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Controllable droplet breakup in microfluidic devices via hydrostatic pressure

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HIGHLIGHTS

- A simple, flexible method for precise control of droplet breakup in microfluidic chip by using hydrostatic pressure.
- The relation between the sizes of daughter droplets and pressures was investigated.
- Unstable breakup due to the existing of chaotic phenomenon was reported.

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ABSTRACT

We developed a simple, flexible method for precise control of droplet breakup in a microfluidic chip is to use hydrostatic pressure. By adjusting the pressures on the continuous phase via liquid columns, water droplets were split into two daughter droplets at a T-junction, and the relation between the sizes of daughter droplets and pressures was investigated experimentally and rationalized theoretically using simple physical arguments. We found that droplet break up was stable only over a certain range of pressure with the size ratio of daughter droplet to mother droplet ranging from 0.3 to 0.7 approximately. In a certain physical system, the behaviour of breakup becomes uncontrollable and uncertain over two ranges of pressures, suggesting a chaotic phenomenon existing. In contrast with other techniques for droplet breakup, the simplicity and flexibility of the pressure-controlled method for droplet breakup and sorting will endow the droplet-based microfluidics for a wide range of applications.

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1. Introduction

Droplet-based microfluidics has become an attractive platform for fundamental or technical research in the fields of chemistry (Dressler et al.), biology (Bai et al., 2017) and physics (Tabeling, 2014). In microfluidic devices, droplets isolate minute quantities of one fluid from a second immiscible fluid (Chiu and Lorenz; Chiu et al.; Thorsen et al.), so that chemical or biological agents can be well-confined and the dispersion from the droplet to the external phase is under control (Link et al.; Salkin et al.; Schiller et al., 2015). To explore the full potential of droplet-based microfluidics, many technologies have been developed to generate, manipulate and functionalize droplets (Garstecki et al.; Tran et al.; Wang et al.). The manipulations performed on droplets in microfluidic devices include droplet breakup, fusion and sorting (Ahmadi et al., 2019; Lan et al.; Simon and Lee, 2012). Among them, droplet breakup allows volume and chemical concentration of each droplet to be further adjusted after their generations (Fukuyama and Hibara; Tan et al.), which will facilitate the applications of droplets as microreactors.

Droplet breakup at a bifurcating junction in microchannels can be achieved either passively or actively (Cong et al., 2014; Ting et al., 2008). The most common passive method uses the geometry of the channels to control droplet breakup (Jullien et al.; Link et al.; Marshall and Walker, 2019). At a T-junction bifurcation, a droplet with a critical size can be split passively into two smaller daughter droplets and the size of the daughter droplets depends on the fluidic resistance of the bifurcation branches (Link et al.). Since droplet breakup is only governed by geometry of microchannels, geometrically mediated breakup lacks of flexibility when implemented. Alternatively, active methods use external fields to control

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droplet breakup, such as electric field, temperature field and pressure field. Link et al. (Link et al., 2010) reported an electric control method to manipulate droplet breakup in microfluidic devices. In the presence of an electric field, the polarized droplets could break into two oppositely charged daughter droplets. Ting et al. (Ting et al.) proposed thermally mediated breakup of droplets, and the process of droplet breakup could be controlled by thermally induced surface tension gradients using a heater. Though electric and thermal control is flexible for droplet breakup, they need relative complicated operation and devices such as microelectrodes and microheaters. Song et al. (SONG, 2003) firstly mentioned that the droplet breakup can be affected by pressure at one outlet of the bifurcations. However, up to now systemic studies on pressure-controlled breakup of droplet in microchannels have not been reported.

In this paper, pressure is considered as a major factor to manipulate the droplet breakup and determine the size of daughter droplets. Here, we established a simple and flexible method for droplets control on microfluidic devices by using hydrostatic pressure which was generated by liquid columns and imposed on continuous phase to control the droplet breakup. A theoretical expression was deduced to predict droplet breakup controlled by hydrostatic pressure, and it agrees well with the experimental results. By using this technique, droplet breakup can be controlled actively and precisely without complicated devices. In addition, this method would avoid the negative effects of electronic or thermal field on the properties of contents encapsulated within microdroplets, especially for charge- or temperature- sensitive molecules and bio-samples.

2. Experimental

The microfluidic devices were fabricated in polydimethylsiloxane (PDMS Sylgard 184) using standard soft lithography technique. In brief, SU-8 negative photoresist (Microchem, Newton, CA) was spin-coated onto silicon wafers and patterned by photolithography. The patterned master was silanized by exposure to tridecafluoro-1,1,2,2-tetrahydrooctyl trichlorosilane vapor (Sigma Chemical), then PDMS (Dow Corning) based and curing agent (10:1 by mass) were poured onto the master, degassing and curing. After peeling off from the SU-8 master, the PDMS device is sealed on a glass slide coated with a thin layer of PDMS such that all walls of the channel are PDMS. As illustrated in Fig. 1(b), each chip has two T-junction configurations, the left one was for the generation of mother droplets and the right one for droplet breakup. The micro-channels have a rectangular cross section of 100 × 33.3 μm, and all distances from T-junctions to adjacent reservoirs are 5 mm, as well as the distance between the two junctions.

A home-made hydrostatic pressure system with three transfusion pipes (3 mm i.d.) along a ruler was set up to manipulate droplets, and the pressure on microchannels was precisely adjusted by the height of liquid column (see Fig. 1(a)). Existing technologies for droplet manipulation using pumps or valves cannot adjust pressure in microchannels precisely. In order to investigate how the pressure affects droplet breakup, we built a hydrostatic pressure control system. As shown in Fig. S1 (see in ESI), the fluids are introduced in to the microfluidic channel through pressurized reservoirs containing water and oil. The reservoirs are connected to the tubing with tens of centimetres of 3 mm i.d. Pressure was applied to the reservoirs with liquid column, and the adjustable precision is 1 mm. In our experiments, hexadecane mixed with 3% Span 80 was used as a continuous oil phase, and purified water as the dispersed phase. The pressure of oil channel (main channel), PM, was adjusted by hexadecane column, and the pressures on water channel (Pwater) and side channel (PD) are by water columns, the pressure on outlet channel (PO) is equal to atmospheric pressure. The size of mother droplet could be tuned precisely by water and oil pressures (see Fig. 1(a)), and the droplet breakup was controlled by pressure on the side channel with the pressures on oil and water channels fixed. The movement of droplets was recorded by a high-resolution CCD camera equipped on a LEICA microscope in a format of 10 fps @ 800 × 600.

3. Results and discussion

3.1. Droplet breakup controlled by hydrostatic pressure

For droplet breakup, capillary number (Ca = μv/γ, where μ, v and γ denote the dynamic viscosity, the flow velocity of the carried fluid and the liquid-liquid interfacial tension, respectively), dynamic viscosity ratio and the flow rate ratio between the dispersed and the continuous phases are considered as the main control parameters (Fu et al.; Leshansky and Pismen; Yamada et al.). While in our experiments, we found that in a fabricated chip with fixable geometrical configuration, droplet breakup can be controlled by hydrostatic pressures on the continuous phase. When mother droplets from main channel reach the T-junction, we observed three types of droplet breakup mediated by hydrostatic pressures, as shown in Fig. 2.

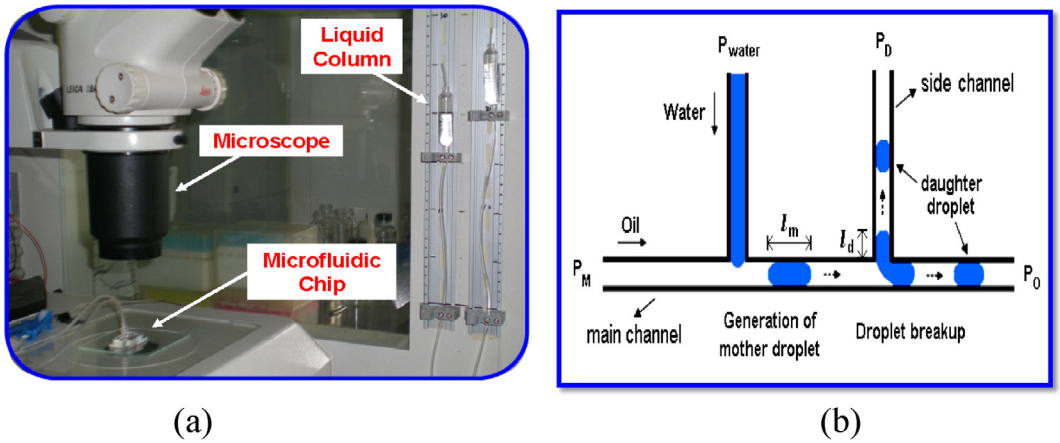

Fig. 1. (a) Experimental setup of the hydrostatic pressure control system for droplet manipulation in microfluidic chip; (b) Schematic illustration of the generation and breakup of droplets controlled by hydrostatic pressure in microchannel.

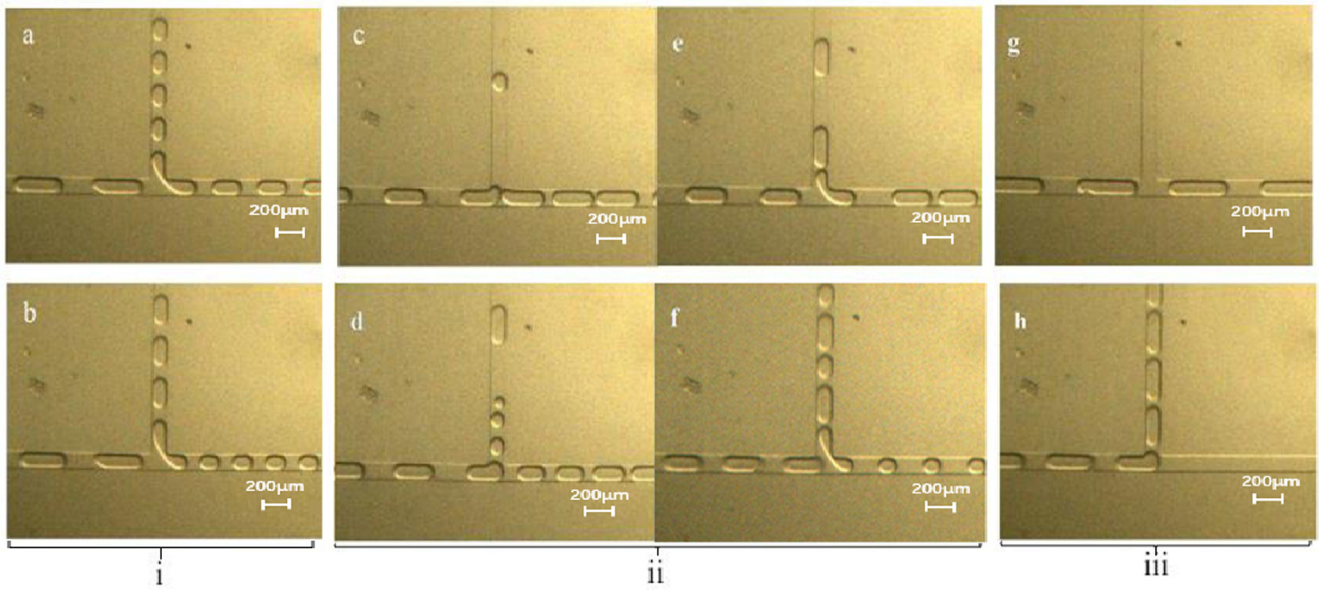

Fig. 2. Three types of droplet breakup at the T-junction controlled by hydrostatic pressure. (a–b) stable breakup: mother droplets break up one by one and sizes of daughter droplets in side channel are identical; (c–f) unstable breakup: mother droplets cannot breakup at T junction one by one or the sizes of daughter droplets in side channel are of different sizes; (g–h) non-breakup: mother droplets would not breakup at T-junction and all mother droplets move on in main channel or turn to the side channel.

(i) The mother droplets breakup into two daughter droplets at T-junction one by one, and sizes of daughter droplets in side channel are identical (Fig. 2a–b). We call this behavior "stable breakup". Generally, in this case, the sizes of daughter droplets in side channel decrease when the pressure on side channel increased.

(ii) The mother droplets do not breakup at T-junction one by one, or the sizes of daughter droplets in side channel are of different sizes (Fig. 2c–f). We call this "unstable breakup". It is the previous research that unstable phenomenon was reported in control of droplet breakup. Noting that unstable breakup doesn't mean there is no regularity in breakup (Schmit et al., 2015). In most situations, droplet breakup takes place occasionally (Fig. 2c) and the sizes of daughter droplets obey a certain random distribution. While in some cases, breakup occurs every two mother droplets and daughter droplets in main channel are of same sizes (Fig. 2e), and sometimes we can observe that mother droplet go through the side channel alternately (Fig. 2f).

(iii) All mother droplets move on in main channel (Fig. 2g) or turn to side channel (Fig. 3h), without breakup at T-junction. We call this "non-breakup". For this situation, the sizes of daughter droplets in side channel always equal to either zero or sizes of mother droplets, indicating that the side channel shows a close or open state, functions as a valve.

In the current work, we used the length ratio of daughter droplet to mother droplet (ld/lm) to evaluate droplets breakup. To investigate the effect of pressure on droplet breakup, the relationship between ld/lm and pressures imposed on droplet were systematically studied. Fig. 3 shows the experimental value of ld/lm versus hydrostatic pressure Pd imposed on the side channel, which equals to the pressure difference between PD and atmospheric pressure, under conditions of different oil inlet pressures. It is obvious that there exist three areas of ld/lm in Fig. 3, which respectively corresponded to the three types of droplets breakup as mentioned above. For the stable breakup, as shown in the middle

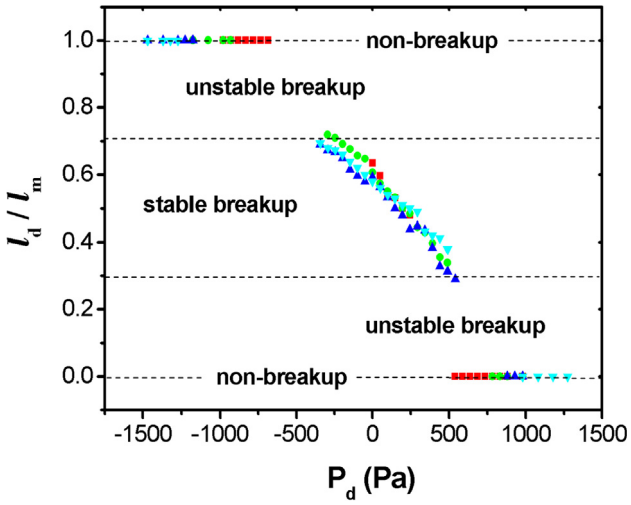

Fig. 3. Demonstration of the length ratio of daughter droplets to mother droplets versus pressure of side channel under conditions of different oil inlet pressures: 1136.8 Pa (■), 1591.5 Pa (●), 1894.6 Pa (▲) and 2273.5 Pa (▼). The two blank zones without experimental data in the figure mean that droplet breakup is unstable and the value of l_d/l_m cannot be calculated.

zone with value of ld/lm ranging approximately from 0.3 to 0.7 in Fig. 3, and the value of ld/lm varied strictly with Pd within a certain pressure range. For the unstable breakup, mother droplets undergo different breakup fates, no uniform value of ld/lm can be defined to describe the droplet breakup, so there exist two blank zones for ld/lm without experimental data. Correspondingly, Pd of the two unstable areas lie in positive-pressure zone and negative-pressures zone respectively. For the non-breakup, when the pressure of side channel exceeds a critical value, the value of ld/lm is always 0 or 1, so this situation can also be considered as an extreme situation of stable breakup. Considering the controllability condition of droplet breakup when implemented, in this paper we will focus on the stable breakup, including the stable breakup and the so-called non-breakup.

3.2. Theoretical estimation

To evaluate how the pressure affects droplet breakup, we built a theoretical description of "breakup degree" by ld/lm ($0 \le$ ld/lm ≤ 1). In this study, we simply assumed that the overall pressure drop is the sum of pressure drops derived from each component, when capillary and Reynolds numbers are small, one has the following relations (Link et al.):

$$P_D + R_d Q_d + \gamma(h^{-1} + w^{-1}) = P_O + R_o Q_o + \gamma(h^{-1} + w^{-1}) = P_M - R_m Q_m + \gamma(h^{-1} + w^{-1})$$

in which Rm, Rd and Ro are the hydrodynamic resistances of the main, side, and outlet channels, respectively. Qm, Qd, Qo, PM, PD, and PO are the corresponding flow rates and pressures, γ the interfacial tension between the two fluids, h and w are the height and width of microchannels respectively. Here we assumed that the volume ratios of the dispersed and continuous phases would be equal before and after breakup. That is, the volume ratio of the two daughter droplets was expected to be equal to the ratio of the volumetric flow rates into the two branch channels (Suryo and Basaran). Additionally, according to mass conservation we have Qm = Qd + Qo, so the volume ratio of daughter to mother droplet should be equal to the ratio of volumetric flow ratio in the daughter channel and main channel. Combined with the above-mentioned relationships among pressure, hydraulic resistance and surface tension, the length ratio of the daughter droplet in side channel to mother droplet in main channel can be estimated as follow:

$$\frac{l_d}{l_m} \approx \frac{A_m Q_d}{A_d Q_m} = \frac{A_m \times R_m \times \left[\frac{\left(\frac{P_M}{R_m} + \frac{P_O}{R_o} + \frac{P_D}{R_d}\right)}{\left(\frac{1}{R_m} + \frac{1}{R_o} + \frac{1}{R_d}\right)} - P_D \right]}{A_d \times R_d \times \left[P_M - \frac{\left(\frac{P_M}{R_m} + \frac{P_O}{R_o} + \frac{P_D}{R_d}\right)}{\left(\frac{1}{R_m} + \frac{1}{R_o} + \frac{1}{R_d}\right)} \right]} \quad (1)$$

In which Am and Ad denote the cross-section area of main channel and side channel respectively. Eq. (1) shows that the length ratio of the daughter droplet to mother droplet is determined by cross-section area of channels, flow resistance of channels and the pressure imposed on channels. For a fabricated microfluidic chip, the width of channels and hydraulic resistances were determined, and then the length ratio of daughter-mother droplet would depend on the pressure imposed on the channels. This is the theoretical basis of the pressure-controlled technique for droplet breakup.

In order to simplify the analysis, the configuration of microchannels was designed to be symmetrical, and then a simple expression for droplet breakup degree in this chip could be obtained:

$$\frac{l_d}{l_m} = \frac{P_M + P_O - 2P_D}{2P_M - P_O - P_D} \quad (2)$$

In which, $P_M = \rho_{oil} g h_m + P_O = P_m + P_O$, $P_D = \rho_{water} g h_d + P_O = P_d + P_O$, where h_m and h_d are the height of liquid columns connected with main channel and side channel respectively, and Pm and Pd are the hydrostatic pressure on the corresponding channels. Then Eq. (2) could be reformulated to a function with only one independent variable,

$$\frac{l_d}{l_m} = \frac{P_m - 2P_d}{2P_m - P_d} \quad \text{or} \quad \frac{l_d}{l_m} = \frac{1 - 2 \times \left(\frac{P_d}{P_m}\right)}{2 - \left(\frac{P_d}{P_m}\right)} \quad (3)$$

Fig. 4 shows the function image derived from Eq. (3), and we can easily predict droplet breakup from this function: (1) when $P_d \geqslant \frac{1}{2} P_m$, ld/lm = 0, meaning that mother droplets would move on in main channel without breakup; (2) when Pd = 0, ld/lm = 1/2, meaning that mother droplets would breakup into two daughter droplets with equal size; (3) when $P_d \leqslant -P_m$, ld/lm = 1, meaning that mother droplets would enter side channel without breakup.

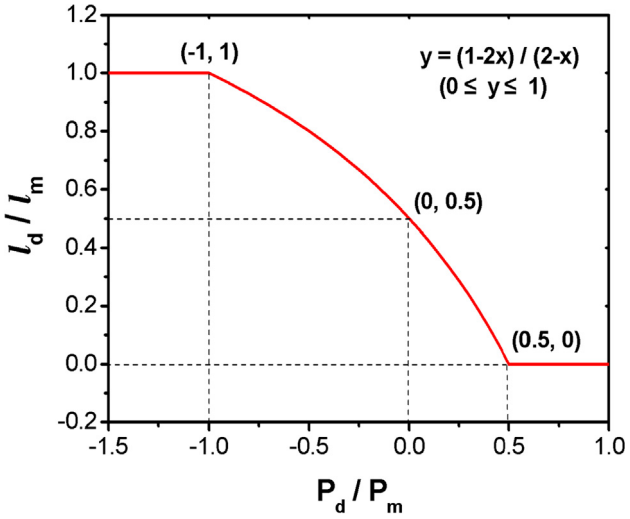

Fig. 4. Relation between the theoretical length ratio of daughter droplet to mother droplet and the pressure ratio of side channel to main channel.

According to this formula, it seems that any value of ld/lm can be precisely obtained by tuning Pd/Pm from −1 to 1/2. However, the validity of prediction doesn't work under some pressure conditions, and unstable droplet breakup was observed in our experiment, which was described in the second type of droplet breakup. It is noteworthy that random phenomena appeared in a system with determinate formula, which indicates chaos-like coming into existence. These unstable events will be studied in details from the angle of chaos-like theory in another paper, and here we will focus on the stable breakup of droplet to guide the application of this pressure-controlled technique.

3.3. Correction of theoretical model

From Eq. (3), we predicted the value of ld/lm should be 1/2 if hydrostatic pressure on side channel (Pd) is equal to zero. However, in the practical test, for different chips with same geometrical design, the value of ld/lm under these pressure conditions deviate from 1/2 was found. The reasons for this deviation were the nonuniformity of surface roughness, channel width and inlet position. We assume that these factors make the hydraulic resistance of channels deviate from calculated value, and the Eq. (3) must be modified according to these effects. Here we used effective length of channels to eliminate the influence of hydraulic resistance errors. To simplify the calculation, the deviation was supposed to origin only from the side channel, and its effective length was set as k, then Eq. (3) would be corrected to be:

$$\frac{l_d}{l_m} = \frac{P_m - 2P_d}{\left(1 + \frac{k}{5}\right) \times P_m - P_d} \quad (4)$$

Table 1
Pressure range of stable droplet breakup.

P_m	P_d	P_d/P_m	l_d/l_m
1136.8 Pa	0–245 Pa	0–0.22	0.48–0.63
1591.5 Pa	−294–490 Pa	−0.18–0.31	0.34–0.72
1894.6 Pa	−343–539 Pa	−0.18–0.28	0.29–0.69
2273.5 Pa	−343–490 Pa	−0.15–0.22	0.38–0.69

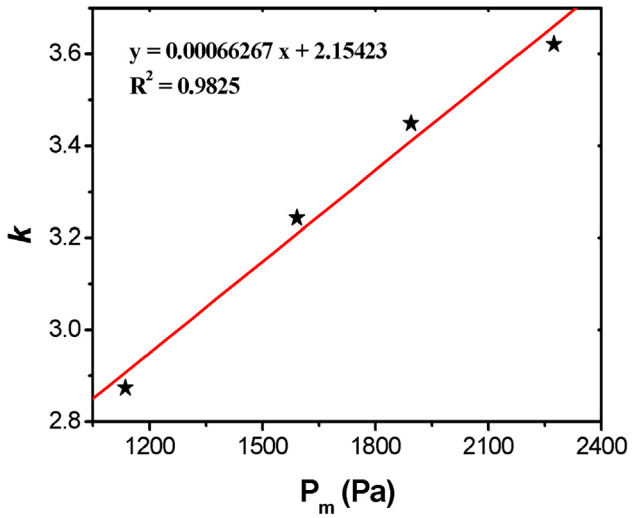

Fig. 5. Relation between the corrected length of side channel and pressure of main channel.

Then k in Eq. (4) was calculated according to experimental value of ld/lm on the condition of Pd = 0, and four corrected formula were obtained with four oil pressure conditions (Table 1).

From these relations shown in Table 1, we can conclude that the deviation cannot be attributed only to fabrication errors but also some factors related to oil pressure conditions. So the theoretical model cannot be corrected only by hydraulic resistance. The effects of oil pressures must be considered to perfect the model, so the relation between k and hydrostatic pressure of oil inlet channel (Pm) was investigated. Then a linear equation, $k = (0.00066 \cdot Pa^{-1}) \times P_m + 2.15423$, was found, as is shown in Fig. 5. In this equation, the slope must be given Pa-1 as unit to keep dimension uniform. Using this function, k can be substituted by Pm, and a final theoretical formula governing the length ratio of daughter to mother droplet was obtained (Eq. (5)).

$$\frac{l_d}{l_m} = \frac{5P_m - 10P_d}{(0.00066 \cdot Pa^{-1}) \times (P_m)^2 + 7.154P_m - 5P_d} \tag{5}$$

Eq. (5) establishes a relation that only pressures affect breakup degree of droplet, for a given microfluidic chip.

3.4. Comparison between the theoretical expression and the experimental results

To test the validity of the corrected theoretical expression (Eq. (5)), we compared experimental values of ld/lm to theoretical values (Fig. 6). For the stable breakup, the trends of ld/lm changing with Pd were in accordance with both the original theoretical

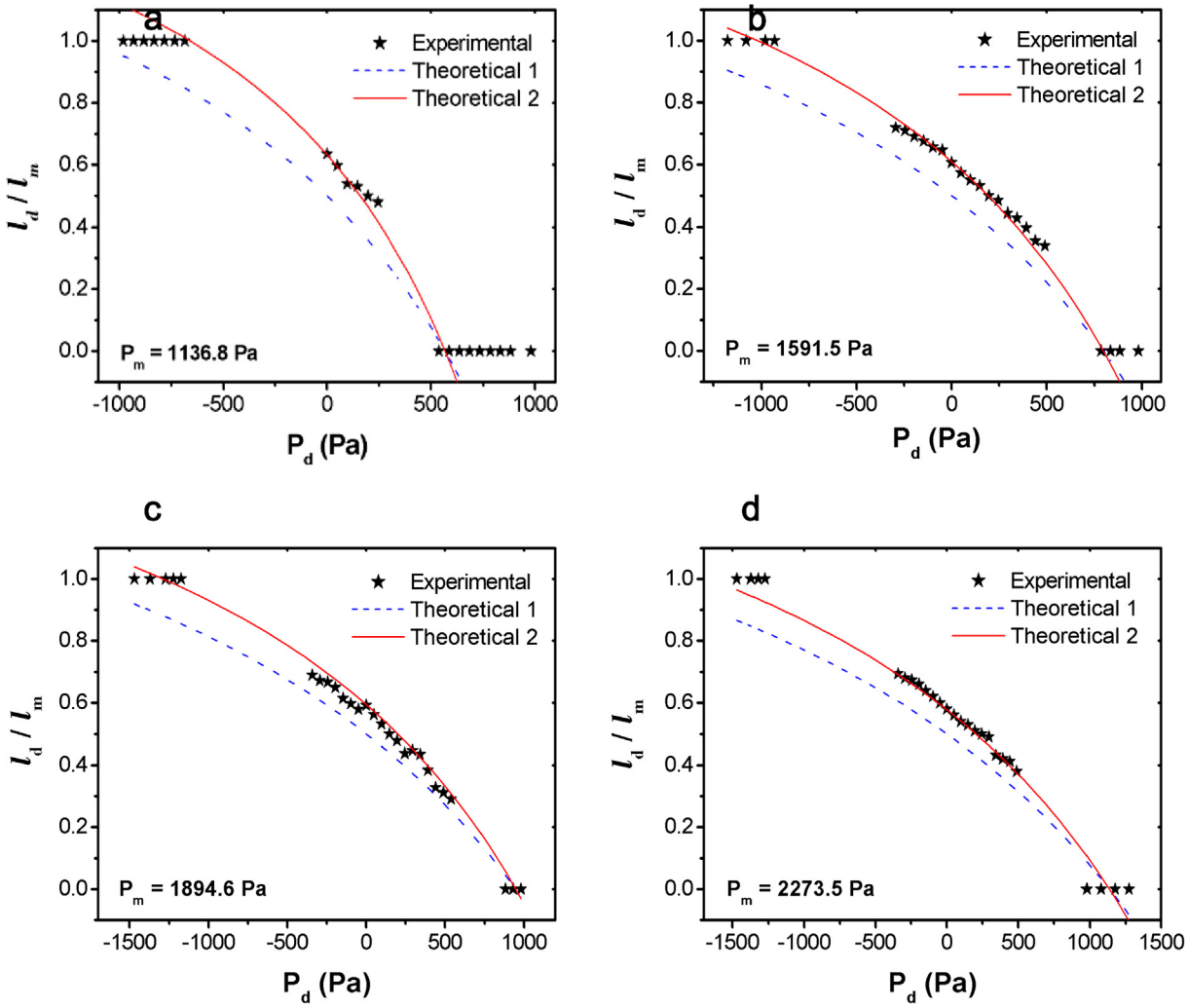

Fig. 6. Comparison between the theoretical expression and the experimental data under conditions of different oil inlet pressures: (a) P_m = 1136.8 Pa, (b) P_m = 1591.5 Pa, (c) P_m = 1894.6 Pa and (d) P_m = 2273.5 Pa. The dashed lines are given by the Eq. (3) and the solid lines come from Eq. (5).

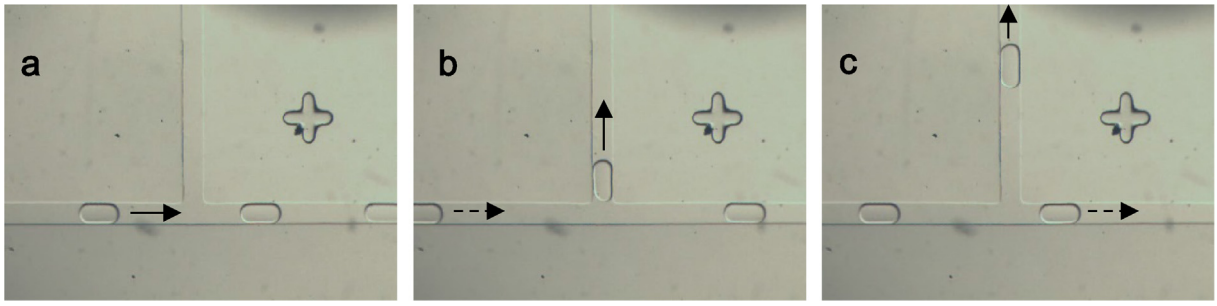

Fig. 7. Process of single-droplet sorting controlled by hydrostatic pressure: (a) a targeted droplet moves to the T-junction, (b) the targeted droplet reached at the T-junction and turns to the side channel, (c) the targeted droplet moves along the side channel and the other droplets move along the main channel.

model and the corrected model. Moreover, the experimental results agree with the theoretical values derived from the corrected formula (Eq. (5)) quite well, indicating that the size of daughter droplets can be predicted precisely by the theoretical expression, so we can use this theoretical model to control droplet breakup by adjusting the hydrostatic pressure of oil inlet and side channel. For the unstable breakup, the model cannot predict the experimental results. In addition, we also compare the experimental data with theoretical values calculated from Eq. (3), the theoretical expression without correction, and almost all data points lie outside the model curve, especially in the stable breakup area. It suggests that the correction expression is valid for precise prediction of droplet breakup. We believe that many factors in the fabrication of microfluidic devices and the disturbance from operation system would influence droplet breakup, so it is important to obtain a corrected expression according to the concrete conditions before the use of this pressure-controlled technique.

3.5. On-demand droplet sorting controlled by hydrostatic pressure

As described above, in the case of non-breakup, the moving direction of droplets or single droplet could be controlled by hydrostatic pressure on side channel. Based on this characterization, we proposed a method for on-demand droplet sorting. Fig. 7a–c shows the process of sorting a single droplet from mother droplets at the T-junction (see Movie S1, ESI). Theoretically, if a positive hydrostatic pressure, equals to Pm/2, is imposed on the side channel, each mother droplet moves along the main channel without breakup and turning (Fig. 7a). When the target droplet is arriving at the bifurcation, the corresponding pressure was changed to –Pm, then the target droplet will turn into the side channel (Fig. 7b). The implemental time of negative pressure depends on the moving rate of droplet, number of droplets wanted and the spacing between droplets. Once the turning process completed, the pressure should be tuned back to Pm/2, in order to assure that mother droplets unwanted would not be sorted out (Fig. 7c).

Droplet sorting systems provides an efficient way for on-demand droplet to be processed in the microchannel. Several approaches have already been demonstrated, including devices that sort droplets by dielectrophoretic actuation, electro kinetic actuation and so on (Ahn et al.; Tan et al.; Zheng et al.). Comparatively, pressure-control method for droplet sorting needs not complicated or expensive equipment, and the operation is obviously facile and flexible.

4. Conclusions

We have presented a simple microfluidic-developed technology for controlling droplet breakup by using a hydrostatic pressure system. To predict droplet breakup controlled by pressure, a theoretical model for droplet breakup, which is described by a mathematical expression, was deduced and corrected. On one hand, this technology offers capabilities for the active and precise control of the size of daughter droplets during droplet breakup, and it allows for single-droplet sorting. On the other hand, the gentle operation conditions for pressure-controlled droplet breakup and sorting will avoid the violent stimulation acted on content of droplets, such as high voltage or high temperature. We believe that this pressure-controlled method has a great promise in droplet-based microfluidic systems, especially in biological research because of their simplicity and flexibility.

Author contributions

The manuscript is written with contributions of all authors who have given their approval to its final version.

CRedit author statement

Pei Liang: Conceptualization, Data curation, Formal analysis, Funding acquisition, Resources and Software, Writing original draft and Writing - review & editing. **Jiaming Ye:** Conceptualization, Data curation, Project administration, Writing original draft and Writing - review & editing. **De Zhang:** Formal analysis, Investigation, Methodology, Supervision, Validation, Visualization, Writing original draft and Writing - review & editing. **Xiubing Zhang:** Data curation, Investigation and Methodology, Writing original draft and Writing - review & editing. **Zhi Yu:** Formal analysis , Writing original draft and Writing - review & editing. **Bingcheng Lin:** Conceptualization, Writing original draft and Writing - review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary material

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ces.2020.115856.

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