A MICROFLUIDIC HEAT ENGINE BASED ON EXPLOSIVE EVAPORATION

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Abstract: Although low temperature heat is abundant all around us, it is rarely exploited for practical and economic reasons. This paper presents a new microfluidic heat engine based on the explosive evaporation of a working fluid to convert waste heat into electricity. This approach accumulates thermal energy until the liquid suddenly evaporates, creating a sharp pressure pulse. This pulse is transformed into electricity through a piezoelectric membrane. Continuous operation of the heat engine has been demonstrated experimentally, providing a regular train of pulses. Its average power output was studied under various conditions, showing the existence of distinct operating regimes. The maximum power density achieved was 1.6 μW for a square membrane of 1 cm².

Keywords: Waste Heat Recovery, Energy Harvesting, Explosive Evaporation, Heat Engine, Delayed Eruptive Boiling

INTRODUCTION

Most of the energy used in our society ends up as waste heat rejected in the environment. The heat sources around us range from large-scale power plants to automotive engines, the human body, and even down to the single bit shift in a computer. This waste heat is typically at low temperature, making its recovery inefficient and not economically viable using traditional energy conversion technologies. However, there is a growing interest in harvesting this wasted heat to power distributed wireless sensor nodes or even for running low power electronic devices. Arrays of low cost heat-to-electricity converters are envisioned to be coupled with distributed heat sources to locally provide the power needed [1].

Thermoelectric elements based on the Seebeck effect are the most commonly used and studied devices for distributed waste heat recovery [2]. Alternatively, MEMS-based micro heat engines have been proposed based on their expected high power density [3]. Approaches include the miniaturization of well-known Brayton [4], Rankine [3] and Stirling [5] cycles. The repeated phase change of a fluid in a closed micro chamber has also been studied with either self-actuated [6] or externally actuated principles [7].

The new micro heat engine presented herein is based on a patent pending device [8]. The main driving principle is the explosive evaporation phenomenon. This phenomenon allows the accumulation of energy in a liquid by heating it and suddenly releasing this energy in the form of a mechanical impulse. To the authors' knowledge, it has never been used to implement a heat engine cycle. A recent study [9] has shown that the phenomenon is easier to control at small scales due to smaller and better controlled surfaces. The possibility of using this phenomenon in a micro heat engine is therefore investigated through this paper.

PRINCIPLE OF OPERATION

The proposed heat engine consists of three main phases: 1) pre-heating of the liquid; 2) sudden evaporation of the liquid in a confined chamber, raising the chamber pressure; 3) expansion to provide mechanical work. In a closed cycle, a fourth phase for condensation would follow.

The explosive evaporation approach

Rapid evaporation of a liquid can occur when a liquid is put into unstable conditions that favor a phase change. This can occur if the liquid suddenly comes in contact with a hot surface or if it is pushed beyond its saturation conditions by suddenly lowering the pressure or superheating the liquid above its saturation temperature. The liquid rapidly changes into vapor, creating an increase in pressure when enclosed in a chamber. This explosive evaporation behavior is commonly seen as an undesirable phenomenon during the rupture of pressurized liquid tanks (known as *boiling liquid expanding evaporation*, or *BLEVE*) or flow boiling in microchannels [9]. The approach proposed here leverages the sudden pressure rise as a pressurization mechanism in the heat engine cycle.

The transformation of explosion to electricity

Once the liquid is suddenly transformed into vapor, work can be done by allowing this vapor to expand in a controlled way. This work in the full cycle is given by the integration of the pressure for each infinitesimal volume change along the path of the cycle. Mechanical work is then converted to electricity by deforming a piezoelectric membrane along its polarization axis, inducing electric charges.

EXPERIMENTAL SETUP

Device geometry and fabrication

The device consists of a piezoelectric membrane attached over a planar expansion chamber with fluid ports. A thermocouple is also inserted and the device is coated with epoxy for sealing and mechanical assembly. As shown in figure 1, the chamber is built on a silicon substrate. Its high thermal conductivity allows rapid heating of the dispersed water droplets. Metal shims where used to create the walls of the 1±0.1 cm² square expansion chamber and ensure a uniform 0.5 mm spacing between the substrate and the piezoelectric transducer.

The inlet and outlet fluid ports were formed by inserting capillary tubes between the metal shims. The ports are made of 250±1 µm I.D. fused silica capillary tubes (Polymicro Technologies®) inserted 1 to 2 mm in the chambers sides to ensure that no epoxy is wicked inside. The size of the capillary was chosen as a trade-off between the chamber thickness required to accommodate the capillaries and the apparent strength of the explosions. A commercial piezoelectric buzzer is used as the transducer. It consists of a 230±2 µm piezoceramic bonded to a 200±2 µm brass substrate. The active piezoelectric area is large enough to cover one large face of the expansion chamber. The temperature near the inlet capillary and the edge of the chamber is measured by a standard type K thermocouple. Finally, the device was encapsulated using J-B Weld® steel reinforced epoxy, selected for its temperature resistance.

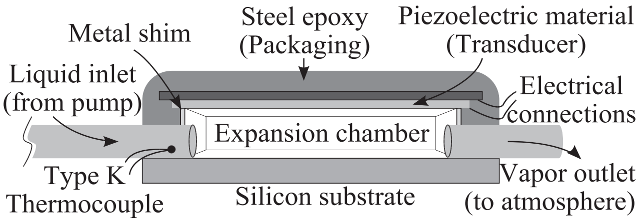

Fig. 1: Schematic cross section of the micro engine.

Characterization setup

The experimental approach consists of heating the bottom wall of the engine while providing a flow of water to the chamber. The characterization setup therefore needs to provide heat, a regulated liquid flow and measurements of temperature and output power.

A syringe pump (PHD2000 by Harvard Apparatus) is used to provide an adjustable flow of liquid at room temperature to the chamber via the inlet capillary. The precision of the flow rate is estimated to be within 10%.

Heat is provided to the device from the bottom silicon substrate by a hot plate. As shown on figure 2, a polished copper mass and silicone thermal grease are used to improve the heat exchange from the ceramic hot plate to the device.

The electrical energy is dissipated and measured using a 50.0±0.5 kΩ resistor, including the oscilloscope probe. This resistor has been chosen to approximately match the electrical impedance of the device to maximize power extraction.

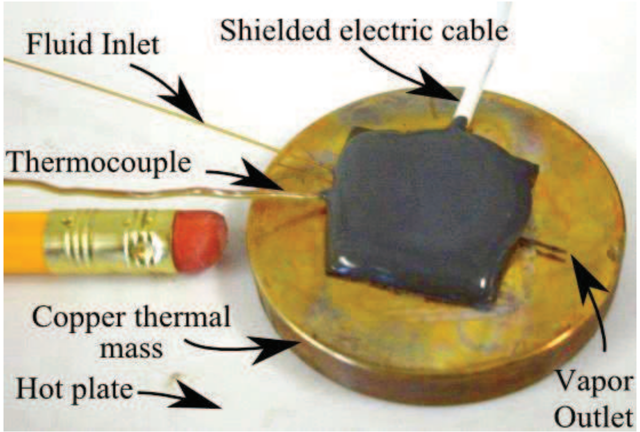

Fig. 2: Optical image of the device.

RESULTS AND DISCUSSION

Single pulse with deionized water

In the study of a heat engine, it is first useful to observe a cycle which is represented here as a pulse. Figure 3 shows the piezoelectric signal measured from one pulse. Before time zero, liquid is injected and heated inside the device. Suddenly, part of the water is quickly vaporized and the pressure inside the chamber rises in less than 10 msec. Although this signal does not provide a direct measurement of pressure, it is a good indicator. The vapor then expands as it is released to the ambient until atmospheric pressure is reached in the chamber. Fresh water provided by the syringe pump then gradually replenishes the evaporated water. The condensation portion for a closed cycle is therefore not accomplished in this open cycle device.

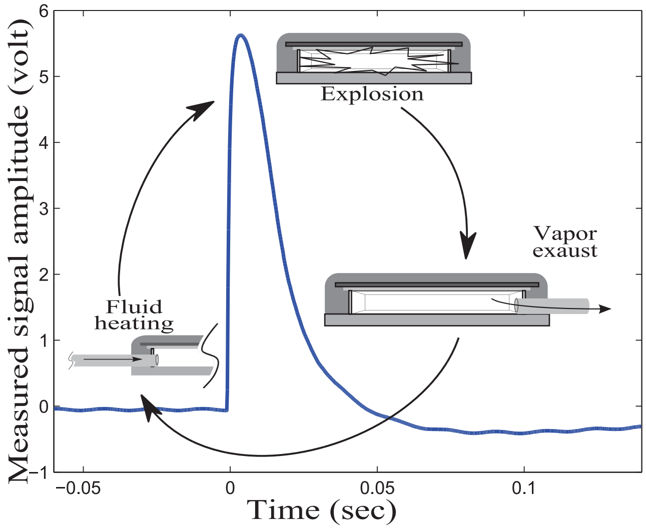

Fig. 3: Typical measured pulse with cycle phases.

Periodic operation with deionized water

With a continuous flow of liquid provided by the syringe pump, the cycle is repeated. Regular periodic pulsations were achieved over extended periods of time (hours), demonstrating the cyclic behavior. The frequency and amplitude of the pulses vary with flow rate and wall temperature. A sample train of pulses is shown in figure 4.

The effects of the heater temperature on the operation of the device are presented in figure 5. These experimental measurements are obtained using a liquid flow of 10 µL/min and averaging power over a 2 s period. It can be seen that, at low temperatures, the harvested power increases with the temperature. Between 135 and 155 °C, the maximum power is extracted. The strength of the pulses suddenly increases by about an order of magnitude, although the frequency decreases at the same time.

This sudden change of behaviour underlines the non-linearity of the underlying phenomenon. For example, in the vicinity of 155°C two modes of operation, strong and weak pulses, alternate in time. The explanation for these two distinct operating modes remains unclear. Finally, at high temperatures the pulse frequency rises again while the amplitude decreases.

The effects of the input liquid flow on the behavior of the system are shown in figure 6. These results are obtained by changing the input flow on the syringe pump while keeping the temperature in the 130 ± 10 °C range.

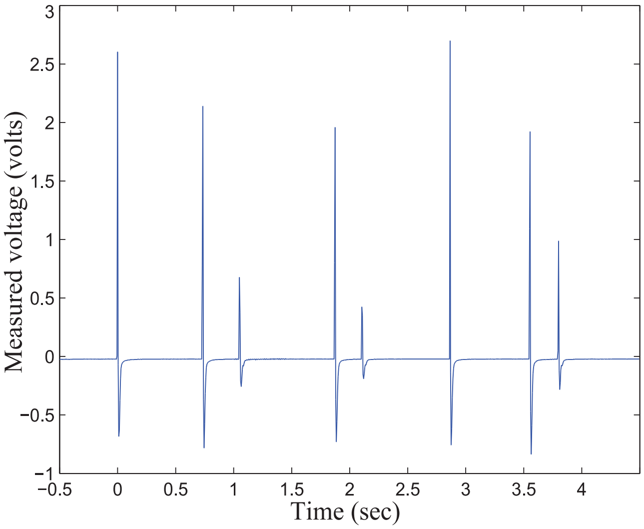

Fig. 4: Measured train of pulses showing continuous engine operation (145°C, 10 µL/min).

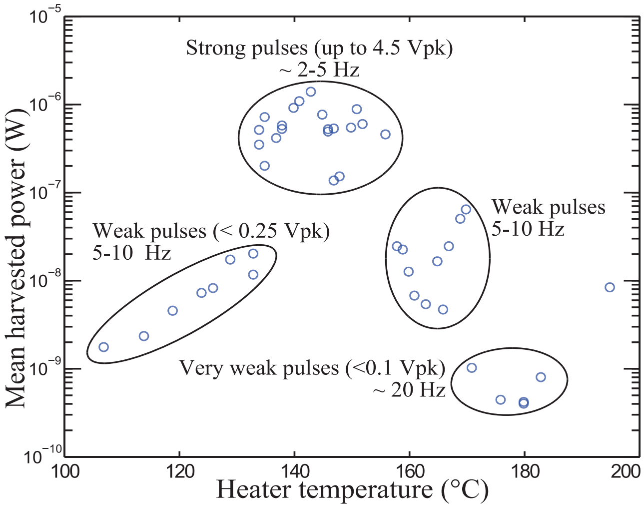

Fig. 5: Effect of heater temperature on the mean harvested electrical power (10 µL /min).

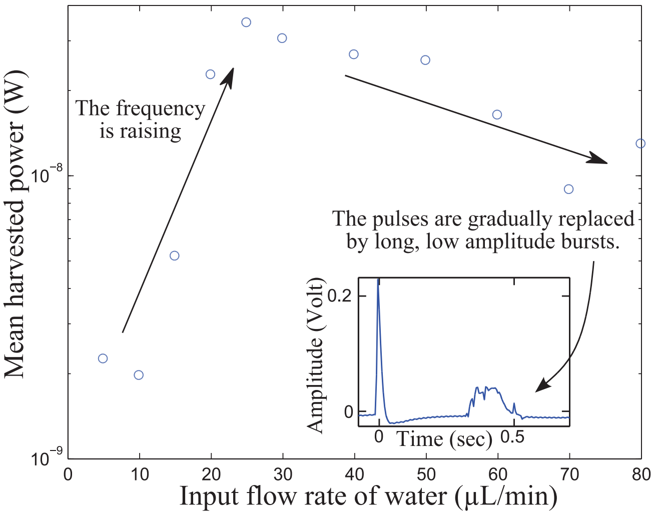

Fig. 6: Mean harvested electrical power at different flow rates of water (130 ±10 °C).

The power is found to initially increase with flow rate. Analysis showed that the pulse strength remains almost constant while the frequency rapidly increases. This is observed up to 25 µL/min, were the power is maximized. Beyond this flow rate, the periodic pulses are gradually replaced by bursts of low amplitude noise and the average power decreases.

Enhancements and potential power density

This demonstration device was intended for investigation of the explosive evaporation micro engine concept and was not optimized for power generation. The energy transfer can be further improved by matching the mechanical impedance between the pressure pulse and the membrane deformation. For example, the relative volume variation can be increased by reducing the dead volume of the expansion chamber, which will induce higher steam pressure and in consequence larger membrane deflection. In addition, using a piezoelectric bimorph membrane transducer without the stiffening epoxy would allow greater deformation of the piezoelectric material for a similar pressure. The cycle can also be closed by integrating a condensing chamber and a pumping mechanism. Finally, the frequency can be increased by adding more capillary inlets.

From figure 6, the current maximum power density of the device is around 1.6 µW/cm². By reasonably placing 12 capillaries around the device and assuming no detrimental coupling effects between them, the frequency can be raised by 12 folds. By reducing the chamber thickness, mechanical coupling is expected to be enhanced by 2 to 4 times. The use of a bimorph membrane transducer can be expected to improve the energy extracted by at least two folds and possibly more. These hypotheses lead to an estimated power density on the order of 50 to 100 µW/cm².

CONCLUSION

The possibility of using the explosive evaporation phenomenon to make a miniature heat engine has been demonstrated for the first time. The device behavior has been studied with water by changing the two main operating parameters: the heater temperature and the liquid input flow rate. This study has identified different operating regimes and an ideal operation zone. Although the device's behavior is still not fully explained, it has been demonstrated to extract up to 1.6 µW/cm² and is estimated to be able to reach 50 to 100 µW/cm² with the proposed enhancements.

Keeping in mind the approach of forming large arrays of such devices attached to heat sources, the planar and relatively simple manufacturing required for this device makes it an attractive solution for waste heat recovery.

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