ICE DROPLET COLLIDER: ULTIMATE ACCELERATION OF DROPLET USING MICROSCALE PHASE TRANSITION FOR CHEMICAL REACTION BY KINETIC ENERGY

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ABSTRACT

We here report on ice droplet collider which uses kinetic energy of the highly accelerated ice droplet for chemical processes by colliding with the target. The method for controlling the ice droplet in gas phase by using microscale phase transition was created. It was confirmed that work given by air pressure directly converts to kinetic energy of the ice droplet. The ice droplet which was accelerated to velocity of 16 m/s at P = 400 kPa of air pressure can get 100 kJ/mol of kinetic energy by using high-pressure system. Chemical reaction can be realized by using this energy for collision.

KEYWORDS

Phase transition, droplet, chemical reaction, supercooling.

INTRODUCTION

Conventional microfluidic devices use molecular diffusion, viscosity of fluid and interfacial tension for chemical processes [1]. In contrast, micro droplet collider which has been developed in our laboratory uses kinetic energy of an accelerated liquid droplet by colliding with the target [2]. While it achieved enhancement of mixing between two droplets having a large volume ratio by using spatial-temporal localized energy in the collision, it was able to obtain only 1/500 of energy required for chemical reaction because velocity of the liquid droplet was limited to 2 m/s due to its breakup by shear force with a microchannel. To realize chemical reaction, we propose to accelerate an ice droplet which does not break up using solid-liquid phase transition in a microchannel. The collision energy of the highly accelerated ice droplet can be used for chemical reaction or mechanical processing in microchannel. However, there are few reports about the method for controlling ice droplets in the air in the microchannel. In this paper, we report on the method of shooting the ice droplet in the microchannel and discuss about potential to apply kinetic energy of the ice droplet to chemical reaction.

THEORY

The ice droplet is shot by detaching from wall of the narrow channel (Figure 1). We propose the ice acceleration model that the dynamics of the ice droplet obeys the energy conservation law. which means that the work given to the ice droplet before shooting directly converts to kinetic energy of the ice droplet. Velocity of the ice droplet (u) is represented as function of applied pressure (P) calculated by using equation (1).

$$\frac{1}{2}\rho S l u^2 = \frac{1}{2} P S l \qquad (1)$$

where ρ, A and l are density, cross section and length of the ice droplet, respectively. Kinetic energy of the ice droplet after shooting is the left side of the equation (1) and work given to the ice droplet by applied air pressure and shear force from channel wall is the right side. Therefore, the velocity is proportional to square root of applied pressure.

EXPERIMENTAL

Figure 1 shows the experimental setup for the ice droplet collider system. A microchip for the ice droplet collider device is composed of three parts: a droplet launcher, an ice droplet launcher and a collision chamber. The droplet launcher and the collision chamber were reported by our group before [2]. Liquid handling is based on the gas-liquid Laplace pressure in the microchannel whose inner surface is modified hydrophobically with an amorphous fluoropolymer (contact angle: ~117°). To make the ice droplet launcher which needs to detach the ice droplet from the channel wall simultaneously, both the upper and the lower substrate were fabricated by the two step photolithographic wet etching technique. The microchip was partially cooled to make an ice droplet from accelerated liquid droplet by the cooling system using circulating liquefied nitrogen and electrically heating. The area of the cooling part was provided by the size of the copper block. The motion of the ice droplet was captured by the high-speed camera with 50,000 fps sampling rate and 1/155,000 s shutter speed at the ice droplet launcher.

The ice droplet is controlled by applied air pressure and ice adhesion strength on the glass substrate. (1) The droplet accelerated by 50 kPa of air pressure is solidified at –27 °C from the supercooling state and stops in the narrow channel (70 μm wide and 30 μm deep) because ice adhesion strength is much larger than applied air pressure. (2) To transport the ice droplet to the ice droplet launcher, ice adhesion strength is weaken by forming liquid layer with warming the cooling part up to near the melting point (0 °C) and 100 ~ 400 kPa of air pressure was applied. (3) At the ice droplet launcher, the ice droplet is shot to the wide channel (90 μm wide and 50 μm deep) when it is detached from the channel wall simultaneously. (4) At the collision chamber, kinetic energy of the ice droplet converts to collision energy in the collision event.

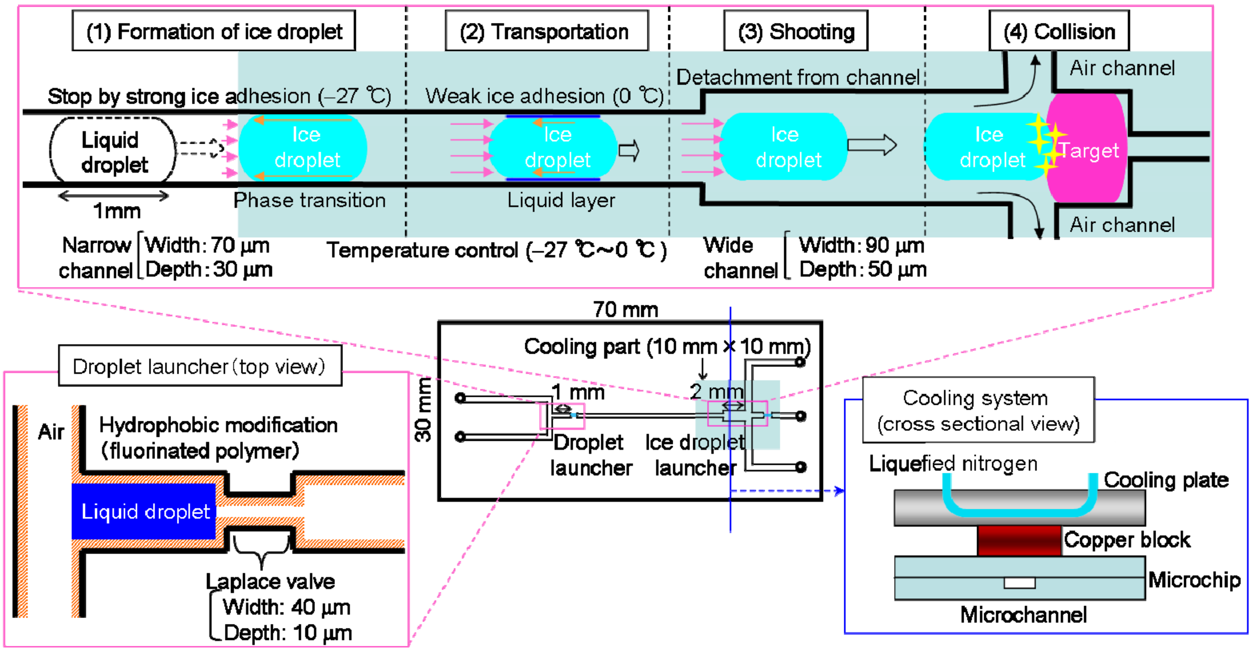

Figure 1. Experimental setup for the ice droplet collider system.

RESULT AND DISCUSSION

Figure 2 shows the time series images of shooting of the ice droplet by applying 400 kPa of air pressure. The rear end of the ice droplet was attached to the narrow channel at $t = t_0$. After detachment of the ice droplet from the narrow channel, the ice droplet was accelerated without friction from the channel wall ($t = t_0 + 0.06$ ms) and reached constant velocity ($t > t_0 + 0.12$ ms). The shooting of the ice droplet was confirmed because the ice droplet did not change its shape at the ice droplet launcher. Head positions of the ice droplet were estimated from the sequences of the captured images and velocity was plotted against the head positions of the ice droplet (Figure 3). The ice droplet was instantaneously accelerated to constant velocity of 16 m/s while velocity of a liquid droplet was constant at the ice droplet launcher. The ice droplet which was 70 times faster than the liquid droplet had 4,900times larger energy at the same condition. These results proved that the ice droplet was accelerated much more efficiently than the liquid droplet.

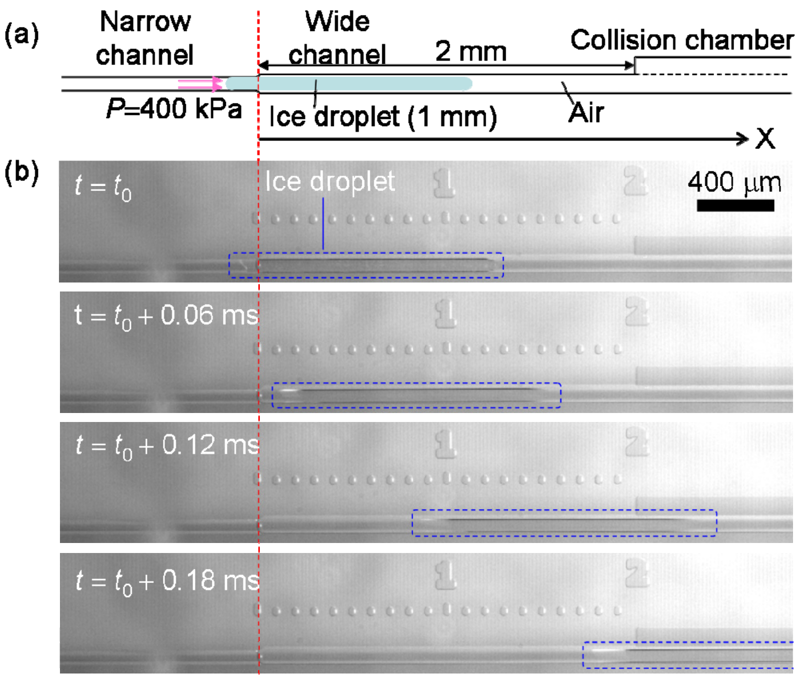

Figure 2. Shooting of an ice droplet at P = 400 kPa.
(a) Schematic illustration of the experiment.
(b) – (e) Time series images of the ice droplet shooting.

Figure 4 shows applied air pressure dependency of velocity of the ice droplet. The experimental data agreed with the theoretical curve which obeyed energy conservation law. From the result, it probed that the ice droplet was efficiently accelerated without energy dispersion with surrounding air. Considering with the model, the ice droplet which was accelerated to velocity of 16 m/s at P = 400 kPa of air pressure can get 100 kJ/mol of kinetic energy by using high-pressure system [3]. Chemical reaction can be realized by using this energy for collision.

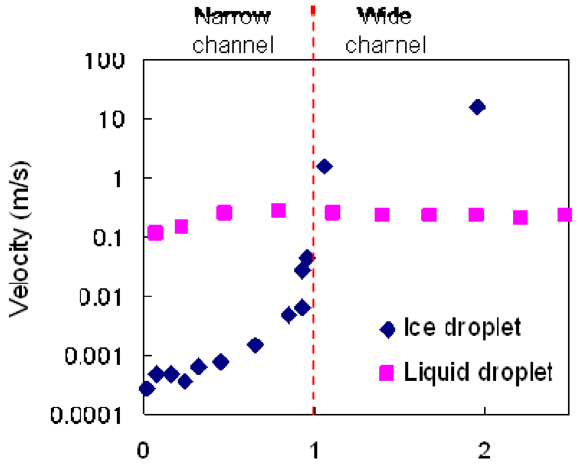

Figure 3. Velocity of the ice droplet or the liquid droplet at the ice droplet launcher at P = 400 kPa.

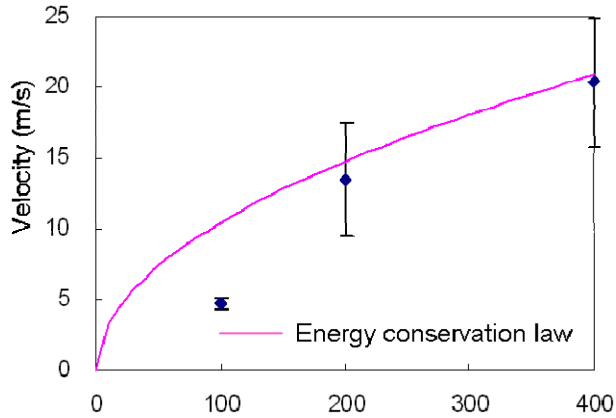

Figure 4. Velocity of the ice droplet as function of applied air pressure compared with theoretical estimation for energy conservation law.

CONCLUSION

In this report, we created the method for controlling the ice droplet in gas phase by using microscale phase transition and confirmed that work given by air pressure directly converts to kinetic energy of the ice droplet. The ice droplet which was accelerated to velocity of 16 m/s at 400 kPa of air pressure can get 100 kJ/mol of kinetic energy by using high-pressure system. Chemical reaction can be realized by using this energy for collision.

ACKNOWLEDGEMENTS

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