ABSTRACT
This paper presents the dynamics of microbubbles that are pinched-off and breakup in micro-jetting. A microjet is generated in two bubble interaction when a laser induced bubble is impacting a static gas bubble in a microchannel. Gas layers with a height of hundreds of nanometer are pinched off from the accelerated gas bubble wall during the jetting process. They are further modified by surface tension and break into small bubbles due to the fluidic instability.

KEYWORDS: Microbubble, Jet, Instability

INTRODUCTION
Jetting is widely used in biomedical applications, such as drug delivery, cell lysis and microsurgery [1-3]. Complex behaviours are observed during high speed jetting [4]. For instance, during interpenetration process between two phases, a strong shear will destabilize the liquid jet, which further fragments into droplets. Jets originate from many different sources, such as liquid burst from nozzle, impact of a liquid container, and bubble collapse near a boundary [5-7]. Recently, jet generated by bubble-bubble interaction attracts attention due to its rich phenomena and its similar dynamics as jet close to an biomaterial. The mutual interaction between two laser induced bubbles associated with jetting and fragmentation have been addressed in a 10-µm high liquid gap [8]. Microjets have also been observed from the interaction of tandem microbubbles, which are generated by laser in a 25-µm liquid layer [9]. Cells placed on the axis of the jet are deformed, and highly localized membrane poration is demonstrated.

In this paper, the jet is generated when a static gas bubble is impacted by a laser-induced bubble in a microchannel with height of 4 µm. During the jetting process, a part of the gas bubble is pinched off from the main body, and break into small bubbles. This novel phenomenon is caused by the confined boundary and instability in the microchannel.

WORKING PRINCIPLE
Figure 1 shows the schematic illustration of jets created by focusing a laser pulse inside a liquid filled microchannel. Optical breakdown leads to a bubble formation by absorption of the high laser energy. Bubble expansion is accompanied with the generation of pressure wave, which travels for a distance $D$ and reflects on the surface of a gas bubble. Liquid is focused by the curved surface and forms a jet penetrating towards the centre of gas bubble. The jetting strength is depending on the laser energy ($E$) and the distance from the laser spot to the gas bubble surface ($D$).

The displacement of the gas bubble surface is different in the vertical direction due to the high shear stress near the channel wall. Figure 2 shows the velocity profile of the impulsive flow in the microchannel with the height of 4 µm. Due
to the non-slip boundary condition, the velocity is zero on the channel wall, and increases to 90% of the maximum velocity when the flow is 250 nm away from the wall. When the gas in the center of the channel is moved with a velocity of \( u_{\text{max}} \), the gas closest to the channel wall is almost static. That makes a thin layer of gas with the thickness of hundreds of nanometers being attached to the channel wall. Then, the baroclinic vorticity causes the thin layer to break from the main part of the gas phase. Surface tension will drive the pinched-off gas sheet contract into a thin gas cylinder.

Figure 3 illustrates that a cylindrical column of initial radius \( a \) is comprised of fluid of density \( \rho \) and bound by surface tension \( \sigma \). The liquid column will break into small packets due to Plateau-Rayleigh instability. For a viscous cylinder, the wavelength \( \lambda \) of the most unstable mode can be predicted from \((2\pi/\lambda)a = 0.47\) for the \( \mu_i/\mu_o = 0.02 \), assuming the cylinder is air (\( \mu_i = 1.78 \times 10^{-5} \text{ Pa s} \)) and surrounded by water (\( \mu_o = 1 \times 10^{-3} \text{ Pa s} \)) [10].

**EXPERIMENTAL SETUP**

The microfluidic chip is fabricated in a 25 × 45 × 0.07 mm borosilicate glass (Pyrex 7740) using standard photolithography and wet chemical etching process. The glass channel’s width and height is 140 µm and 4 µm, respectively. The experimental setup consists of a pulsed Nd:YAG laser (Orion, New Wave Research, Fremont, 532-nm, pulse duration approximately 6 ns), a digital delay generator (model 575, BNC, USA), an inverted microscope (IX-71, Olympus, Japan) and a high speed camera (SA-1.1, Photron, USA). The bubble is generated by focusing the laser pulse with the microscope objective (Olympus, water immersion, 20×, NA = 0.5). The energy of the laser pulse is controlled by delaying the interval between the flash lamp and the Q-switch trigger. The micro/nano-structured channel is filled with blue ink (Maxtec Inc., Hong Kong), which strongly absorbs the green light and yields a good contrast for the bright field illumination. High-speed recording is done at 500,000 frame/s with the lowest possible exposure time of 370 ns.

**RESULTS AND DISCUSSION**

Figure 4(a) demonstrates the typical consequence snapshots of the jetting. The strong pressure gradient causes the rightward deformation of the gas bubble. The flow focusing of the curved surface leads to the formation of a rightward axial jet. Consequently, part of the gas bubble \((h \sim 200 \text{ nm})\) is pinched off from the main body, and forms small bubbles in front of the jet. The measured wavelength \( \lambda \) is approximately 11 µm, which agrees with the calculation. It is astonished that the two segments finally developed into four small bubbles (comparing frames in 1.5 and 6.9 µs). A
reasonable explanation is that two layers of remaining gas are attached to the top and bottom channel wall, respectively, as shown in Fig. 4(b). The development of each layer affects the final number of the bubbles. For example, when one layer of gas breaks into two bubbles while another layer turns into one bubble, the final bubble number is three as shown in Fig. 5(b). If the two layers don’t break up, each gas cylinder shrinks into one bubble, the final number of the shattered bubbles should be two as shown in Fig. 5(a).

Statistical results for the fragmentation number of the shattered bubbles are collected with varied laser energy and fixed distance $D = 64$ µm. In most cases, the split part will be shattered into 2 or 3 bubbles. The probability is as high as 91% when the laser energy is between 3 to 7 µJ. However, the appearance of 4 bubbles occurs dominantly ($P = 87\%$) as the laser energy is higher than 7 µJ. It demonstrated that with higher laser energy, the jetting process is longer and the thread is longer when the break-up happens. That causes the thread to break into more bubbles when the laser energy is higher.

CONCLUSION
In conclusion, 200-nm thick gas layer is pinched-off during the jetting in a microchannel. It is further breaks into small bubbles due to Plateau-Payleigh instability. This study gains insights in the instability occurring in the confined systems and offers new opportunities for the microjets in biomedical applications.

ACKNOWLEDGEMENTS
This work is supported by the Environmental and Water Industry Development Council of Singapore (Research project Grant No. 1102-IRIS-05-01).

REFERENCES

CONTACT
*A. Q. Liu, Tel: +65-6790-4336; Email: eaqliu@ntu.edu.sg