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EFFECT OF EVAPORATOR LENGTH ON THE PERFORMANCE OF A SELF-OSCILLATING FLUIDIC HEAT ENGINE (SOFHE)

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Abstract — This paper reports the effect of evaporator length on the performance of a self-oscillating fluidic heat engine (SOFHE). The SOFHE is a thermal energy harvester, when coupled with an electro-mechanical transducer that was proposed to power wireless sensors widely used in the Internet of Things (IoT). The mechanical power of the SOFHE is in the order of fraction of milliwatts, which makes it a promising power supply for a range of wireless sensors with the power requirements of 10s µW. The SOFHE consists of a vapor bubble trapped by an oscillating liquid plug acting as a piston. The working principle of the SOFHE is similar to a single-branch pulsating heat pipe. The engine is a small tube (inner diameter of 2 mm) filled with deionized water heated from a closed end and cooled from the opposite open end. By perturbing the equilibrium of the vapor bubble-liquid plug, oscillation start and are sustained by cyclic evaporation-condensation from a thin film in the vapor bubble. To characterize SOFHE's mechanical power as a function of the evaporator length, measurements of pressure, oscillation amplitude, and frequency are conducted. As the evaporator length decreases (from 7 cm to 1 cm), the oscillation amplitude decreases (from 5.9 mm to 1.5 mm) while the frequency increases (from 27 Hz to 52 Hz). In theory, the power of SOFHE is proportional to the square of frequency and amplitude, so the trend in power is not obvious given the opposing effects. The results show a decrease in the mechanical power from 380 µW to 180 µW, which implies that the negative effect of the amplitude decrease dominates over the increase in frequency. A fourfold decrease was also observed in the net evaporation rate (from 1027 to 242 µg/s), which explains why the amplitude decreases with the evaporator length. The research findings contribute to the design of both SOFHEs and pulsating heat pipes by suggesting that a longer heated zone improves the performance.

Keywords- heat engine, self-oscillation, evaporator length, evaporation-condensation, thermal energy harvester

I. INTRODUCTION

Finding a sustainable and autonomous means to power billions of sensors that are used to connect objects for the Interne of Things (IoT) has become a challenge. Energy harvesting has emerged to address this need by generating electricity from available energy in the ambient. Thermal energy harvesters converts heat directly into electricity like thermoelectric generators (TEGs) [1], or indirectly (thermal-to-mechanical-to-electrical) like micro heat engines coupled with an electromechanical transducer [2–6]. A self-oscillating fluidic micro heat engine (SOFHE) is a recently discovered micro heat engine with a unique thermodynamic cycle [7]. The SOFHE is a vapor bubble trapped by an oscillating liquid plug acting as a piston. The pressure build-up inside the vapor bubble is the mechanical force that is then converted into electrical energy by coupling the SOFHE with a transducer (Fig. 1).

This vapor bubble-liquid plug is modeled as a damped (friction) mass-spring system [8–12]. The frequency of the system, defined by square root of the ratio of stiffness to mass, is inversely proportional to length of vapor bubble and liquid plug. The oscillation is sustained by cyclic evaporation-condensation of a thin film in the vapor bubble. The oscillation starts when the force from the evaporation-condensation (change of mass of vapor) is greater than that of friction [12,13]. To increase the oscillation amplitude, the evaporation-condensation rate must increase and be synchronized with the displacement [14]. Theoretically, SOFHE's power is proportional to the square of amplitude and frequency. However, it is not clear how amplitude and frequency, and consequently the power, is affected as we change the length of the heated zone (that mostly equals to the length of the vapor bubble). In this paper, the length of the heated zone is experimentally varied and the pressure, amplitude, and frequency measurements are carried out to evaluate the power of SOFHE. The experimental setup and procedure used to vary the heated zone length are explained in methodology section. The amplitude and frequency measurements as a function of the evaporator length are presented in the result section A. The effect of evaporator length on the net evaporation rate is then discussed in results section B. The thermodynamic cycle, work, and power of SOFHE are evaluated in results section C. Finally, the efficiency of SOFHE is presented is results section D.

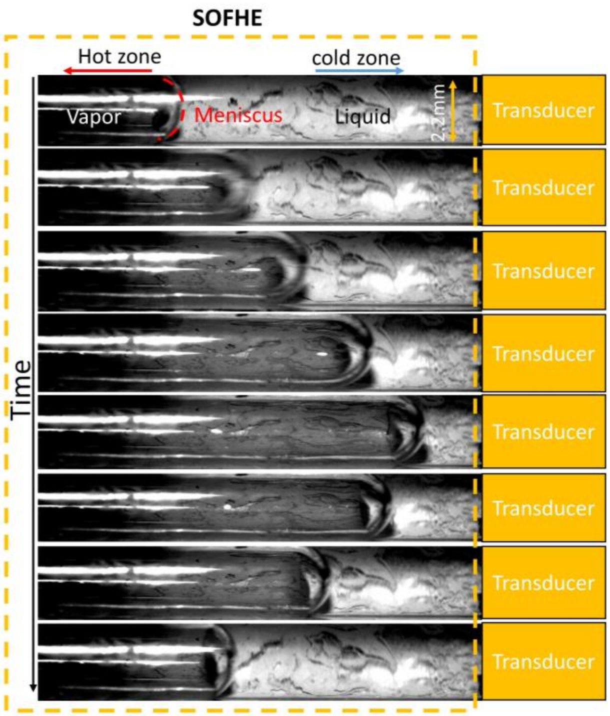
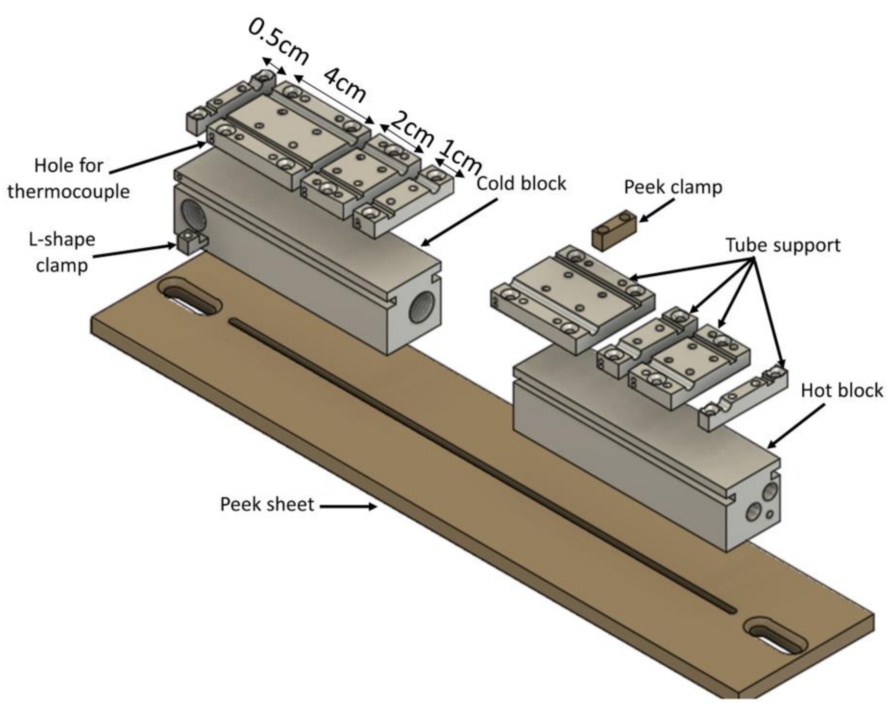


Figure 1. The SOFHE's cycle of generating work through compression-expamsion of the vapor bubble, which becomes a thermal energy harvester when coupled with a transducer.

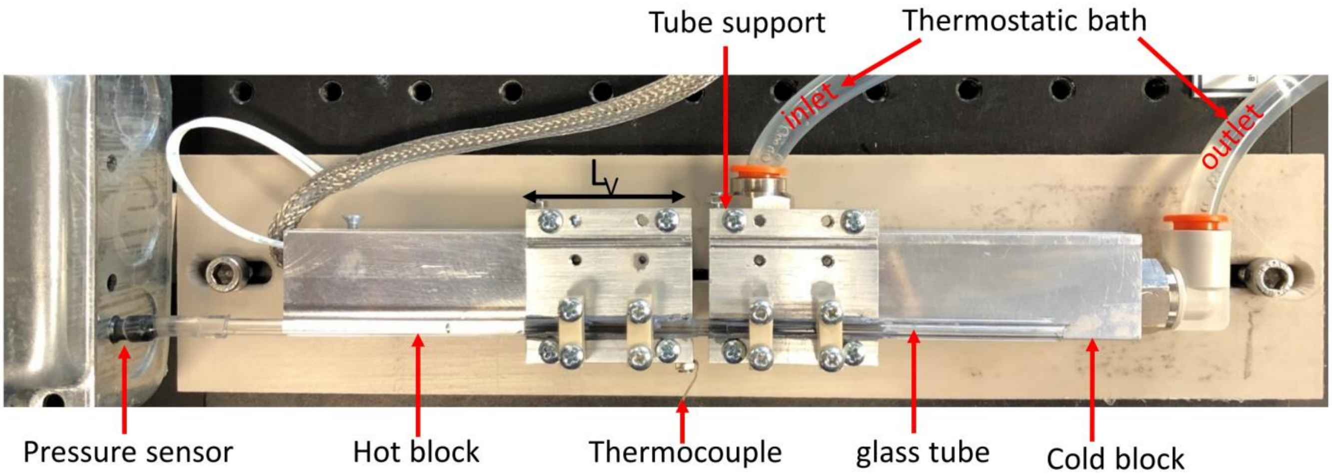
II. METHODOLOGY

A. Experimental Setup

The SOFHE is a glass tube (with an inner (D_{in}) and outer (D_{out}) diameter of 2 and 4 mm) that is filled with deionized water. The tube is horizontally placed in a semi-circular groove on two blocks, one heated with a cartridge heater and one cooled with cold water from a thermostatic bath. The heated end of the tube is closed with a pressure sensor (PX26, OMEGA Engineering) and the cooled end is open and monitored with high-speed camera to simultaneously measure motion and pressure. As the exploded-view in Fig.2 a shows, the experimental setup has two hot and cold Aluminum (Al) blocks. The blocks are installed on an insulating Peek sheet with a slot that allows to control the distance between the heated and cooled blocks (so-called adiabatic zone). To adjust the length of the heated and cooled zone, tube supports at different lengths are designed with a semi-circular groove to accommodate the SOFHE. The tube supports are screwed to the blocks using thermal paste (TG-7) between them. A set of thermocouples and temperature controllers are used to control the temperature of the heated and cooled blocks.



a)



b)

Figure 2. The experimental setup used to vary the length of the evaporator a) 3-D exploded view b) top view photograph with the SOFHE (capillary glass tube) mounted on top [15].

B. Experimental Procedure

The first step to start a test is oxygen plasma treatment of the glass tube for cleaning and hydrophilicity (power at 100 W for 1 min). The tube is then filled with water and connected to the pressure sensor. A fiber (capillary with closed ends, Polymicro, external diameter of 350µm) is inserted inside the tube into the hot zone to create a thin film that feeds the evaporation-condensation. The fiber acts as a wicking structure and pumps liquid from the liquid plug into the evaporator [14]. The temperature of the condenser is set at 20℃. As the heating process starts, a vapor bubble forms and grows lengthwise reaching an equilibrium point (normally in the adiabatic zone). Perturbing the equilibrium by increasing temperature of the heat source (T_H) leads to oscillation startup. The pressure and position measurement are synchronized using a data acquisition board (USB-1608GX). The uncertainty of the amplitude measurement is ±4% that is caused by the conversion from pixel to meter. The pressure uncertainty calculated based on the pressure sensor specifications is at ±70 Pa. The propagation of these uncertainties in the secondary variables, including work, power, and net evaporation rate are calculated and the results are shown as error bars or shading. The tests are carried out at four evaporator lengths (L_v) of 7, 5, 3, and 1 cm while keeping the fiber length at 1cm inside the evaporator, the heat source temperature at 120℃, the liquid length (L_l) at 5.5 cm, and the adiabatic length at 4mm. The total volume of the SOFHE equals the product of the cross-section area ($A=\pi D^2_{out}/4$) and the total length ($L_T= L_v+L_l$) that varies between 1.6 and 0.8 cm^3 depending the length of the evaporator.

III. RESULTS

A. Amplitude and Frequency

Figure 3 shows that as the evaporator length decreases from 7 cm to 1 cm, the peak-to-peak amplitude of the oscillations decreases from 5.9 to 1.5 mm while the frequency increases from 27 to 52 Hz. The variation of frequency with evaporator length is in agreement with the natural frequency of the equivalent mass-spring system in which the frequency is inversely proportional to the square of vapor length [12]. To explain the decrease of the amplitude, we need to calculate the net evaporation rate on which the amplitude is highly dependent [7,14]. The net evaporation rate is discussed in section B.

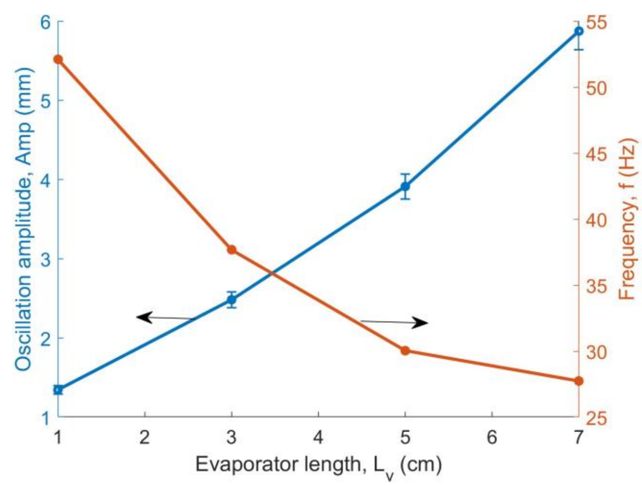


Figure 3. The frequency and oscillation amplitude of the SOFHE as a function of the evaporator length.

B. Net Evaporation Rate

The net evaporation rate (rate of change of vapor mass) is calculated using the ideal gas law (m_v=RT_v/P_vV_v) and experimental data on pressure (P_v), volume (V_v), and temperature (T_v) [14]. Figure 4 shows the net evaporation rate as a function of time at four different evaporator lengths. The negative and positive values show net condensation and net evaporation, respectively. The results show the decrease of net evaporation rate (peak-to-peak amplitude decreases from 1027 to 242 µg/s) as the evaporator length decreases leading to the decrease of the amplitude.

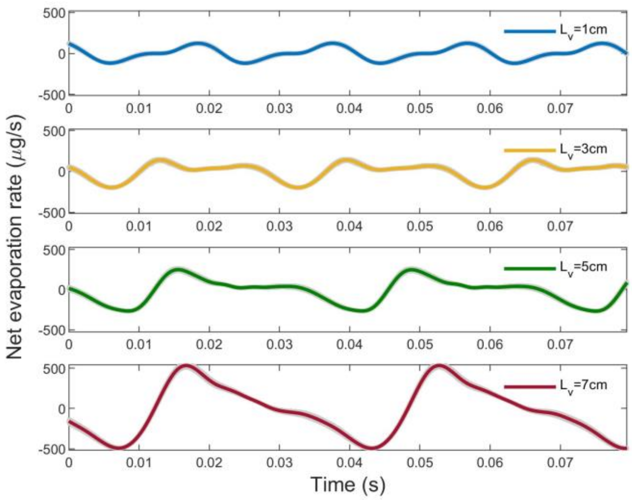


Figure 4. The net evaporation rate as a function of time for four different evaporator lengths.

C. Work and power

To evaluate how the variation of amplitude and frequency affect the power of SOFHE, the thermodynamic cycle (P_v-V_v) of SOFHE at different evaporator lengths are plotted in Fig. 5. The integration of the area in the P_v-V_v curve yields the work done in each cycle. The cycles shrink as the evaporator length decreases leading to a decrease in the thermodynamic work per cycle. It is shown that for SOFHE at optimum load, nearly half of the thermodynamic work per cycle is used to overcome the viscous friction [7]. Therefore, the available net work per cycle that can be harvested by a transducer can be estimated as half of the thermodynamic cycle work. The power of SOFHE is the product of the net work per cycle and frequency. As Tessier-Poirier showed [12] [16], the generated power by SOFHE is from a velocity damped force (F_d = $c\dot{x}$) created by the net evaporation rate (the change of mass of vapor). Theoretically, the power from this force in an oscillating motion ($x = A \sin(\omega t)$) is proportional to the square of amplitude and frequency (Power=$cA^2\omega^2/2$). Figure 6 shows the power of SOFHE as a function of the evaporator length. A decreasing trend for power shows that the negative effect of decreasing evaporator length on the amplitude overcome the positive effect of frequency increase. However, at smaller evaporator length, the slope of the graph flattens implying the fact that the power is less and less dependent on the evaporator length.

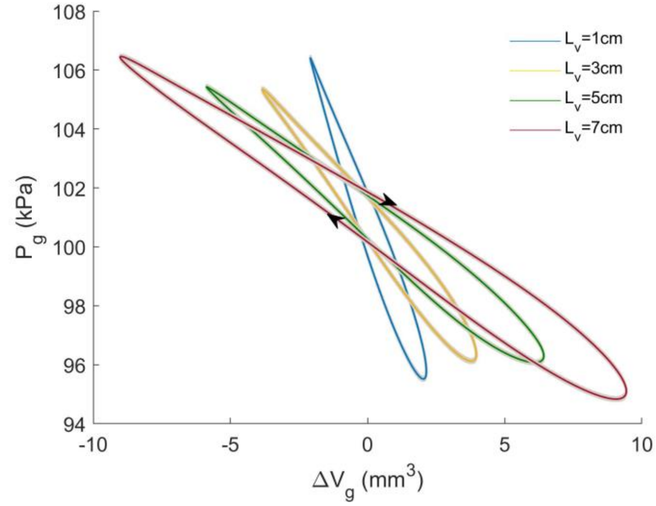


Figure 5. Thermodynamic cycle (P_v-V_v) of SOFHE for four different evaporator lengths.

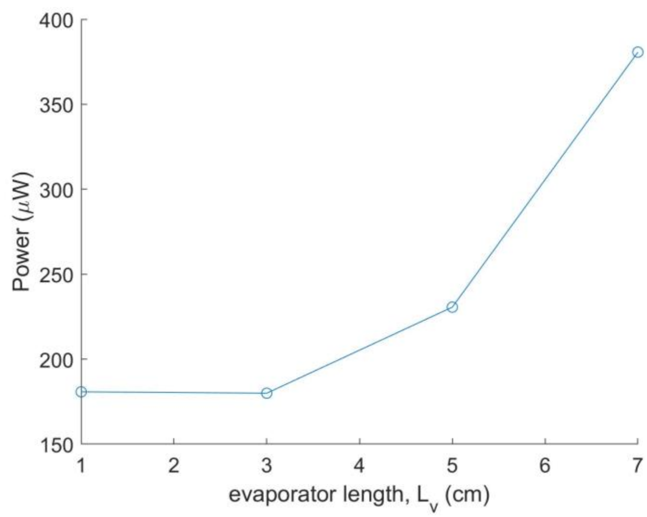


Figure 6. Power of the SOFHE as a function of the evaporator length.

D. Efficiency

The efficiency of SOFHE is estimated by calculating the heat that is required for the evaporation-condensation (sensible heat is negligible [7]) and the net work per cycle (η_{SOFHE}=W_{net}/Q_{in}). The efficiency of the SOFHE decreases from 0.3 % to 0.1 % as the evaporator length decreases from 7 to 1 cm. The Carnot efficiency of SOFHE (T_C= 20℃ and T_H= 120℃) is 25%. The relative efficiency of SOFHE with respect to the Carnot efficiency is 1%. However, for SOFHE as an energy harvester that uses waste heat as an input energy, efficiency is not a main metric to evaluate but rather power density is important. The mechanical power density of SOFHE is between 0.1-0.2 mW/cm^3. Therefore, the SOFHE is capable of generating mechanical power density that is an order of magnitude greater than the power requirements of a range of wireless sensors (10s microWatt).

CONCLUSION

In this paper, we experimentally investigated the effect of evaporator length on the performance of a self-oscillating fluidic heat engine (SOFHE) in terms of mechanical power. To do so, the SOFHE was tested at four different evaporator lengths and the amplitude, frequency, and pressure are experimentally measured. The results show that the frequency increases as the vapor length decreases while a decreasing trend is observed for the amplitude. The counteractive effect of the frequency and amplitude leads to a decrease in the mechanical power of SOFHE. This shows that the negative effect of decreasing vapor length on the amplitude overcomes the positive effect of frequency increase. The decrease of the amplitude can be associated to the reduction of the net evaporation rate at shorter evaporator lengths. The findings improve SOFHE design by offering that a longer evaporator zone yields a higher mechanical power. Alternatively, approaches to increase the phase change could also be used instead of changing the evaporator length. For example, increasing the thin film area provided by the fiber [14] and adding wicking microstructures [17] have been shown to increase the amplitude, without noticeable effect on the frequency. This approach circumvents the compromise between amplitude and frequency observed here.

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