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Experimental and numerical investigation of the fluid flow in a side-ported rotary engine

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ABSTRACT

The side-ported rotary engine is a potential alternative to the reciprocating engine because of its favorable performance at low speed. The performance of side-ported rotary engines is strongly influenced by the flow field in the combustion chamber. In this study, an optical side-ported rotary engine test-bed was built and PIV was employed to measure the flow field in the rotor housing central plane. From experiment results, a counterclockwise swirl was detected in the rotor housing central plane. Meanwhile, a three-dimensional dynamic mesh and turbulent flow model was integrated and simulated using the Fluent CFD software. The three-dimensional dynamic simulation model was validated by comparison with experimental results. In addition, the effect of three major parameters on the flow field in the combustion chamber, namely rotating speed, intake pressure and intake angle were numerically investigated. The results show that a swirl forms in the middle and front of the combustion chamber during the intake stroke under low rotating speed. This is in line with the swirl detected in the rotor housing central plane though the PIV experiment at 600 rpm. Furthermore, the flow field, volume coefficient and average turbulence kinetic energy in the combustion chamber were studied in detail by varying rotating speed, intake pressure and intake angle.

1. Introduction

The Wankel rotary engine is a promising energy system. There are two main types of rotary engines, based on the different ways of intake: side ported rotary engines and peripheral ported rotary engines [1]. Advantages of the Wankel rotary engine over the conventional reciprocating engine includes large specific power output from high allowable engine speed, simple and compact design due to less moving parts, multi-fuel capability and low noise and vibration levels [2]. For these reasons, the Wankel rotary engine is mostly used in stationary and mobile applications [3–5]. Nevertheless, the disadvantages which should not be ignored are its poor performance at low speed, sealing and leakage problems, lower efficiency, and higher unburned hydrocarbon emissions resulting from the flattened combustion chamber. Since the 1980s, several studies have attempted to improve the fuel efficiency and exhaust emissions of the Wankel rotary engine [6–8]. Recently, new apex seals were designed for the rotary engine to improve sealing [9]. Direct-injection and turbocharged systems also were used to improve efficiency of engines [10,11]. Amrouche et al. added hydrogen to gasoline to improve the thermal efficiency and power output [12]. Despite these works, the research on the flow mechanisms of rotary engines is still insufficient, which is a determining factor for fuel efficiency [13–15]. DeFilippis et al. used Laser Doppler Velocimetry (LDV) to measure the flow field in the rotor housing central plane of a peripheral ported rotary engine [16]. The velocity and direction of swirl were determined. But with very few measuring points, they could not reveal the overall flow pattern in the combustion chamber. Reflection type Schlieren method was used by Hasegawa and Yamaguchi [17] to study the flow field in the rotor housing central plane of a side ported rotary engine. Their work made significant contributions on the study of flow field in side ported rotary engines. However, neither the swirl velocity nor vortex direction, only the position of the swirl in the rotor housing central plane, were reported. Meanwhile, due to the limitations of the experimental set-up, only the flow field at low-speed was measured, that is, the flow field under normal engine operating conditions (4000 rpm or above) could not be tested. In terms of numerical simulations, although the mathematical models have been greatly improved over the past two decades, the three dimensional investigation coupled with reasonable

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turbulence model on the flow process inside the combustion chamber of a side ported rotary engine is still rare. In recent years, there has been an increasing emphasis on the study of side ported rotary engines, because it is more likely to be a potential alternative to the reciprocating engine as compared with the peripheral ported rotary engine in terms of its favorable performance at low speed.

In this study, an optical side ported rotary engine test-bed was built and a Particle Image Velocimetry (PIV) was used to visualize the flow field in the rotor housing central plane at a low rotating speed. To understand three-dimension flow in the combustion chamber, in-depth information of the flow field is required, as such the conclusions drawn from experimental studies are limited. Using the Fluent CFD software, a three dimensional dynamic simulation model was established. Dynamic mesh and appropriate turbulent model were incorporated. The three-dimensional dynamic simulation model was validated by comparing it with the experimental results. A swirl was observed in the rotor housing central plane of the side ported rotary engines in the PIV experiment, and the mechanism on the formation of the vortex was revealed. Furthermore, at different rotating speeds, intake pressures and angles, various flow patterns in the combustion chamber, during the intake stroke, were simulated. The differences in the flow field were reflected in terms of the volume coefficient and the average turbulence kinetic energy in the combustion chamber. This work provides a theoretical foundation to improve and optimize the design of a rotary engine, like fuel atomization, mixture formation and stratified combustion.

2. Experimental apparatus and methods

The side ported engine used in this test is a 0.16 L single rotor, air cooled Wankel engine, with a single spark plug. The schematic of the Wankel engine is shown in Fig. 1. Technical specifications of the engine are listed in Table 1.

Fig. 2 shows the schematic and photo of the optical rotary engine. Fig. 3 shows the schematic and photo of the PIV experimental set up in the laboratory. In this study, the visualization was performed under the engine speed of 400 rpm and 600 rpm. An arched quartz glass window was installed at the top of the rotor housing to introduce the laser light sheet into the combustion chamber. It is difficult to insert the quartz glass into the molded line of the cylinder block. So a segment of arched quartz glass was used as a part of the cylinder block. The visible zone covers about six quarters of the engine, allowing continuous observation of flow fields inside the combustion chamber during intake-compression stroke. In order to prevent air leakage from both sides

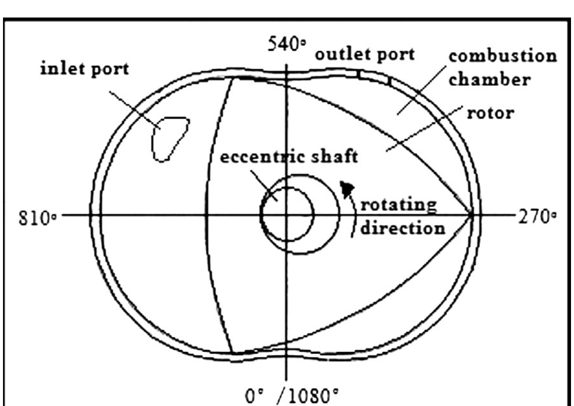

Fig. 1. Schematic of the side ported rotary engine.

Table 1
Engine technical specifications.

Engine parameters	Value
Number of rotors	Single rotor
Cooling	Air cooled
Ignition source	Spark plug
Displacement	160 cm^3
Compression ratio	8-1
Generating radius	69 mm
Eccentricity	11 mm
Chamber width	40 mm
Number of rotors	1
Intake timing	Advance angle 70°(ATDC), delay angle 63°(ATDC)
Exhaust timing	Advance angle 62°(BBDC), delay angle 70.5°(ABDC)

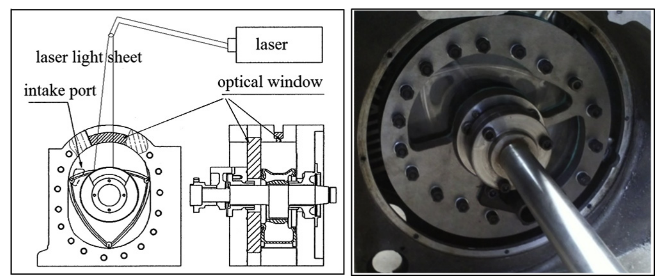

Fig. 2. Schematic and photo of optical engine.

of the arched quartz glass window, a sealant was applied. Furthermore, the front quartz glass window, which has the same structure as the upper cylinder head, was fabricated to replace the upper cylinder head for taking photos using a CCD camera.

As shown in Fig. 3, apart from the optical engine, the experimental set up includes a frequency converter and a motor, the PIV system, a shaft encoder (model LEC-S1-10φ) and a smoke generator (model MV-FOGMACHINE1500). The PIV is a whole-field laser measurement device, which can provide the instantaneous velocity vectors by a non-intrusive approach. The PIV system includes the image capture component (CCD cameras and frame grabbers), the illumination component (laser and light sheet optics), a synchronizer, and a data analyzer. A very thin vertical light sheet with a wavelength of 532 nm is generated by a double-pulsed Nd:YAG laser (New Wave Research Solo 120XT-15HZ) through a set of cylindrical and spherical lenses. The laser pulse duration is 5 ns with energy of 120 mJ per pulse. The repetition rate of the laser pulse is under the control of the shaft encoder by using the synchronizer (TSI, model 610035). The pulse separation value is selectable to match the gas velocity, during which the particle image displacements are typically less than 1/4 of the interrogation window. The frame straddling technique is applied to measure the flow filed. Two successive exposures of tracer particles to the laser light sheet are recorded in two separate frames by a high resolution (2048 × 2048 pixel) CCD camera (TSI, model 660004). The frame grabber in the computer reads the camera images and passes the information to the computer system for processing. The vector fields are calculated by analyzing the recorded images with commercial software Insight 3G provided by TSI. Smoking oil particles were chosen as a tracer considering the lubrication of rotary engine and particle's tracking. Meanwhile, a plastic storage was used to store the smoking oil particles. The particles were naturally aspirated into the combustion chamber during intake process. This can greatly reduce possible disturbance of particles to the in-cylinder flow field. In addition, the uncertainty in PIV measurements involves the following: (1) inhomogeneity in particle distributions, (2) particle image size and (3) information processing. Among them, particle distribution is the main