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A Qualitative Comparison between Three Different Microfluidic Devices with Roughened Surfaces Regarding Cavitation Inception

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Abstract

Small bubbles generated via hydrodynamic cavitation as a result of the decrease in pressure within flow restrictive elements have wide applications. The recent studies have demonstrated their potentials in the biomedical applications, image processing and energy sectors. Therefore, the formation of the cavitation bubbles with the consideration of the surface topology has taken considerable attention particularly in the micro scale. In this study, two different microfluidic devices, which house significantly and slightly roughened microchannels, were fabricated to investigate the inception of the cavitation phenomenon. The roughness elements were created as nano grasses on the surface of the channels with the aid of the techniques adopted from semiconductor based microfabrication. Accordingly, the liquid flow was guided into the devices at different upstream pressures to record the inception of the cavitation and to investigate the size effect of the surface roughness. The results indicate that the significantly roughened (the peak-to-peak roughness is about 5 μm) device has the potential for leading to cavitation inception at lower upstream pressures.

Moreover, the intensity of cavitating flows forming inside this device is high enough to fill the entire microchannel even at lower upstream pressures. On the other hand, cavitating flows do not extend along the microchannel for the device with smaller roughness element (the peak-to-peak roughness is about 1 μm) even at high upstream pressures. The concept of this study could be employed in the design of microfluidic devices, which could use to facilitate intense cavitating flows.

1. Introduction

Cavitation phenomenon has attracted much attention in engineering applications, so the industry has provided considerable funding during recent years. Despite the simplicity and rather low price of small devices generating cavitation bubbles, the physics behind the creation and collapse of these bubbles is still not well understood particularly in micro/nano scale [1]. Generation of the cavitation bubbles or inception in its general name, flow hysteresis, flow patterns, collapse, and the released energy from the collapse of cavitation bubbles are the most important parameters exhibiting different behavior in micro scale. Hydrodynamic cavitation enables new possible technologies in numerous application areas. It could make it possible to achieve new power generation possibilities in order to achieve clean technology and energy savings which can be well generated in micro scale [2, 3].

Various studies in the micro scale hydrodynamic cavitation have shown that the intensity of the bubble generation sharply increased once the size of the channel was reduced [4,5]. Therefore, in-depth studies on fundamentals of micro scale hydrodynamic cavitation are required to reveal new physics of small scale hydrodynamic cavitation. In this regard, Ghorbani et al. [6] studied microfluidic devices with rough surfaces, so that a fundamental study on "Hydrodynamic Cavitation on Chip" was performed. This study emphasized that the geometry and topology of the microfluidic devices could substantially affect the generation of the cavitation and its further development.

In this study, it is aimed to show the effect of the surface roughness elements' height on the generation of cavitation bubbles. For this, three different microfluidic devices with surface roughness height of 1, 2 and 5 μm were fabricated according to the techniques adopted from semiconductor based microfabrication techniques, and the cavitation experiments were performed inside each device at different

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upstream pressures from 2 to 4 MPa. The results show considerable effect of the roughness height on the generation of cavitation bubbles.

2. Methods and Materials

The experimental setup is shown in Figure 1, where the microfluidic device is connected to the appropriate tubes and fittings. A high-pressure pure nitrogen tank (Linde Gas, Gebze, Kocaeli) provides the required upstream pressure for the system. This tank is connected to a 1 Gallon fluid reservoir (Swagelok, Erbusco BS, Italy), which is filled with de-ionized (DI) water and serves as the working fluid. The reservoir is connected to the system with adaptor fittings. Four pressure sensors (Omega, USA) are mounted at the end of the tubing system and on the device package to measure the pressures. Two fine control valves (Swagelok) are integrated to the system to control the flow at the desired locations. A micro T-type filter (Swagelok) with a nominal pore size of 15 µm is used to filter any particles larger than 15 µm. A power LED source serves for illumination to have high quality records.

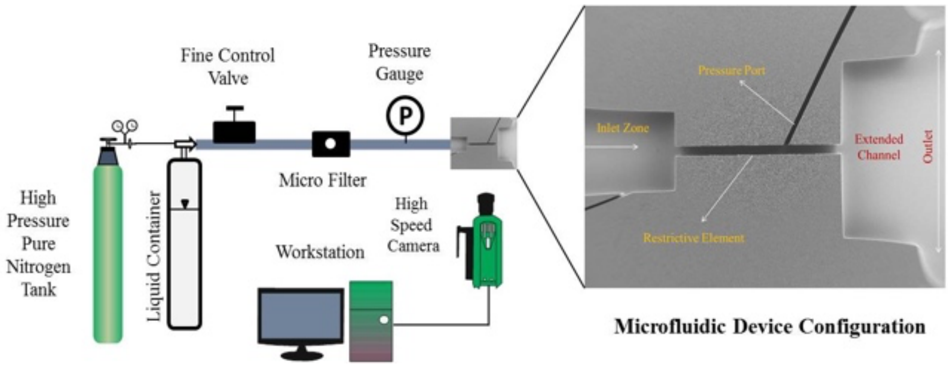

Figure 1: A schematic of the setup for generating cavitation bubbles and micro/mini cavitating jets and a typical microfluidic device.

The inlet pressure varies between 2 to 4 MPa. Although devices have different roughness elements, they all have the same inlet structure, which fits to the same package. The microfluidic devices are sandwiched to the package with proper bolts to allow for withstanding inlet pressures of the liquid up to around 4 MPa. Liquid flow is controlled by valves at different locations. There are three pressure gauges on the setup to check for the pressure values, which are inlet, outlet, and the pressure at the location of the vena contracta. Images are recorded with a high speed camera, which has 1280x800 resolutions with very short time delay. The typical duration of the light pulses was 0.05–0.07 ms, while the time delay between the two successive images was adjusted to the local flow velocity in a range from 1 to 3 ms.

Microfluidic devices were fabricated out of double side polished silicon wafers with a thickness of 380 µm. A schematic of the process flow (Villanueva et al. [7]) is shown in Figure 2.

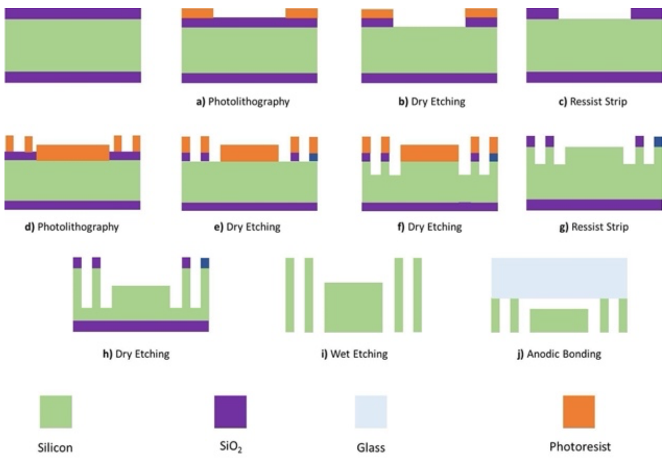

Figure 2: A schematic of the fabrication process of the microchips

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Results

In this study, cavitation is qualitatively investigated inside the microfluidic devices with different roughened surfaces at various upstream pressures. The surfaces of the devices have peak to peak roughnesses of 1, 2 and 5 µm, while the hydraulic diameter of the all devices is 75 µm. The results show that the surface roughness elements have substantial effects on the inception of the cavitation and development of the cavitating flow in micro scale. Recently, it was demonstrated that apart from the working fluid inside microfluidic devices, surface roughness elements have a significant effect on the generation of cavitation bubbles [8]. Therefore, it is of great significance to investigate the surface characteristics by focusing on substrate nanoengineering techniques to achieve intense bubble generation and earlier cavitation inception to be utilized in energy and biomedical applications.

Figure 3 illustrates that for a low height of the surface roughness elements (1 µm), there is almost no cavitation generation inside the microchannel of a microfluidic device. The experiments were performed at various upstream pressures from 2 to 4 MPa, however, in spite of the high upstream pressure, no cavitation inception was recorded for this device. The experiments were carried out for an identical microfluidic device with a surface roughness of 2 µm height to investigate the cavitation bubbles generation. The results of this device were presented in Figure 4, where the cavitation inception was observed at upstream pressure of 2 MPa. Figure 4 shows that despite the pressure increase from 2 to 4 MPa, there is no a considerable change in the flow regime appearance inside the microchannel. The cavitating flow does not develop along the microchannel, and the length of the twin cavities on the wall of the microchannel is almost constant from the inception condition to the high upstream pressure of 4 MPa. These results indicate that although the cavitation bubbles do not reach to the end of the channel and supercavitation flow regime does not form, this device with a 2 µm height roughness elements is capable of generation of cavitation bubbles.

Further studies were performed with a rather high surface roughness microfluidic device under the same conditions as in the previous devices. Figure 5 exhibits various cavitating flow regimes inside the microfluidic devices with 5 µm height surface roughness at upstream pressures between 2 to 4 MPa. Accordingly, the cavitation bubbles extended to the outlet of the microchannel even at the upstream pressure of 3 MPa, while supercavitation flow regime was observed at high upstream pressure of 4 MPa. Figure 5a shows clear separation of the twin cavities from the walls of the channel, while the surface roughness is presented inside the microchannel. Thus, roughness of the surface plays a significant role in nucleation of the cavitation bubbles.

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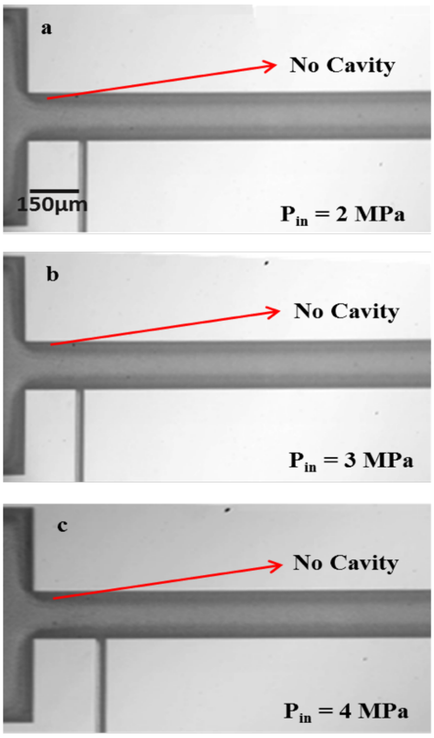

Figure 3: Fluid flow inside the microfluidic device with 1 µm surface roughness at different upstream pressures

Therefore, an increase in the roughness significantly affects the flow patterns, and early inception can be observed with roughened surfaces. The pattern for the surface roughness channel with 5 µm peak to peak roughness corresponds to fully developed super-cavitation at inlet pressure of 4 MPa, which is not seen in the other channels with surface roughness elements of 1 and 2 µm at this pressure. Therefore, it could be concluded that roughness leads to early transitions between flow patterns [9].

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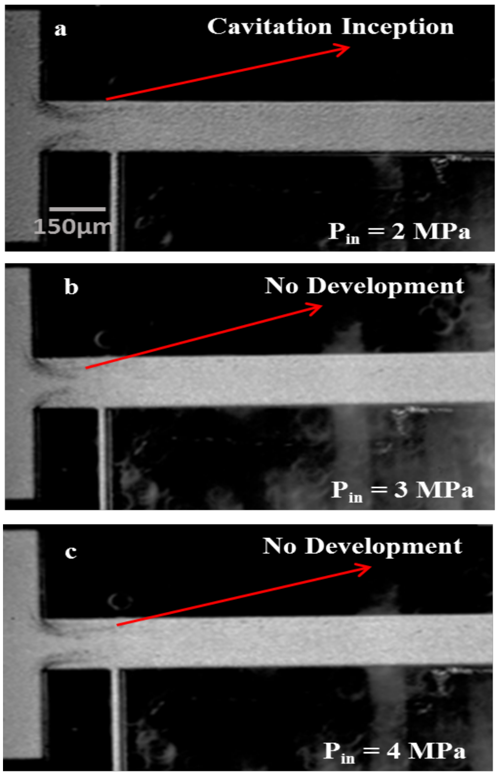

Figure 4: Cavitating flow inside the microfluidic device with 2 µm surface roughness at different up-stream pressures

Conclusion

In this study, the cavitation phenomenon inside microfluidic devices with different surface roughness elements was studied. It is shown that the cavitation bubbles are easily generated inside short micro channels with high surface roughness. The surface roughness has a significant effect on the generation of cavitation bubbles. It is possible to reach developed cavitating flows and supercavitation conditions in a roughened microfluidic device at a significantly lower upstream pressure.

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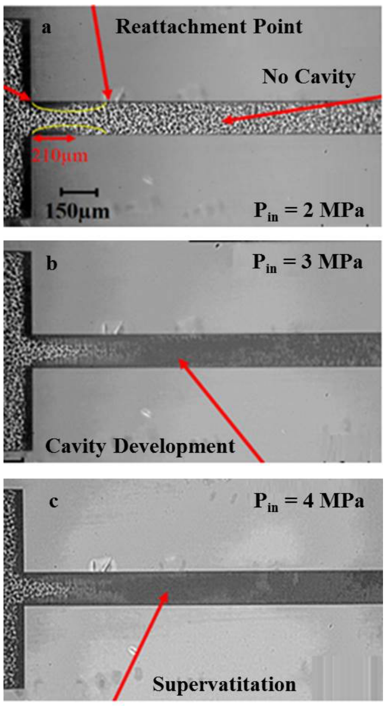

Figure 5: Cavitating flow inside the microfluidic device with 5 µm surface roughness at different upstream pressures

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