

Hydrodynamic Cavitation-Driven Energy Harvesting in Microfluidic Devices Using Thermoelectric Conversion

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Abstract -This experimental study focuses on harvesting electrical energy from hydrodynamic cavitation (HC) in a microfluidic device with the use of a thermoelectric generator (TEG). In microscale “cavitation-on-a-chip” reactors, the collapse of vapor bubbles produces intense local heat generation and shockwaves that can be converted into electrical power via the Seebeck effect. Three reactor configurations with microchannel widths of 172 μm , 75 μm , and 40 μm were tested under upstream pressures up to ~ 4.1 MPa at room temperature. The best performance was observed in the smallest channels, where open-circuit voltages reached up to ~ 18 mV and short-circuit currents up to ~ 0.61 mA, corresponding to a maximum estimated power output of $\sim 11 \mu\text{W}/\text{cm}^2$, comparable to wearable TEG systems where the temperature difference is low. These results prove the feasibility of converting microscale cavitation-induced thermal energy directly into electrical power.

Keywords: Hydrodynamic cavitation, microfluidic device, thermoelectric generator, cavitation-on-a-chip, Seebeck effect, microscale energy harvesting, power generation.

1. Introduction

Hydrodynamic cavitation occurs when a liquid’s pressure falls below its vapor pressure, creating vapor bubbles that collapse violently upon pressure recovery. These collapses generate heat, pressure shockwaves, and micro-jets [1]. While cavitation has traditionally been considered as detrimental in turbomachinery [1], recent research has explored its potential for use in specific applications such as water treatment [2], chemical synthesis [3], and energy harvesting [4].

Advances in microfluidic device technology have led to the development of “cavitation-on-a-chip” devices, where the controlled formation of hydrodynamic cavitation within microscale channels can generate highly energetic collapses and heat [4], [5]. In this study, we integrated a commercial Bi_2Te_3 -based TEG at the outlet of microfluidic HC reactors to directly convert the heat generated by bubble collapses on the surface of TEGs into electrical energy. Although numerous studies focus on macroscale hydrodynamic cavitation (HC) and its applications, studies specifically addressing direct microscale energy harvesting from microscale cavitation are relatively scarce in the literature. This study examines the effect of microchannel geometry on the electrical power generation of the TEG.

2. Experimental Setup

2.1. Microfluidic Cavitation Reactors

Three reactor designs were fabricated from silicon and glass, each with a channel depth of 60 μm and a downstream extension for the generation of shear cavities:

- Reactor 1: 37 channels, 40 μm wide.
- Reactor 2: 21 channels, 75 μm wide.
- Reactor 3: 9 channels, 172 μm wide.

Trapezoidal roughness elements (4.8–8.9 μm in height) were patterned on the channel inlet walls to promote cavitation inception [6]. A pressurized deionized water supply was provided using a nitrogen tank, and upstream pressures were varied starting the formation of the bubbly flow (approximately 1.0 MPa) to 4.1 MPa (Figure 1).

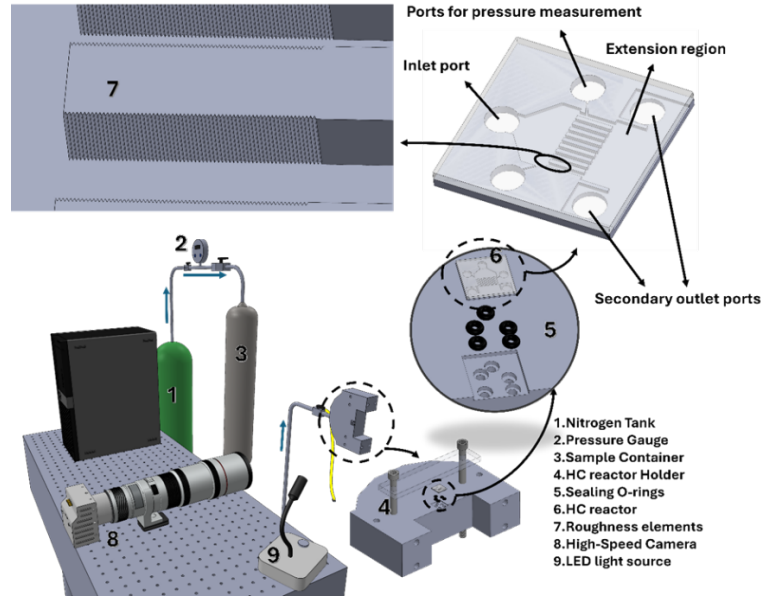


Figure 1: Experimental setup for flow visualization including nitrogen tank, containers, HC reactor, and high-speed camera

2.2. Thermoelectric Generator (TEG) Installation

A commercially available Bi_2Te_3 -based TEG was installed directly at the reactor's outlet extension with a distance of 5 centimeters. The TEG's cold side was exposed to ambient air as natural convection cooling. Electrical parameters measured, namely Open-circuit voltage (V_{oc}) and short-circuit current (I_{sc}), were measured via a high-impedance digital multimeter. Tests were conducted at room temperature ($\sim 23^\circ\text{C}$) to assess the impact of cavitation and device geometry on electrical power output. The maximum harvested power is estimated using the following relationship:

$$P_{max} = V_{oc} \cdot I_{sc} \quad (1)$$

3. Results and Discussion

Key observations from the experiments are summarized in Table 1. A comparison among reactors indicates that reactor 1 has the best performance in power output of $\sim 9.28 \mu\text{W}/\text{cm}^2$, while high-speed camera images (Figure 2) also confirm the generation of more intense cavitation in the same reactor. As the hydraulic diameter (reactor 2) is increased, it can be observed that power output (due to less cavitation intensity) decreases to a maximum level of $\sim 1.35 \mu\text{W}/\text{cm}^2$. A further increase in hydraulic diameter results in an increase in the intensity of cavitation and, consequently, electrical output to a maximum of $\sim 2.5 \mu\text{W}/\text{cm}^2$. These observations highlight the role of scale effects, where viscous and surface tension forces become increasingly dominant at the microscale. As channel size decreases, the surface-to-volume ratio increases, leading to greater viscous energy losses within the flow. These losses reduce the effective flow velocity and pressure gradients, which in turn weakens cavitation. This explains the drop in cavitation intensity observed when the channel size decreases from $172 \mu\text{m}$ to $75 \mu\text{m}$. However, velocity gradients also play a critical role. When the channel size is further reduced to $40 \mu\text{m}$, the resulting higher shear between fluid layers at the channel exit induces fluid rupture, leading to more intense cavity formation despite the stronger viscous damping.

The low conversion efficiency is attributed to thermal coupling and response, where TEG's material slow heat-up limits the capture of rapid microsecond-scale heat pulses. Significant thermal energy is also dissipated into the fluid and reactor structure. Future improvements will include integrating micro-TEGs directly on the cavitation section surface, enhancing thermal insulation, and employing advanced passive cooling strategies. Scaling the system by increasing the number of channels or using multiple TEG modules could also boost the overall power output.

Table 1: Average Short circuit current and Open circuit voltage for Reactors

Pressure (Mpa)	Reactor 1 (Small channel)		Reactor 2 (Middle channel)		Reactor 3 (Big channel)	
	Mean Current(mA)	Mean Voltage (mV)	Mean Current(mA)	Mean Voltage (mV)	Mean Current(mA)	Mean Voltage (mV)
1	0.09	0	0.04	0	0.05	3
1.7	0.17	5	0.1	2	0.1	3.5
2.4	0.41	5	0.22	4.3	0.23	6
3.1	0.5	11	0.25	4.8	0.27	7.6
4.1	0.58	16	0.27	5	0.3	8.3

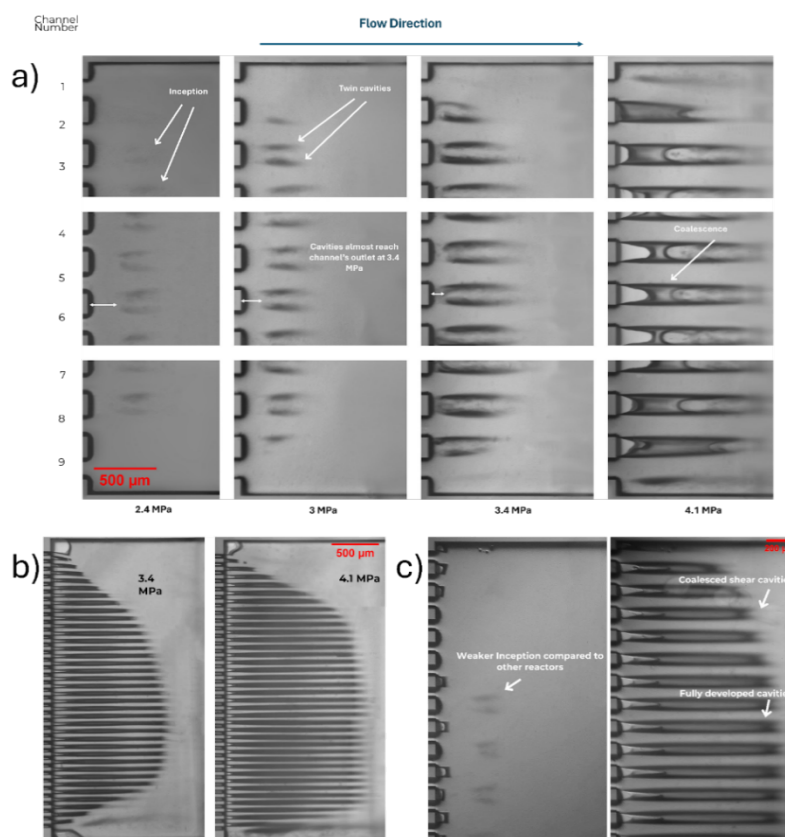


Figure 2: cavitating flow patterns at the outlet of the microchannels for a) reactor 3, b) reactor 1, and c) reactor 2

4. Conclusion

This study focuses on the feasibility of using a thermoelectric generator to harvest electrical energy from microscale hydrodynamic cavitation. The experiments show that smaller channel dimensions and higher upstream pressures yield higher electrical outputs, with Reactor 1 (40 μm channels) achieving up to ~ 13 mV and ~ 0.42 mA at the upstream pressure 4.1 MPa. Although the maximum power density (~ 5.5 $\mu\text{W}/\text{cm}^2$) is at a modest level, it is comparable to simple TEG systems used in wearable applications. Future research directions will involve optimizing thermal coupling, minimizing heat losses, and enhancing cooling to improve conversion efficiency. Future research may explore micro-TEG integration and alternative working fluids to boost the performance, thereby opening avenues for self-powered microsystems in industrial and sensor applications.

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