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Thermoelectric-coupled hydrodynamic cavitation energy harvesting system

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Abstract: The ever growing energy demand has led to the advent of different energy harvesting systems. This study investigates the performance of a thermoelectric coupled hydrodynamic cavitation system as an energy harvesting device. The effect of changing the working fluid from water to Titania-water nanofluid on the heat generation of the cavitation system is discussed in this study and also the coupling of the cavitation system with one of the micro thermoelectric generators in the literature is included. At the end, the device performance is quantified by comparing its power generation with the required power for the daily used miniature electrical devices.

Introduction/Background: As reported in the Annual Energy Outlook 2019 [1], the green resources share in power generation will continue with its increasing trend until 2050 and reach 13% by then. The decreasing share of coal and nuclear resources in this report as well as the increasing number of publications and patents in green energy harvesting systems reveal the growing attraction of researchers in this field.

During the past decade, the energy release from the cavitating flows has opened a new gate to the applications of this phenomenon, namely water treatment [2], surface cleaning [3], biomedical applications like breaking urinary stones [4], and energy harvesting [5]. The local high temperature $5000\ \mathrm{K}$ and high pressure $500\ \mathrm{atm}$ points upon bubble collapse is the main motivation behind these applications.

In this study, a hydrodynamic cavitation system is designed, and microfluidic devices are fabricated. Water and Titania-water nanofluid are introduced to the system as the working fluids to observe the inception, development, supercavitation, and chocked flow in the microfluidic device. The rate of temperature rise on the end wall as a result of the bubble collapse is estimated for both fluids. The energy harvesting system prototype, in which the cavitation system is coupled with a micro thermoelectric generator is presented and the power generation is calculated. At the end, the amount of the power generation is compared with the common daily used miniature systems.

Experimental setup: The microfluidic device in this experiment is a dry etched micro orifice in a double side polished $< 100 >$ silicon wafer bonded to a Borofloat 33 glass. The geometry consists of an inlet with the width and length of $900\mu\text{m}$ and $2000\mu\text{m}$, respectively. The width of the orifice is $152\mu\text{m}$ with wall roughness of height $1.5\mu m$. The length of the orifice is $2000\mu\text{m}$ and the depth of the microfluidic device is $70\mu\text{m}$. Figure 1-a shows the geometry of the microfluidic device. The microfluidic device is sandwiched on an aluminium package with Pyrex caps so that the flow pattern visualization is possible. A high speed camera and a proper light source are used to see the fluid behaviour while doing the experiments. Three pressure gauges are installed at the inlet, micro orifice, and outlet of the microfluidic device to measure the static pressure. A high pressure nitrogen tank is used to push the working fluid to the system. The experimental setup is shown in Figure 1-b.

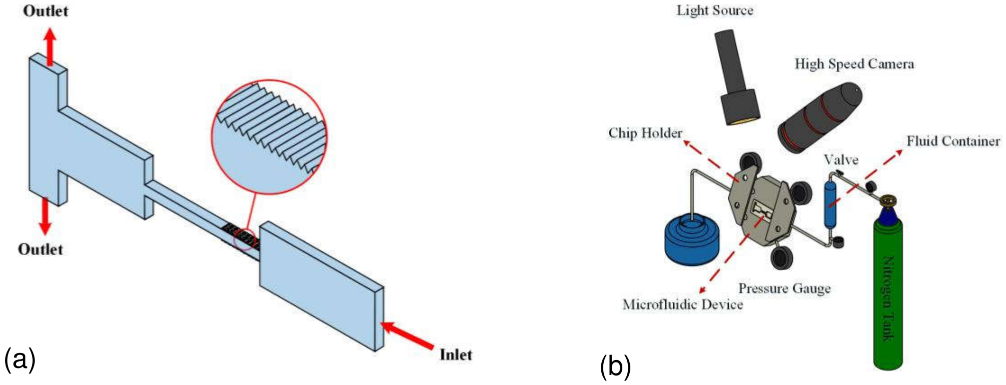

Figure 1 – a) the geometry of the microfluidic device with one inlet and two outlets, b) the experimental setup consisting of the high pressure nitrogen tank, fluid container, microfluidic device, high speed camera and light source

Two different working fluids (water and TiO_2-water nanofluid) are used to investigate the temperature rise on the end wall of the orifice as a result of the cavitating bubble collapse. The temperature rise in this location could be used to generate power using a thermoelectric device.

Nanofluid preparation: Spherical commercial titanium oxide powder rutile (Ionic Liquids Technologies, IoLiTec GmbH, Germany) with particle mean diameter of $10 - 30\text{nm}$ was used to make the suspension with the weight ratio of 0.05% in distilled water as the base fluid. Three sets of DLS measurements were done and in each measurement, the fluid was tested for 17 times. The reported z-average showed the mean diameter of the particles as 304.9 nm.

Device characterization: Increasing the inlet pressure leads to the increase in the flowrate of the working fluid in the microfluidic device. When the cross sectional area of the fluid flow path decreases dramatically in the micro orifice section, the velocity increases and consequently the static pressure decreases. The static pressure drop less than the vapor pressure leads to the cavitating bubble nucleation. The bubbles continue growing in size until they reach a high pressure zone and burst. The collapse of the cavitating bubbles releases a huge amount of energy within a very short time.

In the cavitation device, for water as the working fluid, inception was observed at $21.4\ \mathrm{bar}$, while the inception for the nanofluid occurred at $17.2\ \mathrm{bar}$. The reason for this is the heterogeneous bubble nucleation on the interface of the nanoparticles and the base fluid.

Discussion and Results: The potential energy of the bubbles could be calculated as $\mathrm{E_{pot}} = 4/3\,\pi \mathrm{R}^3(\mathrm{P_{stat}} - \mathrm{P_v})$ where $\mathrm{P_v}$ is the vapor pressure, $\mathrm{P_{stat}}$ is the static pressure, and R is the radius of the bubbles. Half of the potential energy turns to heat upon collapse [6]. On the other hand, the number of bubbles in the micro orifice can be calculated as $\mathrm{n} = \alpha/\frac{4}{3}\pi \mathrm{R}^3 \times \mathrm{V_{occ}}$ where α is the vapor volume fraction which is 1 at supercavitation and $\mathrm{V_{occ}}$ is the occupied volume by the vapor. The image processing of the pictures from the high speed camera shows that the diameter of the bubbles is $3.5\ \mu\mathrm{m}$. From the mentioned equations, the heat energy, which is released from the collapse of the cavitating bubbles occupying the micro orifice in the case working with water, is $1.053\mu\mathrm{J}$. The flowrate at supercavitation for water was measured as $719.49\ \mu\mathrm{L/s}$. As a result, the velocity of the working fluid at the micro orifice could be calculated as $67.57\mathrm{m/s}$. Therefore, the rate of the heat given to the end wall is $44.48\ \mu\mathrm{W}$.

The working fluid velocity in the case working with the nanofluid is $59.86\ \mathrm{m/s}$. With the same calculations, the generated heat on the end wall is $39.4\ \mu\mathrm{W}$. It is suggested that the cavitation system is coupled with a thermoelectric generator to harvest the generated heat energy to electricity. Considering a silicon dioxide wall as the thermoelectric generator, the rate of temperature rise on the bulk of the silicon dioxide could be calculated through $\dot{\mathrm{Q}} = \mathrm{mC}\frac{\mathrm{dT}}{\mathrm{dt}} = \rho.\mathrm{V.C.}\frac{\mathrm{dT}}{\mathrm{dt}}$, where $\mathrm{m}\ [\mathrm{kg}]$ and $\mathrm{C}\ [\mathrm{j/Kg.K}]$ are the mass and specific heat capacity of silicon dioxide, respectively. m could be written as density multiplied by the volume of the silicon dioxide bulk. As a result, the rate of the temperature rise on a silicon dioxide plane with a nominal thickness of $500\ \mu\mathrm{m}$ with the area of $6.5 \times 5\ \mathrm{mm}^2$ would be $1.52 \times 10^{-3}\ \mathrm{K/s}$ and $1.35 \times 10^{-3}\ \mathrm{K/s}$ for water and nanofluid, respectively.

The µ-TEG, which is used in this design, consists of 127 pairs of micro pillars. The Seebeck coefficient of electroplated Bi_2Te_3 as the n-type material and Sb_2Te_3 as the p-type material are reported as $-63\,\mu V/K$ and $116\,\mu V/K$, respectively. The maximum power generation of the thermoelectric generators is calculated as $P_{max} = (S\Delta T)^2/4R$. Where S is the Seebeck coefficient and R is the resistance of the thermoelectric generator which is 13Ω in this study.

Figure 2 shows the power generation of the energy harvesting system working with water and nanofluid under super cavitation flow conditions.

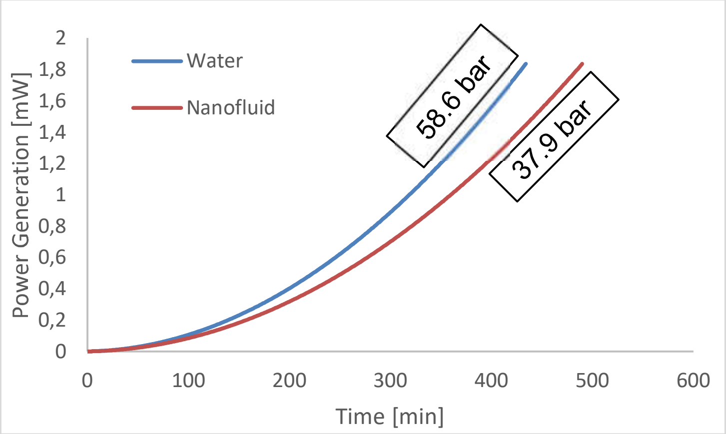

Figure 2 – The device performance working with water and nanofluid at supercavitation

The maximum power generation of the device is $3.96mW$. The power required to run most of the daily used miniature electrical devices are reported in our previous study [5]. The generated power by this system is in the range of the required power to run some electrical devices such as LEDs, antenna GPS, thermometers and other devices.

Summary/Conclusions

This study as the first part of an energy harvesting study shows the performance of a hydrodynamic cavitation system working with water and Titania-water nanofluid. The rate of the temperature rise on a silicon dioxide wall is estimated to show the feasibility of the energy harvesting system. The second part of the present study will show the performance of the thermoelectric coupled energy harvesting system.

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