IMPROVED POWER GENERATION OF A SMALL-SCALE, NATURALLY ASPIRATED AND LIQUID FUEL INJECTED ROTARY ENGINE

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Abstract: A small-scale rotary engine (S1500) with a volume displacement of 1500 mm^3, and two intake/exhaust side ports has been developed and characterized. The engine has produced a maximum mechanical power of 40.6 W, and the corresponding thermal efficiency is determined as 4.7 %. Comparing with the previous work, the power has been increased by 19 % while the efficiency has been increased by 20 %. The maximum and average specific powers have been estimated as 190 W/kg and 150 W/kg. The improvement of the engine performance has been achieved by having a longer droplet evaporation time, and minimizing blow-by losses within the engine.

Key Words: Rotary engine, Small-scale combustion, Liquid fuel, Mechanical power, Portable power

1. INTRODUCTION

Fast market growth of integrated portable devices demands a power source with a high energy density, light weight, long life, and short recharging time. Batteries have been the most commonly used for powering small portable electrical devices because of their low price and convenience of replacement. The rapid rate of advances in battery technology, however, has slowed, and fundamental breakthroughs are not expected to chase high power demand of upcoming portable devices with a single cell technology [1]. Multi-cell battery designs are a feasible solution for high power demand, but they increase overall weight, volume and cost of small devices.

Thermo-chemical devices, on the other hand, have a potential to answer high power demands since hydrocarbon contains 45 MJ/kg of stored energy and conversion efficiencies of 5-10% are expected, whereas the electrochemical energy storage such as lithium ion batteries has 0.7 MJ/kg [2]. With utilizing as low as 5 % of the chemical energy in hydrocarbons, thermo-chemical devices have advantages over batteries in terms of size, weight and cost. Several small-scale thermo-chemical devices have been developed and practical thermo-chemical devices are introduced [2, 3, 4].

Microelectromechanical systems (MEMS) are attractive for small-scale power generation because of their favorable characteristics of low cost and mass production. The potentials and challenges of micro-scale power generation have been thoroughly reviewed [5].

The University of California at Berkeley has been developing MEMS based rotary engines for portable power generation. Small-scale rotary engines have been constructed to investigate combustion characteristics, and design challenges of reducing the size down to the micro-scale. The rotary engines are particularly suitable for micro-scale power generation because of their simple design, planar motion, few moving parts, and no need of an intake/exhaust valve system. The engines have been tested both with gaseous fuel (Hydrogen) and liquid fuel (Methanol based) [2, 6]. Liquid fuel operation, however, has advantages since liquid fuel is easily stored and has a higher energy density. Liquid fuel delivery systems for small-scale engines have been investigated by using Commercial-Off-The-Shelf (COTS) injectors [7] and MEMS technologies [8].

2. DESIGN AND EXPERIMENTAL

2.1 Engine Design

A S1500 rotary engine has been designed and fabricated (Figure 1). The engine has a volume displacement of 1500 mm^3, and has adapted two side ports for the intake and exhaust. The side port design is chosen over a peripheral port design to eliminate the overlap of two ports and, in consequence, to reduce the contamination of a fresh intake charge with combusted exhaust gases.

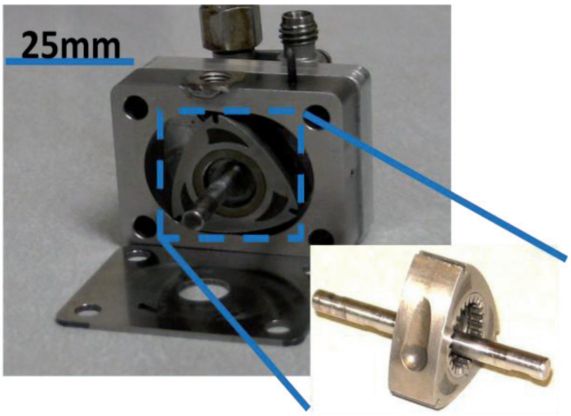

Figure 1: Liquid fuel operated side ported S1500 rotary engine, and rotor with an inverted teardrop-shaped combustion pocket.

The overlapping port design has greater specific power production, but suffers from smaller operating spaces and less stable idling conditions making the system more challenging from determining the operational optimization.

A teardrop-shaped combustion pocket has been adapted to increase the depth of the combustion pocket. The increased depth is designed to reduce conduction heat losses to the low temperature engine rotor to allow the ignition kernel to be grown, and to maximize the combustion efficiency. In addition, an inverted teardrop shape pocket increases the mixing and the reaction rate using the squish flow effect [9] .

The engine has been fabricated with M2 tool steel with wire electrical discharge machining (EDM), which has a 3 μm tolerance.

2.2 Test Apparatus

The schematic of the engine performance testing apparatus is shown in

. The apparatus consists of a fuel injection system (Figure 2, (b)), a universal dynamometer (Figure 2, (e)), an ignition system (Figure 2, (c), (h)) and a mechanical power measurement system (Figure 2, (f), (g)).

A pulse controlled dispensing solenoid valve (Lee Company, INKA2457210H) has been implemented as a fuel injector. The injector is controlled by a pulse duty cycle and the back pressure to deliver 10-100 mg/s of liquid fuel. A brushless electrical motor (Maxon, EC80) has been used as a universal dynamometer. Initially, the motor drives the engine and then, becomes the

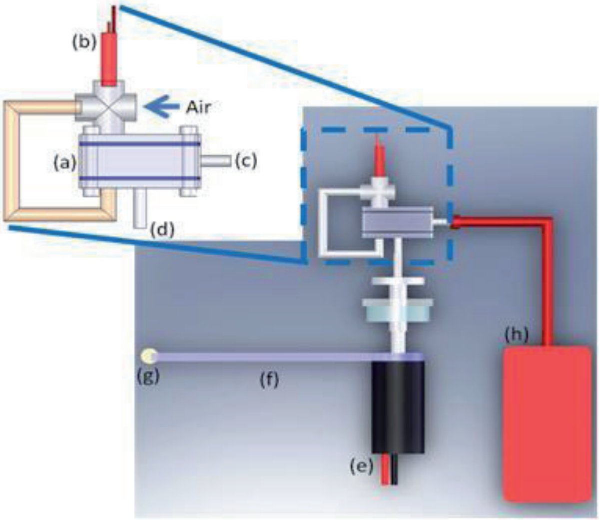

Figure 2: Schmetic of the engine performance test setup: (a) S1500 en gine, (b) Liquid fuel injector, (c) Ignitor, (d) Shaft, (e) Universal dynamometer, (f) Torque arm, (g) Load cell, (h) Ignition system.

generator for measuring the electrical power after the engine runs by itself. The ignition system consists of a commercially available ¼” spark plug (CH Electronics, Rimfire plug #111), and an automotive ignition system (MSD, 5900). The automotive system has been adapted to ensure reliable ignition power during high speed engine operations. A mechanical power measurement system consists of a customized torque arm (23.5 cm long) and a load cell (Sensotec, #31). The torque arm is attached to the floating dynamometer, which rotates freely in the shaft rotating direction. The rotating shaft creates torque to push down the load cell, which is capable of measuring up to 2.5 N. The engine speed is monitored by an optical sensor (ROS, 5W) and a tachometer (Monarch Instruments, ACT-3). Spark ignition timing has been controlled using an optical sensor with an ignition delay. The sensor accurately detects the position of the shaft, and the rotor. A function generator creates a delay for the ignition with respect to the rotor position.

A liquid fuel blend, which is composed of methanol, nitromethane, and oil, is injected to the engine. The mixtures are 50 % (by volume) methanol, 30 % nitromethane, and 20 % castor oil. Castor oil has been used as a lubricant, and it has a coefficient of friction for steel on steel of 0.095 [10].

3. RESULTS

The S1500 has generated positive mechanical power being naturally aspirated and for liquid fuel injected operation. The fuel flow rate has been measured as 45 mg/s. The engine is motored to 4000 rpm, and the ignition system is turned on.

The torque has been measured by loading a dynamometer with series of rheostats. The engine shaft experiences a resistive force, which is created by the loaded dynamometer, and generates a torque to push the torque arm. The mechanical power has been measured and shown in Figure 3.

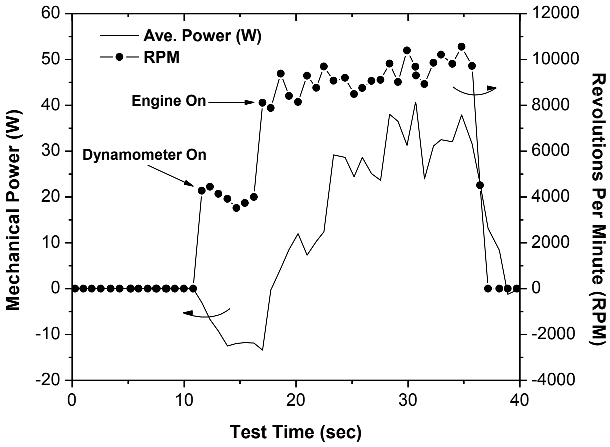

Figure 3: Positive power is generated for a naturally aspirated operation of the S1500 engine. The engine produces a peak power of 40.6 W at 9600 rpm.

The engine has generated the maximum sustained mechanical power of 40.6 W and the corresponding engine speed is determined as 9600 rpm. The ignition timing has been set as 30º after top dead center (ATDC). The engine sustains this power for 20 seconds, and is shut down for cooling to prevent engine seizing. The average mechanical power during the test is determined as 31.5 W.

Comparing with the fuel chemical energy input of 855 W, the maximum efficiency of the engine is determined as 4.7 %, whereas the averaged efficiency is estimated as 3.7 %. The mass of the engine is 210 g and therefore, the specific peak and average power is determined as 193 W/kg, and 150 W/kg, respectively.

The engine housing temperature is monitored during the engine performance test (Figure 4). As the engine starts to generate its own power at 9000 rpm, the housing temperature increases to 90 ºC. During the engine operation, the temperature reaches up to 111 ºC. The housing temperature provides a measure of the combustion efficiency.

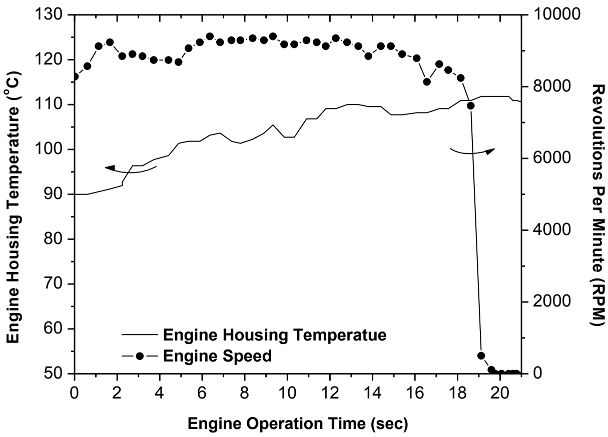

Figure 4: Measurement of the housing temperature of the S1500 engine, which provides a measure to determine the combustion efficiency.

4. DISCUSSION

The S1500 rotary engine demonstrated an improved power generation compared with the previous work [2]. The maximum mechanical power increased from 33 W to 40.6 W and, in consequence, the maximum engine efficiency was improved from 3.9 % to 4.7%. The engine generated the maximum power for a retarded spark ignition timing. The spark ignition timing was delayed from 20º ATDC, as used in the previous work, to 30º ATDC, and it results in a maximum power output.

The delay of the spark ignition timing affects the engine performance because it increases the liquid fuel droplet evaporation time. As the engine operates at high speed the total residence time decreases. At 9600 rpm, the residence time is determined to be less than 5 ms. The fuel droplet is required to evaporate, mix, combust, and produce power during the residence time. Therefore, the evaporation time is limited whereas the engine requires the diameter of the droplets to be less than 40 μm. The COTS fuel injector, however, does not reliably inject fine droplets into the engine, which causes an increase of the droplet evaporation time. A ten degree delay of the ignition timing provides an increase of 0.2 ms in the compression stroke. The increased time is utilized as extra evaporation time. The increased mass of evaporated fuel enhances the combustion efficiency and the maximum power. In general, it is not recommended to delay the ignition timing since the delay reduces the combustion and the expansion stroke time, which produces work.

The path of blow-by is further reduced compared to the previous work [2]. The blow-by path is created between the combustion chamber and the intake chamber as the rotor passes by the spark plug hole (Figure 5). The previous work reduced the path by decreasing the recess of the spark plug, and it induced the reduction of fresh charge contamination by high-pressure combusted exhaust gases.

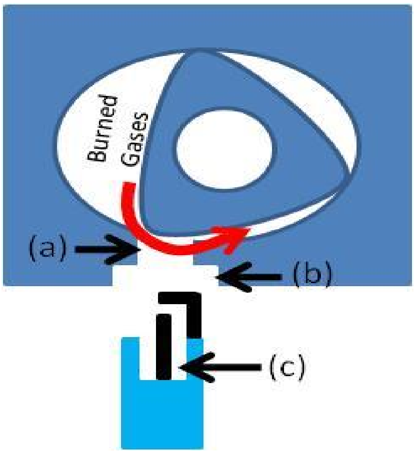

Figure 5: The path of blow-by is open when the rotor passes the spark plug hole: (a) Spark plug recess, (b) Spark plug hole, (c) Dead volume in spark plug.

In the current work, the minimization of the dead volume of the spark plug was achieved by filling the recess with thermally insulated material. By flattening out the spark plug recess, and filling up the dead volume of the spark plug, the blow-by path has been minimized and the engine efficiency increased.

5. CONCLUSION

The S1500 rotary engine has been developed and tested. The maximum mechanical power and the average power were determined as 40.6 W and 31.5 W, respectively. The maximum mechanical power and the efficiency have been increased by 19 % and 20 % compared to the previous work. The increased efficiency is due to a longer droplet evaporation time, and minimization of the blow-by path.

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