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The influence of hydrogen injection strategy on mixture formation and combustion process in a port injection (PI) rotary engine fueled with natural gas/hydrogen blends

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ABSTRACT

This work aimed to numerically study the effect of hydrogen injection strategy on mixture formation and combustion process in a port injection (PI) rotary engine fueled with natural gas/hydrogen blends. The two main considered factors were hydrogen injection timing (IT) and hydrogen injection duration (ID). Simulation results indicated that for mixture formation, in terms of hydrogen IT, hydrogen IT of 390°CA (BTDC) is a watershed. When the hydrogen IT is before 390°CA (BTDC), the changes in hydrogen IT have little effect on the hydrogen distribution at ignition timing. Hydrogen distribution is uniform across the whole combustion chamber. However, when the hydrogen IT is after 390°CA (BTDC), with the retarded hydrogen IT, there is obvious increase in hydrogen stratification phenomenon, and more hydrogen distributes in the middle and back of combustion chamber at ignition timing. In terms of hydrogen ID, at the fixed hydrogen IT of 360°CA (BTDC), with the extended hydrogen ID, more hydrogen distributes in the back of trailing spark plug (TSP). For combustion process, to obtain a higher overall combustion rate for the PI rotary engine, the hydrogen injection strategy should make more hydrogen located at the front of TSP at ignition timing. In engineering applications, for higher peak cylinder pressure to be obtained, the continued optimization of hydrogen IT should be selected between 390°CA (BTDC) and 330°CA (BTDC). Under the hydrogen IT range of 390°CA (BTDC) to 330°CA (BTDC), the continued optimization of hydrogen ID should select between 8°CA and 24°CA.

1. Introduction

As a promising power machine, the rotary engine is quite different from the traditional reciprocating engine. Compared with the reciprocating engine, the crank rod mechanism and the valve mechanism are omitted in the rotary engine [1]. Therefore, the rotary engine has some special advantages like small size, light weight and fewer parts [2]. Because of the above-mentioned advantages, the rotary engine has a wide range of applications in some new fields, such as small unmanned aerial vehicle (SUAV) and the plug-in hybrid electric vehicle (PHEV). This is mainly because the rotary engine can meet well the demands of powerplants for SUAV and PHEV, such as low weight, miniaturization and high-powered density [3]. For the largely spread practical usages described above, much attention has been given to the rotary engine in many countries in recent years [4].

It is undeniable that there are certain disadvantages, including high fuel consumption and unburned hydrocarbon emissions for the gasoline, diesel and other traditional liquid fueled rotary engines [5]. This is mainly because of the incomplete combustion and the low combustion rate. There are two reasons for the low combustion rate of the rotary engine [6]. One reason is that it is difficult to atomize liquid fuels in the combustion chamber with a long and narrow shape. The other reason is that in power stroke, the fuel at back of combustion chamber cannot be burned timely. In recent years, natural gas is identified as a new clean energy source which has been widely used in the engine field [7,8]. Especially for the rotor engine, natural gas is a promising fuel. This is mainly because as a gas fuel, natural gas can avoid the poor atomization of liquid fuel in rotary engine. Thus, the natural gas fueled rotary engine is considered a clean and promising internal combustion engine [2]. However, combustion rate of the rotary engine fueled by natural gas still requires significant refinements [3]. This is mainly because although the natural gas can avoid the poor atomization of liquid fuel in

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Nomenclature

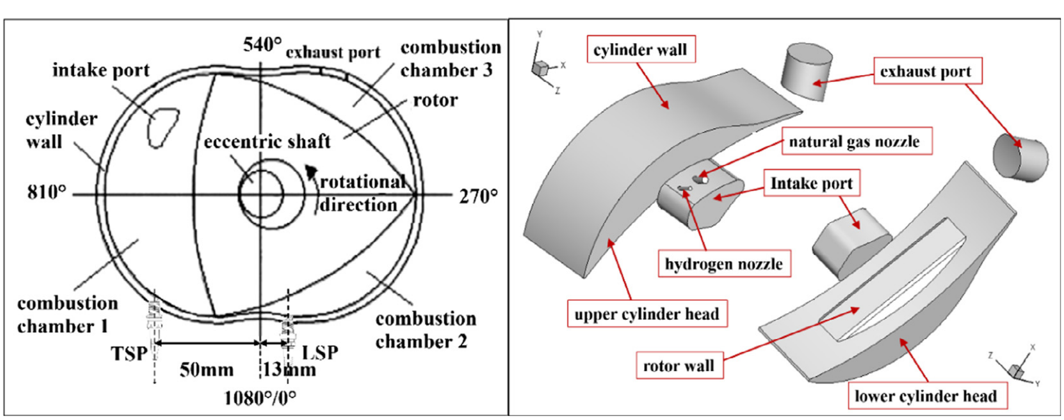
PI	port injection
DI	direct injection
IT	injection timing
ID	injection duration
CA	crank angle
BTDC	before top dead center
TDC	top dead center
ATDC	after top dead center
TSP	trailing spark plug
LSP	leading spark plug
SUAV	small unmanned aerial vehicle
PHEV	plug-in hybrid electric vehicle
RHCP	rotor housing central plan
PIV	particle image velocimetry
CFD	computational fluid dynamics
RPM	Revolutions Per Minute
UDF	user defined function
EDC	Eddy-dissipation concept

rotary engine, the rotary engine fueled with natural gas still cannot overcome the drawback that the natural gas in the back of combustion chamber cannot be burned timely. The above inevitable defect is determined by the structure and operation mode of rotary engine [5,6].

To overcome two above-mentioned drawbacks that lead to restriction of combustion rate in the rotary engine, many scholars have been trying a lot of technology to improve combustion rate [9–12]. For example, the laser ignition system was used by Zambalov et al. [9] to decrease ignition delay and improve ignition reliability. The recess size of rotor is designed by Jeng et al. [10] to acquire a higher pressure in the burning stage. New apex seals were designed by Warren et al. [11] to increase volumetric efficiency. Hydrogen was used as blending fuel by Ji et al. [12] to increase the combustion rate of basic fuel. Among them, hydrogen addition is one of the most effective ways. The main reason for this is that the combustion rate of original fuel in rotary engine can be improved effectively by hydrogen addition. The comparative combustion properties of hydrogen, methane, gasoline and diesel can be seen in the literature [13]. In addition, it is known that hydrogen addition mode can be divided into port injection (PI) and cylinder direct injection (DI). Compared with PI technology, DI technology has the potential to give a better mixture distribution [14–16]. However, the DI technology needs a higher hardware requirements and production costs [17,18]. Therefore, PI technology is widely used as the mode of hydrogen addition [19]. Meanwhile, to improve combustion efficiency of rotary engine with hydrogen addition using PI technology, the hydrogen motion law in the cylinder and the influence of hydrogen distribution on combustion process must be clarified.

Regarding the study of the hydrogen motion law in the cylinder, it is imperative to study the flow field in cylinder and injection strategy as well, which are two main factors that determined the hydrogen motion. Regarding study of the flow field in cylinder, Maki et al. [20] used particle image velocimetry (PIV) to obtain 2D flow field on the rotor housing central plane (RHCP) on an optical rotary engine. Unfortunately, due to limitation of experimental equipment, the 3D flow field in cylinder has not been measured yet. However, the experimental data still provided some valuable validation data for numerical simulation. With the development of computational fluid dynamics in recent years, numerical simulation method was used by many scholars to obtain some critical information which are difficult to obtain through experiment [10,21,23]. For example, Jeng et al. [10] developed a 2D numerical simulation model by using CFD software FLUENT. The change rule of the 2D flow field from intake stroke to exhaust stroke was acquired. Fan et al. [21] developed a 3D dynamic simulation model on the software FLUENT. The detailed information of the 3D flow field in cylinder was analyzed. These above studies on the flow field in cylinder provided a basis for the study of fuel motion law in the cylinder. In terms of the study of the hydrogen injection strategy in rotary engines, Tabata et al. [22] used high-speed shadowgraph method in constant volume bomb under pressure environment of a rotary engine, to obtain hydrogen jet characteristic. Izweik et al. [23] investigated the mixture formation of a hydrogen DI rotary engine by using CFD software AVL-Fire. However, as far as the authors know, there is insufficient research on effect of PI hydrogen injection strategy on rotary engines with hydrogen addition. By contrast, there are many studies on injection strategy in hydrogen PI reciprocating engines. For example, the effects of injection mode [24], injection timing [25] and injection pressure [26] on the mixture formation and combustion process, were numerically studied by using CFD software.

For the study of effect of hydrogen distribution on combustion process, Ji et al. [27] conducted an experimental study to analyze the effect of hydrogen volume fraction on the combustion rate of a PI hydrogen and n-butanol rotary engine. The results indicated that hydrogen addition can be used to shorten period of flame propagation. Amrouche et al. [28] also experimentally analyzed the effect of hydrogen volume fraction on combustion rate of PI hydrogen-ethanol rotary engine. The results also revealed that hydrogen enrichment can improve combustion efficiency and reduce the cyclic variation. However, like limitation of the experimental study of 3D flow field, the



(a) Schematic (b) Component name

Fig. 1. The schematic and component name of side-ported rotary engine.