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Experimental Study of Foam Generation in a Microfluidic Device

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ABSTRACT: Small scale tests can be conducted using Lab-on-a-chip devices with very tiny amount of fluids. In this paper, bubbles is generated with certain size in a flow focusing microfluidic device. Microfluidic device can be manufactured by SOFT LITHOGRAPHY. When the bubble density is high enough, they come in to contact, and they flow in the form of crystal foam. The flow of the foams in the channel depends on the liquid flow rate and inlet gas pressure. This shall determine dynamic behaviors of the flow such as super-stability. Two types of foam including wet and dry foams are generated in flow focusing device. At certain pressure of 600 to 700 (mbar), the foam behavior is switched to non-linear behavior in which the shape of bubble is changed in period of time. At specific flow rate of 0.1 and 0.2 (ml/hr), it is observed that bubbles are generated in one raw and some others are in two within channel which are called hex-one and hex-two. The effects of increasing the flow rate at constant pressure (which reduces the size of the bubble) and the effects of increasing the pressure in the constant flow rate (which increases the size of the bubble) are investigated

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1. INTRODUCTION

Foam is dispersion of gas in liquid where the gas phase is discontinuous phase and liquid is continuous phase [1]. In the cent-metric bubbling process, buoyancy detaches bubbles that were linked to the inlet tube by capillarity, while at small scales buoyancy forces are inefficient compared to capillary forces. At the micro-scale, fluids in channels are governed by interfacial phenomena. Recently, a remarkable activity focused on the improvement of microfluidic methods to generate bubbles. The bubble detachment can be achieved at small scales with the help of a co-flowing liquid stream [2, 3]. This is the flow-focusing method, where the liquid stream focuses the gas jet through a tiny orifice [4]. In this paper, a microfluidic flow-focusing device was fabricated by using soft lithography. The discontinuous phase (nitrogen gas) and the continuous phase (the surfactant solution) were injected into the inlet channels and these phases are in contact at the orifice region, then pinch off occurs in the orifice and release bubble. In process of foam break up, the flow rate and pressure variation on bubble volume have been investigated. During the experiments, the nonlinear behavior of foam has been reported and visualized. This behavior is referred to as instability in foam generation. The results can be used in medical science and enhanced oil recovery.

2. METHODOLOGY

2-1- Design and fabrication of Microfluidic device

Foams are generated bubble-bubble within microchannels. The quality of micro-channels relies on the quality of the master pattern created *via* lithography. This paper used Polydimethylsiloxane (PDMS) microfluidic devices were prepared via the standard soft-lithography technique. Fig.1 shows SU-8 mold and PDMS micro-model.

2-2- Experiment set-up

Experiment set-up is shown in Fig. 2. The surfactant solution and gas (nitrogen) are injected into inlets of foam

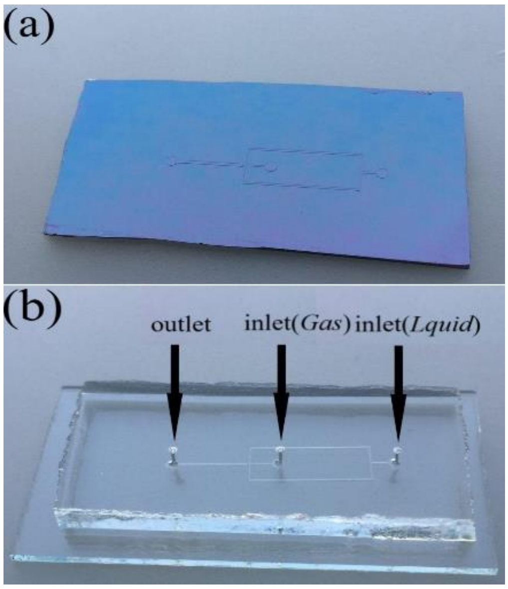

Fig. 1: (a) Photoresist mold (b) PDMS flow-focusing device.

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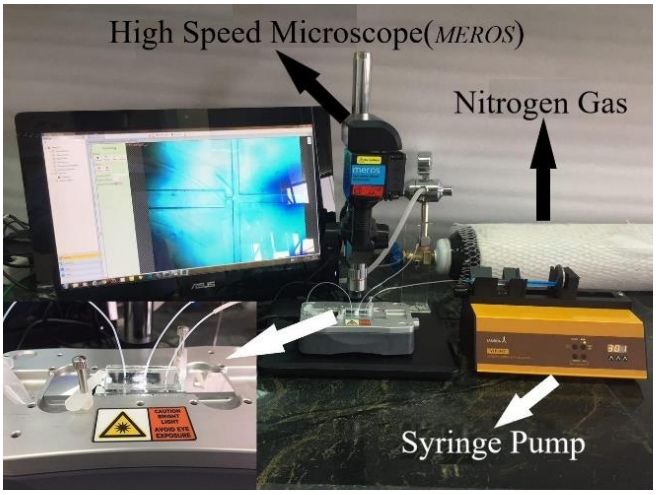

Fig. 2: Experimental set-up

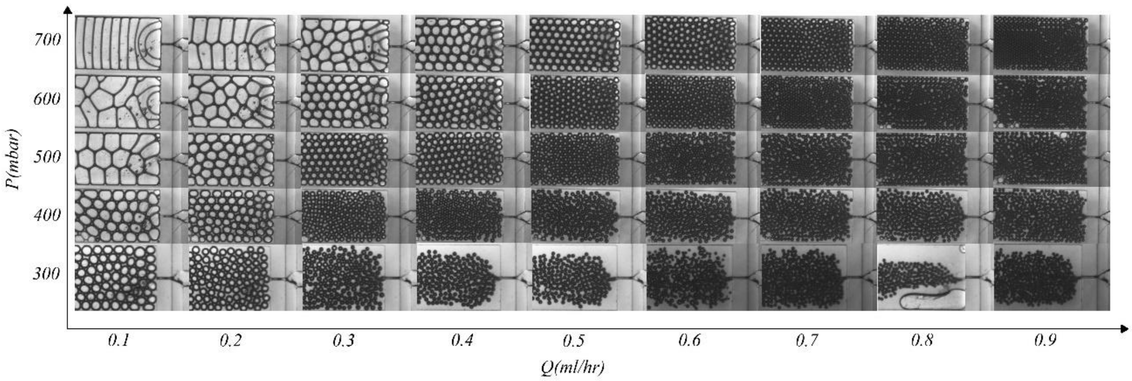

Fig. 3: Experimental results of the foam generation in a wide range of pressure and flow rates.

generator concurrently. Microscope coupled with a high-speed camera records (Dolomite, Meros model) the foam video. The flow rate of the surfactant solution is controlled by a syringe pump (LAMBDA Pump) and its value is $0.1(\frac{ml}{hr})$, and the gas flow rate is controlled by the pressure gauge. Thus, foam quality can be calculated by the flow rate ratio. Microscope (Dolomite) and high-speed camera (MEROS) can provide a high-resolution live view of bubble generation in the microfluidics devices. The properties and type of the surfactant are visible in Table 1.

3- RESULTS AND DISCUSSION

3-1- Self-assembly of the foam in the microchannel

When the density of bubbles is high enough, a foam is formed in the outlet channel. Each bubble is added in a self-repeating way to the foam that acts as a template in the exit

Table 1: properties of the surfactant

Surfactant	TTAB
Type	cationic
Concentration (wt %)	1
Viscosity ($\mathbf{mpas.s}$)	1.002
Interfacial tension ($\mathbf{mN.m^{-1}}$)	37

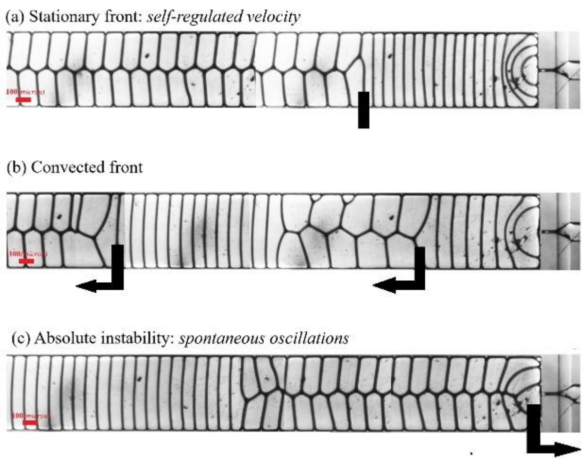

Fig. 4: complex regime: (a) stationary (b) convected (c) absolute non-linear instabilities

channel, with a periodic distribution of bubbles[5, 6]. Ordered hexagonal patterns are named by the number of bubble rows in the channel width: hex-one, hex-

two, hex-three and so on (Fig. 3. P=700 mbar, flow rate 0.1 and 0.2). More complex (non-hexagonal) patterns were also observed in Fig. 3.

3-2- Foam flow

Foam s flow rate is a highly nonlinear function of the applied pressure. Foams are not Newtonian fluids, while liquid and gas are Newtonian fluids. We approximate the foam flow rate using the gas flow rate. The gas flow rate is easily extracted using the recorded velocity of the bubbles, while it is much more difficult to measure the liquid velocity. The salient features of the flow behavior are the following: first, foams flow only above a threshold pressure (P_{cap}). This pressure is interpreted as the pressure necessary to overcome capillarity through the orifice. Second, the flow rate is a power-law in applied pressure. This law is reminiscent of the flow of a single bubble within a capillary tube. The power-law behavior has been rationalized by Isabelle Cantat who enlarged the application of the Bretherton law for single bubbles in a cylindrical tube to foams in a channel.

3-3- Instability in foam generation

In between the regimes with a continuous production of a homogeneous structure, transition regimes produce several structures. These intermediate regimes are associated with the rich dynamical behavior, and result in a structure that varies over space, over time or both. In Fig.4, We distinguish three transition regimes, controlled by the foam velocity V_{foam}: (a) At intermediate foam velocity, the foam continuously rearranges in another structure at a fixed position, see Fig.4. a on which a structure hex-one rearranges to a structure hex-two. The fixed position is a consequence of the presence of a wave of rearrangements (rearrangements are called T_l 's within foams) that travels relative to the foam with a velocity v_{Tl}.This self-regulated flow differs considerably from the behavior of homogeneous structures that have a strong dependence on applied pressure. (b) At higher foam velocity, $v_{foam} > -v_{T_l}$ the transition regime presents rearrangements waves that are not stationary but convected out of the channel. (c) At lower foam velocity, $v_{foam} < -v_{T_l}$ the foam spontaneously oscillates between two structures, with a well-defined time period. These types of transition regimes can be classified using the language of non-linear instabilities. Indeed, each foam structure (hex-one or hex-two) is linearly stable but can be non-linearly unstable when a large amplitude perturbation is applied.

4- CONCLUSION

Bubble generation in microchannel has many applications in medical science and tissue engineering. In this paper, microfluidic flow-focusing device was fabricated by photoresist mold and PDMS in soft lithography method. By tuning two factors such as pressure and flow rate, bubbles can produce at various size in flow-focusing device. Generally, bubbles are produced uniformly in microchannel, while at some pressure and flow rates, this behavior of bubbles is nonlinear. This behavior is counted instability.

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