine in terms of its favorable performance at low speeds. 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 [2]. The side-ported natural gas-fueled rotary engine is considered to be a new, clean and efficient energy system. Because the side-ported natural gas-fueled rotary engine can bring the advantages of the side-ported rotary engine and natural gas together in a highly effective way. However, the flattened combustion chamber of the traditional rotary engine and the low burning speed of natural gas result in high unburnt hydrocarbon emissions [3]. This implies that the combustion efficiency needs improvement urgently. For this reason, the research on how to improve the efficiency of the side-ported natural gas-fueled rotary engine has important practical value and theoretical significance. In recent years, a lot of work has been done to increase the efficiency of the rotary engine. Schlieren method was used by Hasegawa and Yamaguchi to study the effect of the combustion chamber structure on the flow field in the rotor housing central plane of a side-ported rotary engine [4]. Abraham et al. measured the indicator diagrams under different working conditions and numerically studied the effect of combustion chamber shape on the combustion process [5,6]. An in situ laser infrared absorption method with a newly developed optical spark plug sensor was used by Kawahara et al. to investigate the fuel concentration near the spark plug in a commercial rotary engine [7]. Karatsu et al. developed an optical rotary engine fueled with gasoline to observe the combustion in cylinder. By using two high-speed cameras, the combustion in rotary engine was observed by bottom view and side view simultaneously [8]. A commercial computational fluid dynamics (CFD) software, FLUENT, was applied by Jeng et al. and a two-dimensional model was constructed to investigate the influence of fuel type and recess size on the performance of a rotary engine [9].

All the above studies centered on increasing the efficiency of rotary engine by reasonably organizing the flow field, fuel distribution and combustion in cylinder. In recent years, some new technical methods have been applied to the rotary engine. For example, new apex seals were designed for the rotary engine to improve sealing [10]. Direct-injection and turbocharged systems also were used to improve the efficiency of engines [11,12]. Amrouche et al. added hydrogen to gasoline to improve the thermal efficiency and power output [13]. Among them, the use of hydrogen as an enrichment technique is shown to improve the engine emissions and performance for many fuels such as natural gas [14], gasoline [15], ethanol [16], and methanol [17]. Much research about hydrogen induction applied to the conventional reciprocating engine has been done [18,19]. In addition, the experience gained through the years in operating the reciprocating engine with hydrogen has led to the promise of the rotary engine being particularly well suited for hydrogen enrichment [13]. This is mainly because the high hydrogen flame speed and relatively small quenching distance potentially eliminate difficulties with the flame quenching in rotary engine, which can improve the combustion process of the previously mentioned fuels. However, the research about hydrogen blending applied to the natural gas rotary engine is still rare, although there are some studies on the rotary engine fueled with pure hydrogen [20,21]. In addition, different modes of hydrogen blending determines the distribution of hydrogen in the rotary engine fueled with natural gas/hydrogen blends and further affects the combustion process [22–24]. Therefore, a reasonable mode of hydrogen blending not only makes full use of the fuel properties of hydrogen, but also further uses the flow field to organize the distribution of hydrogen rationally. Eventually, the efficiency of the rotary engine can be increased.

As seen above, to meet the gap in this field, the objective of this work is to do a comprehensive study on the performance, combustion and emission characteristics of a hydrogen assisted natural gas rotary engine at various hydrogen blending modes. Through writing dynamic mesh programs, choosing the RNG k-ε turbulent model, the eddy-dissipation concept (EDC) combustion model and a reduced reaction mechanism on the basis of the FLUENT simulation software, a three-dimensional dynamic simulation model based on the chemical reaction kinetics was established. This model was validated by comparing it with the experimental results. Some critical information was reflected, which was difficult to obtain through the experiment, in terms of the flow field, the temperature field and the concentration fields of some intermediate. Meanwhile, further simulations were then conducted to investigate how to impact the combustion process by the coupling function between hydrogen distribution and the flow field inside the cylinder. This study provides a theoretical foundation for the determination of the best hydrogen blending mode under different working conditions.

Geometric model generation and meshing

Computational domain

In the present study, a side-ported rotary engine fueled with natural gas/hydrogen blends is chosen as the research object. 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 is mixed with air outside the engine and enters into with intake flow. Hydrogen is injected into the cylinder. Since the study investigates the effect of different hydrogen blending modes on engine performance and emissions with all engine operation parameters unchanged, the spark timing is kept at 40°CA