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Miniaturization limitations of rotary internal combustion engines

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A R T I C L E I N F O

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A B S T R A C T

With the rapid development of micro electro-mechanical devices, the demands for micro power generation systems have significantly increased in recent years. Traditional chemical batteries have energy densities much lower than hydrocarbon fuels, which makes internal-combustion-engine an attractive technological alternative to batteries.

Micro rotary internal combustion engine has drawn great attractions due to its planar design, which is well-suited for fabrication in MEMS. In this paper, a phenomenological model considering heat transfer and mass leakage has been developed to investigate effects of engine speed, compression ratio, blow-by and heat transfer on the performance of micro rotary engine, which provide the guidelines for preliminary design of rotary engine. The lower possible miniaturization limits of rotary combustion engines are proposed.

1. Introduction

The demand for power sources that have long lifetimes and high energy densities has significantly increased in recent years. Traditional power source i.e., batteries, of which the energy density has only increased by a factor of two (on an average 600 kJ/kg alkaline and 1200 kJ/kg lithium), far less than the increasing demand for high energy density [1,2]. This gap is expected to widen as portable electronic devices need more power to support enhanced functionalities. Hydrocarbon fuels have energy densities (on an average 30,000–40,000 kJ/kg) much greater than the best batteries. Therefore, taking advantage of the high energy density of chemical fuels to generate power becomes an attractive technological alternative to batteries [3]. Even with a 5% of energy conversion efficiency, the energy density of internal combustion engine is still superior to battery-motor electrical systems [4].

Micro-engines are not simply smaller versions of their macro-scale counterparts. Many of the major components cannot be easily reduced in order to achieve proper functioning and it is clear that the micro-scale engine is to be very different from the macro-scale known to us [5–9]. It is important to understand how their performance changes with engine size, and how the key factors affect the minimum size of a practical heat engine so that techniques for alleviating these losses, and reducing the minimum size of practical heat engines, can be developed [10].

In order to reduce the minimum engine size, a number of issues must be considered in the miniaturization process of internal combustion engines, which include quenching, residence time, heat loss and mass leakage. Given the issues above, some researches have been done to investigate the inter-relationships between engine performance and engine size. Menon and Cadou [11] investigated the scaling rules for the performance of miniature two stroke piston engines. The scaling rules are derived from comprehensive dynamometer investigations of nine of the smallest commercially available internal combustion engines. The results show that power and efficiency decrease more rapidly with size in miniature than in larger scale engines. The data showed that the minimum cylinder volume based on present technology is 0.1 cc. Following work [10] has been done to explore the reasons for these trends. It is identified the incomplete combustion is the most important factor. Incomplete combustion is mainly caused by quenching distance [12–14] and residence time [15]. The combustor chamber size is lower than quenching distance, which makes the quenching of the combustion reaction a major concern [16–18]. Both thermal and radical quenching become more significant in micro scale combustion [19]. Some fundamental researches have been done to solve the quenching issue within micro combustion chamber. Kikui et al. [20] and Maruta et al. [21] studied the characteristics of combustion in a heated channel with a temperature gradient. The inner diameter of the channel was slightly smaller than the conventional quenching diameter of the employed mixture. The results showed that flame can be stabilized in the heated channel. Jiang et al. [22] and Bagheri and Hosseini [23] studied the characteristics of micro combustion with

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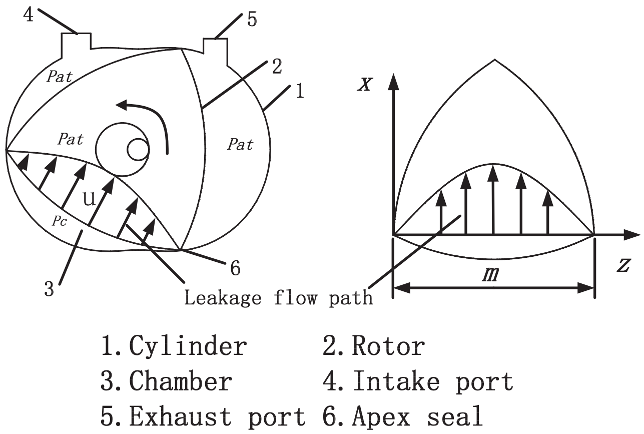

Fig. 1. Schematic sketch of a simple rotary combustion engine.

heat recirculation. It was observed that the flammability and blow-off limits were been extended significantly due to preheating of the reactive mixture. Wang et al. [24] investigated the effect of catalyst on flame stability. The experimental results showed that catalyst was effective to inhibit extinction and extend flammability limits. Catalyst was also applied in a micro gas turbine engine [25]. Catalysts act to decrease reaction times by lowering the activation energy associated with the reaction, thereby increasing reaction rate. Aichlmayr et al. [26] studied HCCI combustion model in micro free piston engines in order to avoid quenching phenomena. A numerical model was developed and validated by experiment data. Heat loss and Leakage were considered. The results indicated that HCCI was possible in spaces 3 mm diameter and 0.3 mm long. Another concern is residence time. In order to maintain high power density of micro engines, high engine velocities must be maintained, which lead to insufficient chemical reaction time. The micro gas turbine engine suffers from the shorter combustor through-flow time because of the high mass flow rate [25].

Besides, heat loss increases significantly due to high surface area to volume ratio at micro scale size. Charge leakage is also unavoidable because of the limited manufacturing level. Sher et al. used numerical simulations of the Otto engine cycle to predict how small piston engine performance should scale with size [4,27]. The first work took the charging efficiency, heat loss and friction loss into consideration to estimate the minimum size of scaling-down HCCI cycle engines. It demonstrated that for a leakage gap width of 10 μm, the minimum possible engine size is 0.4 cm bore (corresponds to 0.05 cc). The second research focused on charge leakage through the piston-cylinder gap and heat loss to estimate a minimum engine size based on homogenous charge compression ignition (HCCI) operation between 0.3 and 0.4 cm^3 at an engine speed of 48,000 rev/min. The temperature change caused by pressure drop along the leakage gap is neglected. Aichlmayr et al. [6] investigated the effect of heat transfer on the limitation of the size of micro free piston engine. A numerical model considering detailed chemical kinetics and diffusion models for heat transfer and radical loss was developed. The results

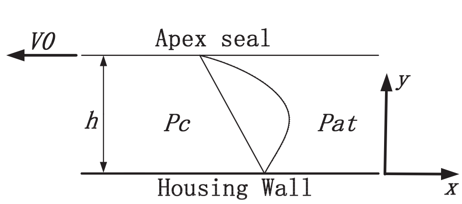

Fig. 2. Apex leakage model schematic.

showed that the minimum engine size is essentially limited by heat transfer. However the exact minimum engine size was not established because the leakage effect was neglected. Formosa and Frechette [28] exploded the scaling effects for free piston stirling engines. From the proposed scaling laws, potential power and efficiency of stirling cycle engines at a millimeter scale can be anticipated. It demonstrated that power density increase with miniaturization. It is also shown that gap leakage presents the highest detrimental effects on efficiency.

As reported in technical literature, many researchers studied the scaling laws for the conventional piston engines. Few efforts have been devoted to investigating the relationship between the micro rotary engine performance and engine size. Fernandez-Pello et al. [29] have conducted research on micro rotary engine, but the authors focused on design and fabrication of the engine components. The objective of the presented paper is to provide a guide for understanding the scale laws of rotary combustion engines. In this paper, a phenomenological model considering thermal dynamic process, heat transfer and charge leakage is developed. Special attention is drawn to the inter-relationships between the charge leakage around the apexes of the rotor and across the rotor faces, the engine speed and the engine geometrical dimensions. This is in order to present scaling laws for the performance of micro rotary internal combustion engine.

2. Theoretical consideration

In this section a comprehensive mathematical model has been developed to characterize the relevant processes inside the cylinder of the micro rotary combustion engine. Fig. 1 shows a schematic sketch of a simple micro rotary combustion engine. The cycle has been simplified and idealized for purpose of constituting the lowest possible scaling-down limit of a rotary engine.

Table 1
Experimental results of different cylinder volumes.

	Volume (cc)	Compression ratio	Engine speed (rev/min)	Output power (W)
Sprague2007 [32]	0.348	7.8	9300	3.8
Sprague2007 [32]	1.5	11.8	8600	33
Yisheng2007 [33]	3	12	15,000	150
OS.49-PI Wankel Engine	5	12	17,000	805

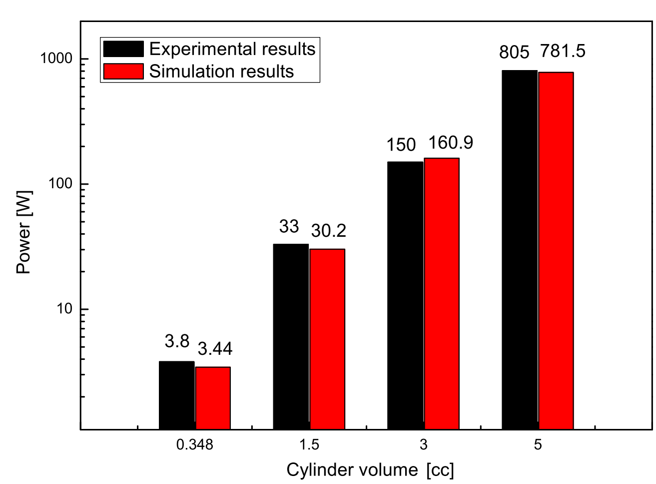

Fig. 3. Comparison of output power of simulation and experimental results.