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Experimental study on mechanical power generation from MEMS internal combustion engine

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Abstract

A micro-electro-mechanical-system internal combustion engine (MEMS IC engine) is fabricated to demonstrate the energy conversion from heat to mechanical power. The dimensions and surface-to-volume ratio of combustion chamber are 5 mm × 3 mm × 1 mm (0.015 cc) and 3.07 mm^{-1}, respectively. The reciprocation motion of a piston can be sustained by the force balance between combustion pressure and the repulsion force of an elastic spring. A premixture gas composed of hydrogen and oxygen is used for fuel under stoichiometric combustion (equivalent ratio is 1). The combustion is confirmed by pressure measurement and the direct observation of flame propagation. A high-speed CMOS camera is adopted for the flame observation. A maximum combustion pressure of 142.6 kPa, a displacement of 9.5 mm^3, and a mechanical power of 29.1 mW were obtained for the MEMS IC engine. This experimental evidence provides a positive outlook for the materialization of the MEMS heat engine concept.

Keywords: Power MEMS; Micro-power generation; Heat engine

1. Introduction

The concept of power MEMS was first proposed by Senturia and Epstein [1]. Since then various concepts, such as micro-gas-turbine, micro-steam-turbine and micro-internal-combustion (IC) engines have been developed to provide compact electric power sources and micro-vehicle propulsion units [2]. The strategy for the development of theses devices is to generate power from a source of heat. The combustion of hydrocarbon and hydrogen fuels is typically adopted for heat generation. However, the micro-IC engines are still in the process of development due to the difficulty of device fabrication and insufficient experimental data to support the design consideration [1,2].

An excellent review written by Fernandez-Pello presents the technical issues of micro-power generation from microscale devices [3]. Fernandez-Pello clarifies and suggests the fundamental technical problems that researchers face in the development of the micro-heat engine. These issues are summarized as follows:

(a) Microfabrication limits the tolerances in the moving parts of the micro-heat engine. Low tolerance control causes fluid leakage. Thermal management causes a low compression ratio. These issues reduce the efficiency of the engine components, i.e., the compressor and combustion chamber.
(b) Heat transfer via conduction through gas to the surrounding surface is significant because the temperature gradients become higher as the characteristic length of the engine components is decreased. Therefore, surface heat loss may reduce the performance of the micro-heat engine.

These issues should be solved for the materialization of the micro-heat engine. In this paper, these issues are investigated for the proposed MEMS IC engine. Microfabrication of the MEMS IC engine and its energy conversion from heat to mechanical power are described. The experimental evidence suggests that the generated mechanical power is relatively small due to low combustion pressure. The effects of fluid leakage and heat transfer on the combustion pressure of the MEMS IC engine will be quantitatively described by introducing the combustion model with loss accounting. The proposed combustion model can predict the pressure loss taking into account the fluid leakage (which is well-known as blow-by in the IC engine) and the heat transfer.

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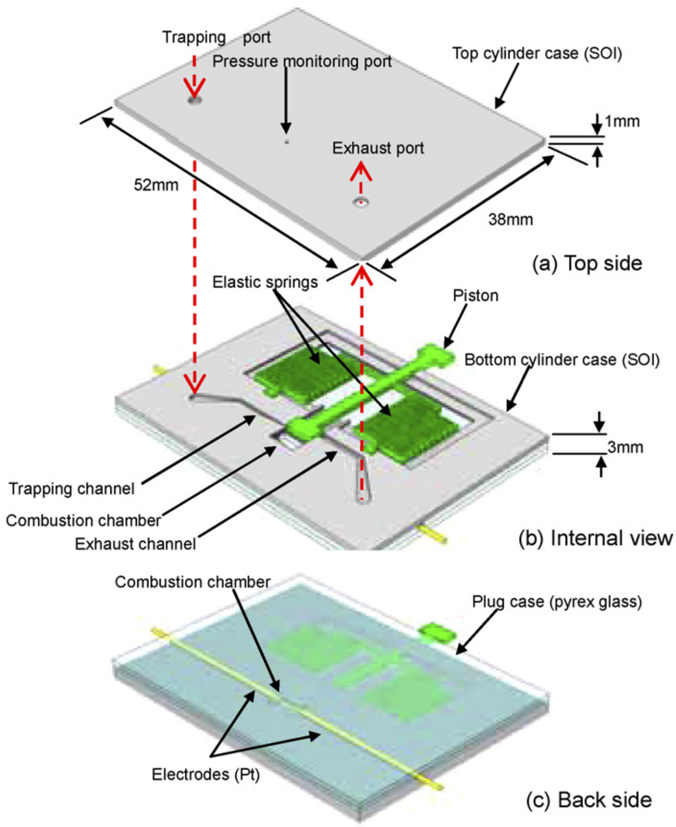

Fig. 1. Schematic of structure of MEMS IC engine.

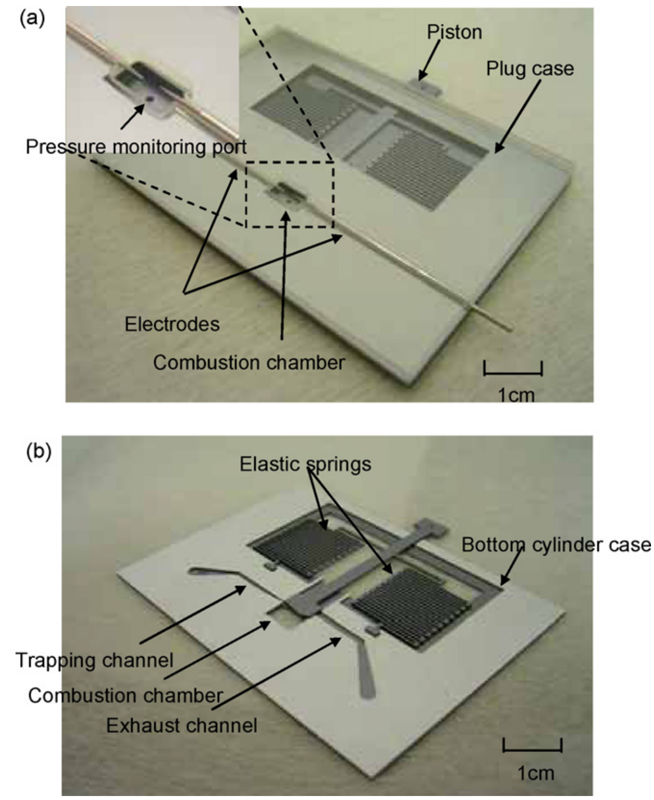

Fig. 2. Fabricated MEMS IC engine. (a) Schematic view and (b) internal view.

2. Engine description

Schematic of the structure of the MEMS IC engine is shown in Fig. 1. The MEMS IC engine is composed of a Si cylinder case with a combustion chamber, a Si piston connected to an elastic spring, and a glass plug case with Pt spark plugs. The cylinder case is composed of top and bottom layers, and the piston is located between them. Photographs of the fabricated MEMS IC engine are shown in Fig. 2. The Pt spark plugs are located on the back surface of the combustion chamber as shown in Fig. 2(a). Fig. 2(b) shows the internal structure and fuel supply-exhaust system of the MEMS IC engine. A premixture gas composed of hydrogen and oxygen is adopted for the combustion fuel. Hydrogen has a relatively wide flammability-limit range, a large lower heating value, a low minimum ignition energy, and a small quenching distance compared with other hydrocarbon fuels (see Table 1) [4]. Therefore, these properties are suitable for the microscale engine design and the experimental demonstration of the working principle. The premixture gas is prepared using the external instruments. It is continuously supplied from the trapping port to the combustion chamber through the trapping channel (Fig. 1). Combustion products are exhausted from the combustion chamber to the surrounding environment through the exhaust channel (Fig. 1). Fig. 3 illustrates the cycle operation of the MEMS IC engine. The period of the fuel supply and exhaust is controlled by the relative position of the piston against the location of the two channels as shown in Fig. 3. A two-stroke cycle is adopted in order to demonstrate the operation without any valves that control the fuel supply-exhaust period. The reciprocation motion of the piston can be sustained by the force balance between the combustion pressure and the spring repulsion force. We have demonstrated the validity of this concept using the MEMS air-piston engine [5].

3. Engine design

The design foundation of the MEMS IC engine is reviewed as follows. The important factors, which dominate the engine performance, are the dimensions of the combustion chamber, the locations of trapping and exhaust ports, design combustion pressure and the cyclic response of the elastic spring system. The

Table 1
Flammability-limit, lower heating value, minimum ignition energy and quenching distance for hydrogen and hydrocarbon fuels

Fuel	Flammability-limit range (ϕ = equivalent ratio)	Lower heating value (kJ/kg)	Minimum ignition energy (mJ)	Quenching distance (mm)
Hydrogen H_2	$0.1 \le \phi \le 7.17$	119,953	0.02	~0.64
Methane CH_4	$0.5 \le \phi \le 1.69$	50,010	0.28	~1.8
Propane C_3H_8	$0.51 \le \phi \le 2.51$	46,352	0.28	~1.8