First experimental demonstration of a Self-Oscillating Fluidic Heat Engine (SOFHE) with piezoelectric power generation

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Abstract. In this paper, we present the working principle and first experimental demonstration of an innovative approach to harvest low-quality heat sources, the Self-Oscillating Fluidic Heat Engine (SOFHE). Thermal energy is first converted into pressure pulsations by a self-excited thermo-fluidic oscillator driven by periodic phase change of a fluid in an enclosed channel. A piezoelectric membrane then converts this mechanical energy into an electrical power. After describing the working principle, an experimental demonstration is presented. The P-V diagram of this new thermodynamic cycle is measured, showing a mechanical power of 3.3mW. Combined with a piezoelectric spiral membrane, the converted electrical power generation achieved is close to 1µW in a 1MΩ load. This work sets the basis for future development of this new type of heat engine for waste heat recovery and to power wireless sensors.

1. Introduction
In this paper, we present for the first time a new principle to convert heat into electricity using a Self-Oscillating Fluidic Heat Engine (SOFHE) [1]. From a constant heat source and heat sink, a thermo-fluidic engine develops cyclic pressure variations that deform a piezoelectric membrane to generate electricity. This approach is suited to take advantage of low temperature waste heat (T<200°C), which is one of the most pervasive energy sources in our environment, and is implemented with low cost component.

In the following, we will first explain the working principle of the SOFHE and its two-stage conversion mechanism. We will then describe in more details the components of the SOFHE as well as the experimental conditions. Finally, we present the performances of the SOFHE both as a heat engine and a thermo-electrical converter.

2. Working principle
The SOFHE piezoelectric demonstrator, presented in Figure 1, is based on an innovative, two-stage, simple conversion mechanism. First, a constant heat source supplies a passive, auto-oscillating mechanism through an evaporator (component 1 in Figure 1) generating mechanical energy via the capillary tube (component 2 in Figure 1). This mechanical energy is then converted into electricity using a piezoelectric membrane (component 3 in Figure 1) during the second step of the conversion.
2.1. **Thermo-fluidic oscillator: from thermal to mechanical energy**

The proof of concept of the thermo-fluidic oscillator is formed by a capillary tube, closed at one end and initially filled with liquid water. A part of the glass tube is inserted in a larger glass tube filled with constant temperature glycerin while the remaining section is cooled by ambient air convection. A vapor bubble is formed in the hot zone. Upon heating, the vapor volume expands until it reaches its thermal equilibrium position. Depending on the temperature gradient at the interface of the vapor and liquid phases, the meniscus begins to oscillate as presented in Figure 2. As a phenomenological approach, this first stage of conversion can be considered as a damped mechanical oscillator excited by the working fluid phase change, as displayed in Figure 3. Evaporation induced when the meniscus enters the hot zone builds pressure in the vapor bubble, pushing the liquid column out until it reaches the cold zone. There, vapor condensates, lowering the pressure in the bubble and pulling the liquid column back into the hot zone. This results in self-sustained periodic oscillations generating pressure fluctuations (Fig. 2) that can be used for mechanical work, driven from a constant source of heat. These dynamics are further analyzed in a complementary paper [2].

2.2. **Piezoelectric conversion: from mechanical to electrical energy**

A dedicated piezoelectric membrane (Figure 4) is used for electromechanical transduction. A silicone layer allows the sealing for a piezoelectric bimorph planar spiral to be deformed by the oscillating pressure. In order to improve the conversion efficiency, the mechanical impedances of the thermo-fluidic engine and the transducer should be matched. The planar spiral shape, allows control of the mechanical stiffness to adapt its impedance.
3. Experimental set-up
The experimental set-up is shown in Figure 5 and detailed hereafter.

3.1. SOFHE piezoelectric generator components and instrumentation
The evaporator is a 30mm diameter glass tube filled with glycerin. A heater located inside the evaporator and connected to a PID controller allows the control of the temperature. A 2mm/4mm inner/outer diameters capillary tube is filled with deionized water and inserted through the glycerin evaporator. One end of the tube is connected to a PX26 pressure sensor (OMEGA Engineering) while the other end is connected to the piezoelectric membrane. The membrane is made by laser micromachining a spiral shape into a commercially available piezoelectric buzzer (PUI Audio Inc. AB4113B). The membrane is mounted to the end of the capillary tube with a 3D printed support. During operation, the meniscus position is captured with a PCO high speed camera, the pressure in the tube is measured, and the membrane output voltage is collected with an Agilent DSO6000 oscilloscope. A data acquisition board (KPCI-3110) enables the acquisition and synchronization of the data.

3.2. Experiments protocol
The initial setup of the SOFHE starts with the cleaning of the capillary tube with a flush of acetone, followed by IPA and rinsed heavily in deionized water. After its insertion through the evaporator, the capillary tube is filled with deionized, degassed water. The pressure sensor is then connected to one of its end and the membrane to the remaining one.

The evaporator temperature is gradually set to a value above 100°C. Once the oscillations appear, the vapor pressure variations are registered and monitored. For a constant temperature, the generator is considered as stable whenever the pressure variation amplitude is constant for 10 minutes at least. The PV-diagram is then registered and the electrical power output is determined.

4. Results and discussion

4.1. Performances of the SOFHE

4.1.1. First stage of conversion – Thermal to Mechanical. At first, the thermo-fluidic oscillator is studied alone, as a heat engine would be (i.e. no load attached to it). For a hot source temperature set to 115°C, the resulting P-V diagram is obtained (Fig. 6). The calculated mechanical power of the thermodynamic cycle is 3.3mW. Although this power is consumed through viscous energy dissipation of the liquid column at the capillary walls, it gives an order of magnitude of the thermodynamic power that can be delivered by this new cycle. Considering the dimensions of the thermo-fluidic oscillator (length=20cm, section=3.14mm²), the calculated power density is 5mW.cm⁻³.
4.1.2. Second stage of conversion – Mechanical to Electrical. The piezoelectric membrane is attached to the thermo-fluidic oscillator and the temperature is raised to 140°C. The output voltage is measured with respect to time with an oscilloscope having an input impedance of 1MΩ. The corresponding graph is presented in Figure 7.

The calculated power dissipated through the electrical load is 0.69 µW. From this initial demonstration, an overall conversion efficiency from the cycle’s mechanical power to electrical power of less than 0.1% was shown.

5. Conclusion
We report a 3.3mW thermodynamic mechanical power and a converted electrical power generation close to 1µW in a 1MΩ load from a low quality heat source. This figure of power generation can be greatly increased by finding the optimal electrical load for the generator as well as further optimization of the piezoelectric membrane. Nonetheless, compared to Seebeck-effect generators, this innovative approach is not limited by material properties and significant engineering improvements can be achieved such as for controlled phase change and better impedance matching between the two stages of conversion.

References
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