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# Speed up bubbling in a tapered co-flow geometry

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## HIGHLIGHTS

- A tapered co-flow microchannel is proposed to generate monodisperse bubbles/droplets.
- The wetting mode and the shearing mode are distinguished to form Taylor bubble train.
- The bubble/droplet sizes and the bubbling frequency are found in perfect exponential proportion to the penetration length of central needle.
- The flow patterns are decided by the gas/liquid flow rates, the bubble length is piecewise linear function of the gas/liquid flow rate ratio.

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## ABSTRACT

A numerical study of massive bubble generation by single-nozzle injection into a co-flowing tapered geometry is reported. Focusing on single-bubble generation in the dynamic and Taylor flow regime, the effects of flow rates and nozzle injection length on bubble/droplet sizes and bubbling frequencies are investigated. The geometry confinement limits bubble's radial expansion, forces the bubble to extrude in both axial directions and blocks the incoming fluxes, and makes effect of "front-end stretching and rear-end squeezing", what is a combination with "stretching" under tapering enhanced co-flow shear and "squeezing" by upstream phase holdup. When bubbles detach, different processes of periodical breakup, including shearing mode and wetting mode, are distinguished to be dependent on gas and liquid flow rates. For the periodical breakup mode, it is found that, with the increase of nozzle injection length, the resulted bubbling frequency increases exponentially with the nozzle injection length, while the sizes of bubble/droplet decrease exponentially in reverse. Therefore, the tapering acceleration of flow enhances the "stretching and squeezing" effect, and generates bubbles in smaller size and with higher frequency. Meanwhile, the pattern diagram is dominated by gas/liquid flow rates and is almost not affected by the nozzle injection length, which functionally decouples the roles of flow rates and the nozzle injection length between flowing modes and bubble size/bubbling frequency controls. Also, it is found that the bubble length is piecewise linear function of the gas/liquid flow rate ratio for both the wetting mode and the shearing mode. All these characteristics of tapered configuration promote the monodispersity and maneuverability of bubbling in co-flowing microdevices.

## 1. Introduction

Microfluidics is a rapidly growing interdisciplinary field combining biochemistry, micro-systems engineering and soft matter physics. Precise droplet volume control and reliable individual droplet generation manipulation have attracted particularly wide interest lately [1,2]. Since geometry and wetting properties of microchannel are crucial factors for monodispersity of droplet, there are several designs of microfluidic devices reported in the recent literature by using gas/liquid or liquid/liquid streams, which typically include cross-flowing devices (i.e. T-shaped junctions [3–5]), co-flowing devices [6,7], and flow focusing devices [8].

In these microscale geometries, the strong influence of viscous stress and the minimal impact of inertia with capillarity lead to regulate breakup of the dispersed phase stream to form monodisperse bubbles and droplets. To control and predict flow patterns, volumetric fractions, uniformity of dispersed/continuous phases

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## Nomenclature

| | |
|---|---|
| $D$ | inlet orifice diameter (m) |
| $d_{in}$ | gas injection nozzle diameter (m) |
| $d_{out}$ | bubble train outlet tube diameter (m) |
| $\theta$ | tapered angle (deg.) |
| $L_L$ | liquid droplet length (m) |
| $L_G$ | gas bubble length (m) |
| $L$ | $(L_G + L_L)$ periodical length (m) |
| $z$ | axial coordinate (m) |
| $r$ | radial coordinate (m) |
| $x$ | injection nozzle relative displacement (m) |
| $u$ | velocity component in $x$-direction (m/s) |
| $v$ | velocity component in $r$-direction (m/s) |
| $\mathbf{u}$ | $(u, v)$ velocity vector (m/s) |
| $U_{TP}$ | superficial two-phase velocity (m/s) |
| $U_G$ | superficial gas velocity (m/s) |
| $U_L$ | superficial liquid velocity (m/s) |
| $t$ | time (s) |
| $\Delta t$ | iteration step size (s) |
| $g$ | gravitational acceleration (m/s$^2$) |
| $Q_L$ | liquid flow rate (ml/s) |
| $Q_G$ | gas flow rate (ml/s) |
| $Q$ | total volumetric flow rate (ml/s) |
| $A_{TP}$ | area of outlet tube cross-section (m$^2$) |
| $P$ | pressure (N/m$^2$) |
| $f$ | bubbling frequency (Hz) |

*Greek characters*

| | |
|---|---|
| $\sigma$ | surface tension (N/m) |
| $\rho$ | density (kg/m$^3$) |
| $\varphi_s$ | static contact angle on the tube surface (deg.) |
| $\mu$ | dynamic viscosity (Pa s) |
| $\kappa$ | mean curvature of the interface (1/m) |
| $\delta$ | liquid film thickness, (m) |
| $v$ | kinematic viscosity, (m$^2$/s) |
| $\alpha$ | volume fraction |

*Dimensionless numbers*

| | |
|---|---|
| $\lambda$ | density ratio$(\rho_G/\rho_L)$ |
| $\eta$ | viscosity ratio$(\mu_G/\mu_L)$ |
| $We_{TP}$ | Weber number$(\rho_L U_{TP}^2 d_{out}/\sigma)$ |
| $Re_{TP}$ | Reynolds number$(\rho_L U_{TP} d_{out}/\mu_L)$ |
| $Ca_{TP}$ | Capillary number$(\mu_L U_{TP}/\sigma)$ |
| $Bo$ | Bond number $(\rho_L g D^2/\sigma)$ |

*Subscripts*

| | |
|---|---|
| $L$ | continuous phase (liquid–water) |
| $G$ | disperse phase (gas–air) |
| $TP$ | two phases |

and their frequencies, which are usually affected by too many factors, such as geometry, flow rates, wettability of microchannel, as well as fluid properties, it is crucial to keep the designs of microfluidic devices primary and no complexity.

A commonly used co-flowing device is to place a gas injection needle or orifice into a liquid with the dispersed phase is introduced in the same direction aligned with liquid flow. For the co-flowing arrangement, a decrease in bubble size is observed with the increase in velocity of the flowing liquid [9–11]. When the outer channel bounding is significant [12,13], the focus of all these studies is on understanding the transition between the dripping and the jetting regimes [14–18]. Dripping is characterized by the fact that no long jets of the dispersed phase are generated. Hence, drops are formed right at the tip of the injection tube. By contrast, when jetting happens, which sets in only at high flow rates, the dispersed phase forms long liquid jets and consequently, drops are emitted right at the tip of the liquid thread [19].

Dripping and jetting modes, which are dominated by shear stresses and surface tension forces, are also mechanisms of bubble or droplet breakup in confined geometry of a T-junction. Furthermore, a new regime, referred to as squeezing mode, is distinguished as a different style [18]. Garstecki et al. [3,36] theoretically discussed the magnitudes of the force generated from the increased resistance to flow of the continuous fluid were expected to be dominant in the breakup dynamics, referred to as "squeezing" effect, which is helpful to produce bubbles or droplets with uniform volume, where the bubble size is primarily dependent on the ratio of the gas/liquid flow rates.

In all those devices, the nondimensional parameters, such as Bond number *Bo*, Reynolds number *Re*, and Capillary number *Ca*, are defined to descript the physical systems. The Bond number *Bo*, which measures the relative importance of gravitational forces to surface tension, is small in microchannel and the effect of gravitation is neglected. The Reynolds number *Re*, which measures the relative importance of inertial forces to viscous forces, is also quite small in microscales and shows characteristic of laminar flowing in microchannels. The Capillary number *Ca*, which measures the relative importance of viscous forces to surface tension forces, shows extra roles to differentiate the breakup regimes, including dripping, jetting or squeezing. At the same time, the density ratio, flow ratio and the viscosity ratio are introduced to account for the dynamics effects of continuous phase to dispersed phase. Additionally, the wettability, size, or inlet configuration of microchannel could also be dominant in some breakup processes [20,21]. For a designed geometry, the fluid properties of wettability, surface tension, viscosity are too expensive to be adjusted, usually changing of the kinematics parameters, such as the flow rates, has been proved an effective alternative.

To determinate the characteristic of Taylor bubble in slug regime on flow pattern diagram, the concern turns to introduce a concept named 'digital microfluidic' in Ref. [22], where controlling of bubble size and bubbling frequency became the core problem in microchannel. Actually, the researchers attempt to put forward the generalized flow pattern diagram to include most effects of controlling parameters. However, the universal chart is far from a conclusion. Even for simple flows in microchannels, the predictive formula for bubble size and bubbling frequency is lack of quantitative uniformity, which is sensitive to the limitation of experimental and measuring apparatus or other factors, such as liquid properties [23,24]. Therefore, to improve the controlling precision and simplicity of a microchannel flow pattern is a challenging work. The T-junctions devices, which aroused too much attention recently, were such kind of design. The linear relation between bubble length and flow rate ratio from Garstecki et al. [3] laid its foundation on applications in microdevices.

Compared with T-junctions, the researches show that the co-flowing configuration has two faults which limit its applications on manipulation of microbubble/microdroplet generation: (1) The index value of power laws on the Capillary number *Ca*, which dominates the generation processes in jetting and dripping regimes