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Micro Newcomen steam engine using two-phase working fluid

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ABSTRACT

A micro steam engine is developed based on Newcomen steam engine. In the micro engine, a flexible ripple tube takes the place of piston and cylinder, to overcome the serious problems of friction and leakage in micro scale. We use two-phase octane as working fluid of the micro engine, because two-phase octane has higher power density than gaseous one. The micro engine is tested under different operational conditions to investigate its performance. It produces a maximum net mechanical work of 0.405 J per cycle with an efficiency of 2.58%. This experiment proves the feasibility of the micro steam engine.

1. Introduction

The power of portable electronic devices, such as laptops, cellular phones, is supplied by battery. Its energy densities are less than 0.5 MJ/kg [1], thus limit the operation period. Micro power system converts chemical energy of hydrocarbon fuels to electricity directly, thus has higher power density [2]. Its performance will excel the conventional battery, if only its efficiency is higher than 1% [3–5]. Although fuel cells have higher efficiency than micro power system [6]. They are made of expensive Pt material and only adapt a few kinds of fuel with high purity.

The first micro gas turbine based on Micro Electro Mechanical System (MEMS) technology was suggested in Massachusetts Institute of Technology (MIT) in 1996 [7]. Then, Jan Peirs developed a single-stage axial micro turbine driven by compressed air [1]. Besides micro turbine, internal combustion micro engine was also proposed [8]. For example, C.H. Lee produced a micro Wankel engine driven by CO_2 [9]. Zhang Shimin fabricated a prototype of micro free-piston swing engine [10]. Homogeneous Charge Compression Ignition (HCCI) was also proposed to improve the micro engine's performance [11–13]. To overcome the serious problems of friction and leakage between mechanical parts in micro engine [14], T. Geng fabricated a micro pulsejet [15]. S. Whalen developed a novel P3 engine, made of an elastic membrane [16,17]. Energy converters based on thermoelectric or thermophotovoltaic material were also proposed [2,18–20].

Technology of manufacture limits the development of micro engine. The low machining accuracy causes friction and abrasion of the mechanical parts. The leakage also induces low efficiency. These problems cause poor performance and instability of micro engine [1].

In this paper, a new micro steam engine is proposed. We try to take the place of piston and cylinder of engine with a flexible ripple tube. It works as one monolithic part, thus solves the problems of friction and leakage. In the experiment, we test the micro engine prototype under different operational conditions, to prove its feasibility.

2. Experimental system

2.1. Experimental facility

The prototype engine is developed based on Newcomen steam engine. For experimental convenience, the engine is powered by electricity instead of fuel. A block diagram of the facility is shown in Fig. 1. The experimental system has a loader and a heater installed, which exchange mechanical energy and heat with the engine, respectively.

The loader consists of a weight, an AC motor and a linear sensor (WS KTR-50). The motor lifts and drops the weight to change the pressure inside the ripple tube. A linear sensor monitors the displacement of ripple tube top.

The boiler has dimensions of 25 × 45 × 52 mm. The heater is a 160-W electrical heating tube installed into it. It is turned on and off to change the temperature of working fluid. A K-type thermal

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Nomenclature

η	efficiency	Q	heat absorption per cycle [J]
ΔT	temperature difference of thermodynamic cycle [K]	Q_{in}	heat absorption during heating [J]
T_{hot}	high temperature of thermodynamic cycle [K]	Q_{net}	net heat absorption per cycle [J]
W	mechanical work output per cycle [J]	C_v	specific heat at constant volume [J/kg K]
p	pressure [kPa]	Q_{out}	heat loss to environment during cooling [J]
T	temperature [K]	V	volume [m^3]
s	entropy [J/K·kg]	v''	specific volume of saturated vapor [m^3/kg]
W_{heat}	mechanical work output during heating [J]	v'	specific volume of saturated liquid [m^3/kg]
W_{out}	total mechanical work output [J]	p_s	saturation pressure [kPa]
W_{ex}	mechanical work output during expansion [J]	T_s	saturation temperature [K]
W_{cool}	mechanical work input during cooling [J]	C_p	constant pressure heat capacity [J/kg K]
W_{in}	total mechanical work input [J]	ρ	fluid density [kg/m^3]
W_{com}	mechanical work input during compression [J]	m	mass of working fluid [kg]
W_{net}	net mechanical work output per cycle [J]	m_{gas}	mass of gas [kg]
		x	displacement [mm]
		Δh	latent heat for vaporization [J]

couple and a diffuse silicon piezoelectric pressure sensor (AOB-131) monitor the temperature and pressure inside, respectively.

A digital data acquisition device (WSP-D806) collects the temperature signal. The pressure and displacement signals are transmitted to the analog input model (I7017). A digital output model (I7050D) controls the switch of loader and heater. All the signals are controlled or monitored by the computer.

The ripple tube is made of stainless steel. It expands and shrinks alternatively to produce mechanical work. A photograph of the ripple tube is shown in Fig. 2. For the convenience of manufacture, assembling and measurement, we use the ripple tube with centimeter-scale in the preliminary experiment. It has dimensions of φ46 × 41 mm and thickness around 0.2 mm.

The engine utilizes two-phase octane as its working fluid [21]. Octane is chosen because of its lower latent heat for vaporization (Δh). According to Clausius–Clapeyron Equation and Carnot equation (Eqs (1)and (2)), while the pressure difference is limited, lower Δh induces higher temperature difference of thermodynamic cycle (ΔT), thus increases the efficiency. Moreover, two-phase octane has higher mechanical work output per cycle. According to Eq (3), while ΔT and volume (V) are fixed, the mechanical work output per cycle (W) is proportional to the density (ρ) and heat capacity (C_p) of working fluid. Saturated liquid octane has ρ and C_p of 700 kg/m^3 and 2293 J/kg K [22], respectively, much higher than gaseous octane (4.97 kg/m^3 and 2092 J/kg K) [23].

$$\frac{d\,p_s}{d\,T_s} = \frac{\Delta h}{T_s(v'' - v')} \tag{1}$$

$$\eta = \frac{\Delta T}{T_{hot}} \tag{2}$$

$$W = \eta \cdot \Delta T \cdot \rho \cdot C_p \cdot V \tag{3}$$

2.2. Operation process

The control system switches the on/off of heater and loader alternatively, using the displacement of the ripple tube top (x) as a benchmark. The operation process of micro engine is shown in Fig. 3. A, during heating, the ripple tube expands from its initial displacement (x_0). Once the displacement reaches certain value (x_1), the weight is lifted and heater is turned off simultaneously. B, the expansion starts. C, the residual heat of octane is lost into the environment through passive natural convective cooling. Corresponding shrink makes the displacement decreases. When it

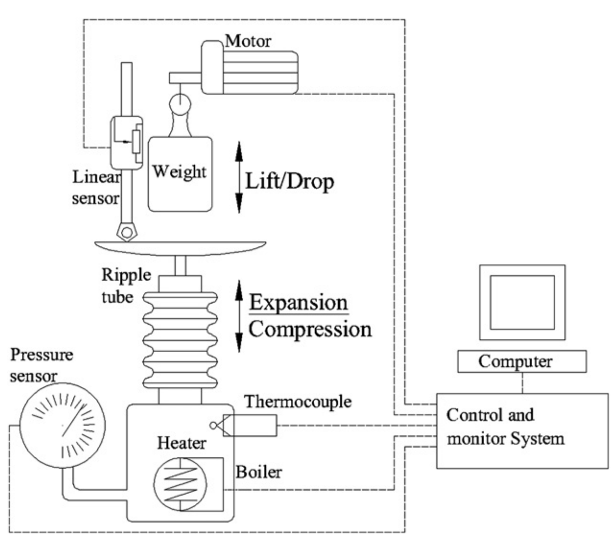

Fig. 1. Experimental system of the micro engine. The dashed lines are the signal routes.

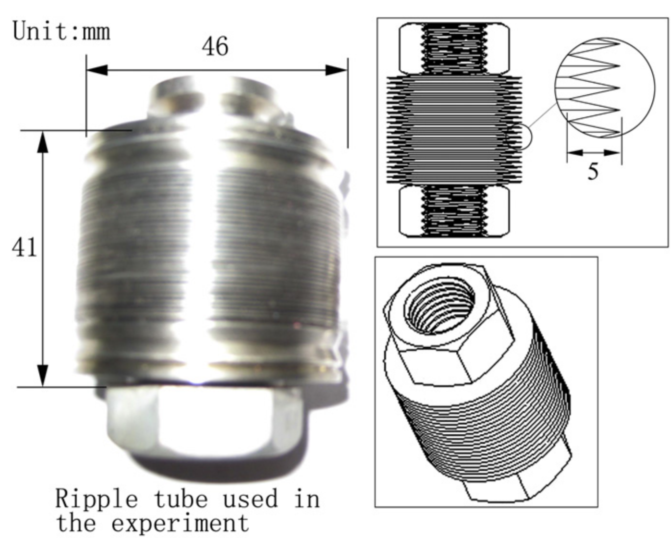

Fig. 2. Photograph of ripple tube.