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Experimental Study of Combustion with Silicon Micro Engine Combustion Rig

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Abstract

A micro reciprocating engine combustion rig was fabricated, and applied to combustion experiment. The combustion rig is mainly fabricated by the MEMS process, and the size is 52mm×38mm×4mm. The combustion rig is composed of a piston and a cylinder case. The size of a combustion chamber is 5mm×3mm×1mm. The piston is reciprocated by the restoration force of a spring instead of the crank. The fuel is hydrogen (H_2), and the oxidant is oxygen (O_2). The engine operates on two cycles. Combustion was confirmed by the direct observation of the flame propagation in the combustion chamber with using a high-speed CMOS camera. In the stoichiometric combustion (equivalent ratio $\phi = 1$), pressure was approximately 50kPa (gauge pressure) , combustion time was 50msec and the piston displacement to the under dead point was 0.2mm.

Keywords: micro reciprocating engine, hydrogen, combustion, combustion speed, displacement

1 INTRODUCTION

In terms of high energy density of hydrocarbon and hydrogen fuels compared to the current batteries, micro heat engines are being studied for the novel power sources of portable devices and miniature vehicle propulsions. At the present, the micro heat engine is typically divided into three types, reciprocating, Wankel and turbine. MIT, Tohoku University and SIMTEC have studied for the micro gas turbine engines [1-3]. As for the micro steam turbine, the research is advanced in Columbia University [4]. The research for the Wankel engine is advanced in UCB and The University of Birmingham [5, 6]. In UCB, rotational speed of 9000 rpm and the output power of 4W have been achieved with the demonstration engine made of steel. The research of the engine production with Si and SiC using the MEMS technology has been also advanced. The reciprocating engines have been studied by KAIST, GIT, Honeywell, The University of Michigan, University of Minnesota and The University of Birmingham [7-12]. The research of the free piston engine is advanced in KAIST. The size of the combustion chamber is 1mm×1mm×1mm. The motion of the piston has been confirmed by the single nock combustion experiment in which mixture of hydrogen and oxygen are used. GIT has obtained high power of 12W with the two stroke engine having 43mm piston stroke. However, the volume of the main body is 13,400mm^3, and the size is relatively large compared to other engines.

The proposed engine is reciprocating type. As for the reciprocating engine, the structures are much simpler compared to the other type of engines. Thus, advantageous points are cost in both production and operation, and the smaller number of technical problems to be solved. Details of the basic concept, the design, and the fabrication process of the micro reciprocating engine reported in [13] and [14]. Confirmation of the piston motion by air and fabrication of the combustion rig had been finished. The combustion experiment and obtained results is described in this paper.

2 STRACTURE OF THE RIG

A basic specification of the combustion rig is shown in Table1.

Table 1. Specification of the combustion rig

Cycle	2cycles
Fuel	H_2
Oxidant	O_2
Form of ignition	Spark
Dimension of combustion chamber [mm]	5×3×1
Dimension of rig [mm]	52×38×4
Mechanism of reciprocating	Restoration force of spring
Piston spring constant [N/m]	100

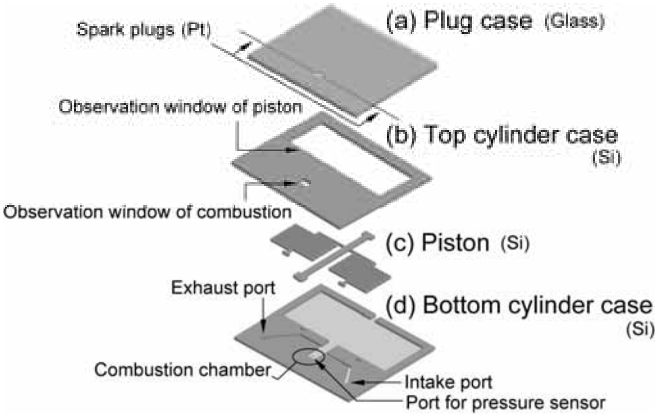


Figure 1. Structure of the combustion rig

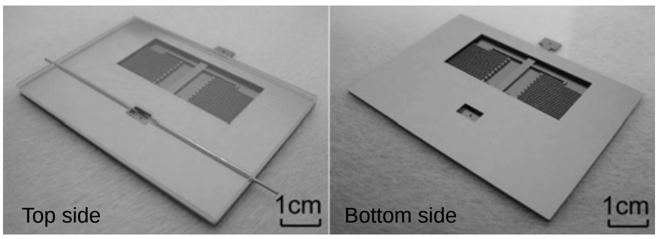


Figure 2. Fabricated combustion rig

The schematic of the structure is shown in Fig.1, and the photograph of the fabricated combustion rig is shown in Fig.2. Si parts are bonded by the Au-Si eutectic bonding to form an engine assembly. The glass plug case and the Si engine assembly are fixed with an alignment jig. Ignition is started by the spark plugs made of Pt. The piston is supported by the spring and reciprocates using the forces due to the pulsed combustion pressure and due to the spring.

3 COMBUSTION EXPERIMENT

Hydrogen (H_2) was selected from the view points of the combustion stability dominated by the range of flammability, the ignitability dominated by the minimum ignition energy, and the relatively longer quenching distance. To achieve certain combustion, oxygen (O_2) was selected as the oxidant. Figures 3 and 4 show the schematic of the experimental instruments. Hydrogen and oxygen mixture was adjusted to gauge pressure of 0.6MPa by the pressure regulator and adjusted to stoichiometric mixing ratio by the mass flow meter. The mixture was supplied to the inlet port of the rig through the explosion-proof valve. The spark ignition was generated by the pulse of function generator amplified by the booster. A single pulse input was used to verify an experimental evidence of single nock combustion. The combustion pressure was measured with a pressure sensor installed under the combustion chamber (Fig.1 (d)). The direct observation of the combustion chamber was possible through the glass plug case corresponding to the upper part of the combustion chamber (Fig.1 (a)). A high-speed CMOS camera was used to observe the combustion (Fig.4).

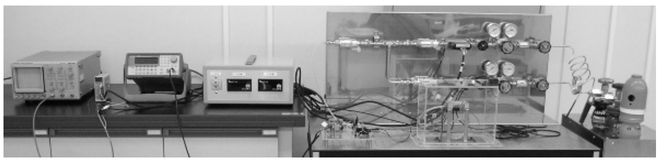


Figure 3. Photograph of experimental instruments

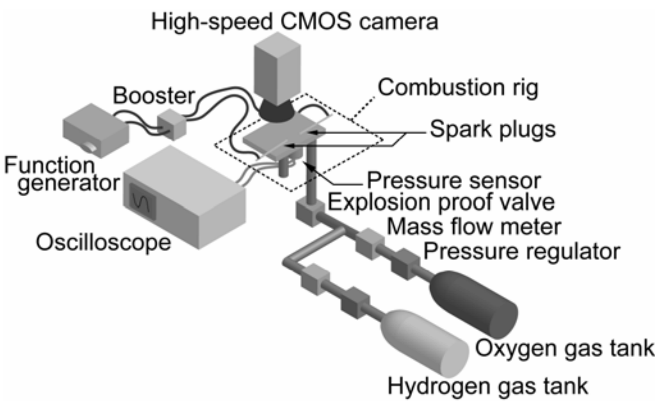


Figure 4. Schematic of experimental instruments

4 RESULTS AND DISCUSSIONS

Figures 5, 6, and 7 show the data obtained from the combustion experiment, respectively. There is a limit of the combustion flame temperature due to the heat dissociation and the heat discharge. As a result, the combustion pressure is estimated as high as 1MPa (absolute pressure). The combustion pressure obtained from the experiment was approximately 50kPa (gage pressure) as shown in Fig.5. Two assumptions about lowering combustion pressure are made. First, because the rig was designed for continual operating, the inlet and the exhaust ports are remained to open during the single nock combustion (Fig.6 (a)). Second, the air leakage from the space between the piston and the cylinder originated from the D-RIE fabrication. The surface area of the combustion chamber occupied by the ports is 2.6%, and by the space between the piston and the cylinder is 0.2%, respectively. The experimental value of the combustion pressure was only 15% of the pressure estimated from the limit of the combustion flame temperature, nevertheless the opening surface area against the combustion chamber was only 2.8%. The combustion time was approximately 50msec as shown in Fig.5. The combustion time calculated from the chamber dimension and the maximum laminar combustion flame speed of hydrogen (2910mm/sec) is ~6msec. However, the combustion flame speed of the rig was calculated to be ~1000mm/sec, and only 33% of the maximum combustion flame speed. The Reynolds number is calculated to be extremely low $Re \cong 10^2$. This proves turbulence flame propagation is difficult to cause for the cylinder in the macro size engine. The crucial factor to decide the limit of the high speed operation of the engine is the combustion flame speed. Therefore, the experimental result suggests the existence of physical limit for the high speed operation of the micro engine. Figure 6 shows the combustion observed by the high-speed CMOS camera. A spark ignition in the combustion chamber can be seen in (b), and the subsequent combustion in (c). Figure 7 shows the relation between the combustion time and the piston displacement based on the results in Fig.6. The negative value shows the displacement to the bottom dead center side.

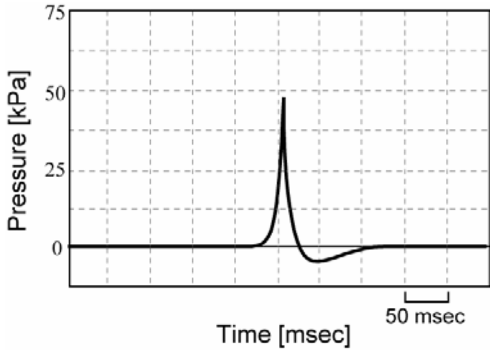
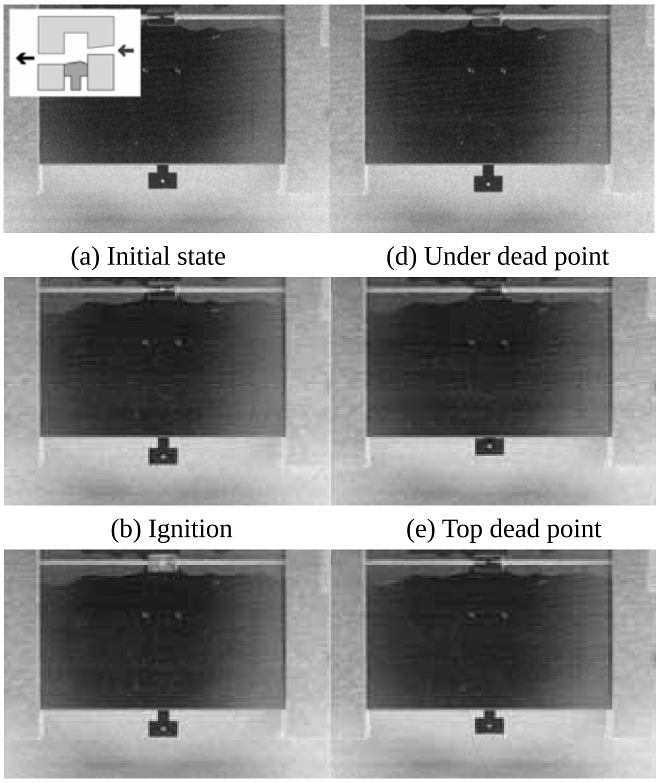


Figure 5. Combustion pressure



(a) Initial state (d) Under dead point

(b) Ignition (e) Top dead point

(c) Combustion (f) Return to initial point

Figure 6. High-speed CMOS camera images of the piston motion

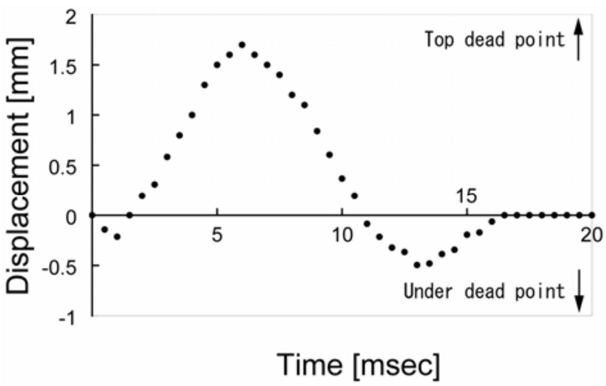


Figure 7. Displacement of piston

The evidences obtained from the experiment are, time used for displacement is 20msec while combustion time is 50msec, the first displacement to the top dead point is larger than that to the under dead point, and second displacement to the under dead point is larger than the first displacement to the under dead point. As a result of preliminary analysis based on the references [13] and [14], the displacement to the under dead point was expected to be larger than that to the top dead point. The reason of inconsistency between the analysis and the experimental evidence has not been solved yet. Further consideration has been remained as an open problem. One reason for the damping of displacement within 20msec is thought to be friction force due to wear. A broken piece of Si was observed during operation. It may be due to wear between the piston and the cylinder case as shown in Fig.8.

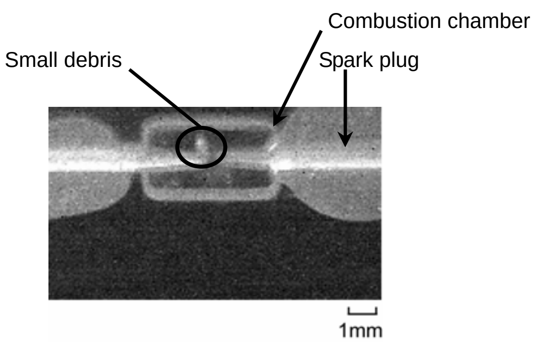


Figure 8. Si debris due to wear

5 CONCLUSIONS

Single nock combustion and the subsequent piston work were confirmed by the experiment. In stoichiometric mixture ratio (equivalent ratio $\phi = 1$), combustion pressure was about 50kPa (gauge pressure), combustion time was 50msec and the piston displacement to under dead point was 0.2mm. The problem of debris caused by wear of Si was raised. Materials other than Si such as the metallic materials will be necessary to prevent wear. Inefficiency of performance of the micro reciprocating engine was mainly due to the air leakage and friction force between the piston and the cylinder walls, and low speed combustion flame propagation ($Re \cong 10^2$) in the small chamber. Through the combustion test, some physical limits for engine performance were suggested, and these results may be useful for a design consideration on the micro reciprocating engine.

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