Experimental Study on the Effect of Locally Convergent Configurations on the Flow Pattern in PMMA Microchips

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Abstract: The geometries of micro-channel play a key role in forming of digital droplets, and can be real-time or effective controlling methodologies. Local convergence regions are designed in the rectangular cross-section channels on PMMA microchips, in which two-phase coaxial jets are introduced by inserting a syringe needle. The two-phase flow (lubricating oil (continuous phase, flow rate $Q_c$) / deionized water (dispersed phase, flow rate $Q_d$)) is considered. Two geometric control variables, the relative position (needle displacement $x$) and tapering characteristics (convergence angle $\alpha$), are naturally adopted to describe such geometry configurations. The micro-flow under the change of these two parameters is mainly studied in this paper. Four kinds of characteristic flow patterns, namely, sausages, slug, dripping and jetting, are found in the experiment, and their occurring parameters and developing dynamic characteristics are discussed. The experiment shows that the increase of inner needle displacement $x$ can produce higher frequency and finer droplets, which is consistent with our previous results obtained in round tube experiments and simulations. While increasing the convergence angle $\alpha$, contrarily, takes opposite effects.

Keywords. Two-phase flow, Convergent coaxial flow, Flow pattern.

1. Introduction
Microfluidic equipment can produce monodisperse sub-micron droplets, bubbles, emulsions and capsules in a continuous way by deforming, stretching and splitting certain substances in the fluids, which can be precipitated and solidified if necessary.

Microfluidic technology prepares droplets with controllable volume, controllable frequency, controllable composition or controllable movement, and large specific surface area with high consistency, and also realizes large-scale droplet productions. Moreover, it can contribute to wide areas such as rapid chemical reaction [1], drug delivery [2], cell capsule, digital PCR (polymerase chain reaction) system [3], protein crystallization [4], polymer microcapsule [5], or microreactor [6], and so on.

Geometrically, there are three main types of micro-channels: cross flow (T-shaped and Y-shaped) [7–10], flow focusing [11–13], and coaxial type [14–16]. The two-phase flow patterns of laminar, slug/plug, drilling, jetting, and annular have been observed in these channels. Moreover, when the viscosity ratio and interfacial tension of the dispersed phase fluid and the continuous phase fluid are small, the sausage flow pattern will appear [17].
2. Experimental Set-ups and Materials

The co-flowing configuration used and experimental apparatus in this research are shown in figure 1. The materials used are 5W-20 lubricating oil (continuous phase, density $\rho_c = 826 \text{ kg/m}^3$, viscosity $\mu_c = 40.96 \text{ mPa-s}$, interfacial tension $\sigma = 20.08 \text{ mN/m}$) and deionized water (dispersed phase, density $\rho_d = 986.2 \text{ kg/m}^3$, viscosity $\mu_d = 1.23 \text{ mPa-s}$, interfacial tension $\sigma = 20.08 \text{ mN/m}$) separately. The devices include microchip, micro-injection-pump (LSP02-2A, Lange), highspeed camera (Phantom V611-16G-M, AMETEK), microlens (AT-X M100 PRO-D, Tokina), light source and computer, as shown in figure 1(a). The material of microfluidic chip is polymethylmethacrylate (PMMA), and its total dimensions are $30 \text{ mm} \times 30 \text{ mm} \times 4 \text{ mm}$.

Figure 1. Schematic diagram of experiments. (a) The apparatus set-ups, (b) the co-flowing in the tapering micro-channel geometry.

Figure 1(b) shows the coaxial flow configuration and geometric parameters of convergent microchannel on a PMMA microchip. The dispersed phase and continuous phase flow in from the left side, and flow out toward the right side. Both phases mix at the convergence area, whose length is $X_L = 2680 \mu m$ and convergence angle $\alpha$. The syringe needle, whose inner diameter is $d = 200 \mu m$ and outer diameter $D = 400 \mu m$, of dispersed phase is inserted into this tapering area to form two-phase flow (region 1). The downstream micro-channel is a straight tunnel (region 2), with rectangular cross-section of width $W_{out} = 400 \mu m$ and height $h = 600 \mu m$. $L_d$ is the axial size (length) of the droplet generated.

The two immiscible liquids, driven by a high-precision two-channel injection pump97 (LSP02-2A, Lange), are injected into a nested coaxial outer-inner annular micro-channel. The dispersed phase
(deionized water) flow rate \( Q_d \) ranges from 8 to 152 \( mL/h \), whereas the continuous phase (5W-20 lubricating oil) flow rate \( Q_c \) varies from 8 to 152\( mL/h \), too.

Many samples of PMMA microchips are prepared. The combinations of the two geometrical parameters, convergence angle \( \alpha \) and needle displacement \( x \), are shown in table 1, labeled as sample A3, B3, C3, D3, C1, C2, C4, C5 and E. The microchips of certain convergence angle \( \alpha \) (\( 0^\circ \), \( 5^\circ \), \( 11^\circ \), \( 17^\circ \) and \( 29^\circ \)) and needle displacement \( x \) (0, 620, 1170, 1620 and \( 2160 \mu m \)) are designed to avoid redundant experimental work. Note ‘A, B, C, and D’ are symbols for convergence angle \( \alpha \) at values of \( 5^\circ \), \( 11^\circ \), \( 17^\circ \), and \( 29^\circ \) respectively. The numbers ‘1, 2, 3, 4 and 5’ represent the needle displacement \( x \) at relative locations 0, 620, 1170, 1620, and \( 2160\mu m \). The sample E, which is used to check the consistency and effectiveness of our experiments with the work of others, is a straight micro-channel without tapering configuration, which is a commonly used and well studied microchip structure.

| Samples | Convergence Angle \( \alpha \) (\( ^\circ \)) | Nozzle Stretch \( x \) (\( \mu m \)) |
|---------|-----------------|-----------------|
| A3      | 5               | 1170            |
| B3      | 11              | 1170            |
| C3      | 17              | 1170            |
| D3      | 29              | 1170            |
| C1      | 17              | 0               |
| C2      | 17              | 620             |
| C4      | 17              | 1620            |
| C5      | 17              | 2160            |
| E       | 0               | -               |

3. Result and Discussion

3.1. Flow Patterns

Many flow patterns can be obtained. Their descriptions are often based on qualitative and sometimes subjective visual discriminations. For instance, in the sample C4 (\( \alpha = 17^\circ \), and \( x = 1620 \mu m \)), four main flow patterns are observed: slug, dripping, jetting and sausages, seen in figure 2. The slug pinches off at the tip of the inner needle tip, and produces a large droplet whose length \( L_d \) far exceeds the size of the channel width. The dripping droplets are gained the similar size to the channel width. These two flow patterns are periodic for generating monodisperse droplet. For the type of sausages, it seems a widening jet with bamboo waves at the interface, which never breaks up and brings any droplets. While the jetting droplets form faraway from the inner needle tip and at the downward inner jet end. The jetting mode may cause very tiny satellite droplets.

In such small scales of micro-channels, the gravity force is usually ignored. The countable transition of two-phase flow pattern is mainly determined by the competitions among three forces, namely, the viscous force of continuous phase, the interfacial tension of two phases and the inertial force of dispersed phase, and we define two non-dimensional parameters to depict their competitions. Those are the capillary number of the continuous phase, \( Ca_c = u_c \mu_c/\sigma \), representing the ratio of the viscous force of the continuous phase to the interfacial tension force; and the Weber number of the dispersed phase, \( We_d = \rho_d u_d^2 d_f/\sigma \), representing the ratio of the inertial force of the dispersed phase to the interfacial tension force. Here, the superficial velocities \( u_c = Q_c/(W_{out} h) \) and \( u_d = Q_d/(W_{out} h) \) are defined on the downward area of rectangular cross-section, and \( d_f = 2W_{out} h(W_{out} + h) \). Note that the subscript 'c' represents the continuous phase and 'd' represents the dispersed phase on no special
cases. We draw a typical flow chart to explain the occurrence of flow patterns in $Ca_c \sim We_d$ space, as shown in figure 3 for sample C4.

![Figure 2. Four typical flow patterns vary with flow rates for sample C4: (a) Slug, (b) dripping, (c) jetting and (d) sausages.](image)

![Figure 3. Flow pattern map in $Ca_c$-$We_d$ space for sample C4 ($\alpha = 17^{\circ}$, and $x = 1620\mu m$).](image)

The four flow regimes, namely, slug, dripping, jetting and sausage as pictures represented in figure 2, are identified in figure 3. Dashed lines for pattern transition separation are used to divide these flow regimes. As a general, the slug regime occurs at low $Ca_c$ with low $We_d$ region, the dripping regime occurs at higher $Ca_c$ with low $We_d$ region, the jetting regime occurs at highest $Ca_c$ with low $We_d$ region, and the sausages regime occurs at high $We_d$ region. The transitions among these regimes are highly correlated with the relative power superiority of interfacial tension force, inertial force and shear stress force. Apparently, the interfacial tension dominates the proceeding of slug forming, the inner inertial force maintains the wavy interface of sausages, the moderate outer shear force and low inner inertial force produce dripping process, and the high outer shear force causes thin jetting.

### 3.2. The Variations of Convergence Angle $\alpha$ and Needle Displacement $x$ on Flow Charts

When the needle displacement $x$ increases, the flow pattern map varies correspondingly. We draw collectively the flow pattern maps for samples C1, C2, C3, C4 and C5 in figure 4. Apparently the convergence angle $\alpha$ is a constant of $17^{\circ}$, and the needle displacement $x$ increases from 0, 620, 1170, 1620 to 2160 $\mu m$.

As can be seen from figure 4, with the increase of $x$, the flow pattern transition boundaries between sausages and slug move downwards, and the area of slug shrinks. The flow pattern transition boundary between slug and dripping moves left-upwards and also suppresses the slug region, and the area of dripping increases. Jetting begins to appear into the scope of our experimental setting parameters from the right side only for samples C4 and C5.

The influence of the convergence angle $\alpha$ on flow patterns is also investigated for samples A3, B3, C3 and D3, as shown in figure 5 for the fixed needle displacement $x = 1170$ $\mu m$. The corresponding convergence angle $\alpha$ of each sample increases from 5$^{\circ}$, 11$^{\circ}$, 17$^{\circ}$ to 29$^{\circ}$ respectively.
Figure 4. Four typical flow patterns vary with flow rates for sample C4. (a) Slug, (b) dripping, (c) jetting and (d) sausages.

Figure 5. Flow pattern transitions in $Ca_c$–$W_e_d$ space for samples A3, B3, C3 and D3 as the convergence angle $\alpha$ increases from 5°, 11°, 17° and 29°.

It can be seen from figure 5 that with the decrease of convergence angle $\alpha$, the flow pattern transition lines between slug and sausages move downwards and compress the area of slug regime. The slug-dripping transition lines move left-upwards and also suppress the slug regime, and the regime of dripping increases with $\alpha$ getting smaller. Jetting begins to appear from the right side only for sample A3 for the smallest $\alpha$ in the present parameter scope.

By comparing figure 5 with figure 4, it is intuitive to see a correlation between the effects of $x$ and $\alpha$ on the occurrence of flow patterns. The increase of the needle displacement $x$ and decrease of the convergence angle $\alpha$ almost have the same influence on flow pattern transitions.

3.3. Scaling up Droplet Formation in Slug and Dripping Regimes

Slug and dripping are idealized flow patterns in heat and mass transfer processes or bio-testing. The droplets formed have high consistency in size and specific surface area, and monodisperse droplets can be obtained efficiently. The size of droplet and the frequency generated are the focus for applications.

The droplet formation at the inner needle tip can be divided into two processes: growth and necking off. Figure 6 shows photographs of droplet growth stages (a)-(c) and necking-shedding stages (d)-(f) in the slug flow pattern, and photographs of droplet growth stages (g)-(i) and necking-shedding stages (j)-(l) in the dripping flow pattern.
Figure 6. Optical micrographs of the evolution of the periodic droplet formation sequences for sample A3. Slug ((a)–(c) for growing and (d)–(f) for necking-pinchoff), and Dripping pattern((g)–(i) for growing and (j)–(l) for necking-pinchoff).

4. Conclusion
The PMMA microchips are designed to take into account the convergence configurations on behaviors of oil/water two-phase coaxial flows in rectangular cross-section micro-channels. The influence of two geometric parameters, needle displacement $x$ and convergence angle $\alpha$ on droplet forming characters is mainly investigated.

Slug, dripping, jetting and sausage modes occur in the present experimental observations. Although all the modes are periodical, the sausage waves never pinch off, and the jetting mode has very tiny satellite droplets evolved, only slug and dripping modes can produce perfect uniform droplets. The decrease of needle displacement $x$ and increase of convergence angle $\alpha$ can both expand the slug and dripping regimes. It is proved that the needle displacement $x$ and convergence angle $\alpha$ are essentially correlated variables, and can be degenerated into a single geometrical variable, which means the great improvement on controlling costs.

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