PASSIVELY TRIGGERING ASYMMETRIC DIGITAL FLOWS AT SYMMETRIC MICROFLUIDIC JUNCTIONS

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ABSTRACT

The diverse and often complex dynamics of digital flows in microfluidic networks is of much current interest to the microfluidic community due to the wide range of applications facilitated by such flows. In this paper, we highlight a counterintuitive phenomenon in the traffic of bubble trains. We show how all bubbles of a train can be sorted exclusively into one of the arms of a symmetric loop by the simply increasing its speed beyond a threshold value. We find that this filter regime is accessed when bubbles lower the hydrodynamic resistance of microchannels, an interesting phenomenon in itself.

KEYWORDS: Multiphase Microfluidics, Digital Microfluidics, Droplets and Bubbles, Bubble Traffic

INTRODUCTION

Multiphase microfluidics, involving the robust creation and transport of drops, bubbles and complex emulsions in engineered microchannels finds increasing applications in a wide array of fields such as analytical biology and chemistry, chemical and colloidal synthesis and drug discovery [1-3]. More often than not the devices used in such applications consist of microchannel networks [1-3]. The dynamics of bubble or droplet traffic through even the simplest microchannel network is complex [4-7]. An ability understand and predict such dynamics coupled with a means to divide, merge, sort, and direct bubbles or droplets in a facile manner as they flow through microfluidic networks is crucial to exploit the full potential of such digital flows.

An essential building block required for the passive regulation of droplet or bubble traffic in microfluidic networks is the “hydrodynamic filter”, which serves to direct all the bubbles or droplets of a train into one of the arms of a junction. Here we report the use of a symmetric microfluidic loop to filter bubble trains. Typical filters for droplet trains use asymmetric junctions with arms of unequal lengths; there the inter-droplet distance (the dilution of the train) dictates the filtering [7]. At high dilutions each droplet arriving at the inlet of the asymmetric junction is directed into the shorter arm as it has a higher rate of flow into it; with a decrease in the dilution of the train the number of droplets in the shorter arm increases, and consequently the hydrodynamic resistance of the shorter arm also increases. At a certain low dilution the resistance of the shorter arm filled with droplets matches that of the completely liquid filled longer arm; any further reduction in the dilution of the train results in the droplets distributing themselves between both the arms of the junction.

We report here experiments that show how there is a threshold speed of propagation above which a train of bubbles filters into one of the arms of a symmetric microfluidic loop. The threshold speed for accessing the filter regime depends only on the bubble length. Given that the junction is symmetric the existence of this filter regime is unexpected and can indeed exist only if bubbles can lower the resistance to flow in the arm they are present in, as each bubble arriving at the inlet of a microfluidic junction is expected to be directed into the arm having a greater rate of flow [4-7].

EXPERIMENTAL

We worked with a microfluidic device fabricated in poly(dimethylsiloxane) using standard photo- and soft-lithography techniques. The device comprised of a symmetric loop (Figure 1a), with identical arms of length L=10.3\textit{cm}, and rectangular cross-section with width \(w=300\text{\textmu m}\) height \(h\sim123\text{\textmu m}\). A standard T-junction bubble generator located upstream of the symmetric loop was used to generate a train of monodisperse nitrogen bubbles in ethanol. Ethanol was pumped using a syringe pump at a flow rate \(q_L\) and nitrogen was fed from a compressed cylinder at a pressure \(p_G\). \(q_L\) and \(p_G\) were varied to control the bubble length \(l_b\), bubble speed \(U\) and length of liquid segments \(L\). The details of the flow and trajectories of the bubbles at the inlet of the symmetric loop were captured using a video camera (Basler pi640) mounted on a stereo microscope (Leica MZ16). We ensured that bubbles did not break up at the inlet of the loop by working at low capillary numbers (\(Ca=\eta U/\sigma\), where \(\eta\) and \(\sigma\) are the viscosity and surface tension of ethanol) and small bubble lengths.

RESULTS AND DISCUSSION

We identified the existence of two regimes in the traffic of bubble trains at the symmetric loop; at low speeds of propagation the “repartition” regime was accessed wherein bubbles were directed into both arms of the loop (Figure 1b and c), beyond a threshold speed the transition to “filter” regime occurred and all bubbles of the train were exclusively directed into one of the arms of the loop (Figure 1d). This threshold speed for transition was independent of the dilution of the train (independent of \(l_b\)) and decreased with an increase in bubble length \(l_b\) (Figure 1e and g).
A bubble arriving at the inlet of the symmetric loop is directed into the arm which has at that instant a greater rate of flow into it or conversely a lower hydrodynamic resistance [4-7]. The hydrodynamic resistance of each arm depends on the size, number and also the speed of flow in the arm, thus with the hydrodynamic resistance of the arms varying dynamically with the entry or exit of bubbles to and from that arm, the trajectories of each bubble arriving at the loop is dependent on the trajectories of past bubbles that have arrived at the loop. The hydrodynamic resistance of arm \( i \) filled with \( n_i \) bubbles of length \( l_B \) can be written as

\[
R_i = R_0 \left[ 1 - \phi \right] + n_i \frac{\Delta P_B}{U_i wh} \tag{1}
\]

\( R_0 = 12 \mu L \left[ h^3 w(1-0.63h/w) \right]^{-1} \) is the hydrodynamic resistance of the arm filled completely with the liquid (for \( h < w \)), \( \phi = n_i L_i / L \) is the fraction of the arm filled with bubbles and \( \Delta P_B \) is the pressure difference across the end caps of a bubble moving with a velocity \( U_i \) through a rectangular microchannel. For a perfectly wetting liquid and \( w/h = 2 \), Wong et al. analytically derived that \( \Delta P_B = 3.15(2\sigma/h)Ca_i^{2/3} \) [8]. We conducted experiments to measure this pressure drop across and find that the theory developed by Wong et al. predicts our experimental results (Figure 1f). Thus equation (1) can be rewritten as
When the filter regime is accessed each bubble arriving at the inlet of the loop is directed into the same arm as the previous bubble; for a symmetric microfluidic loop this can happen only if the arm filled with bubbles has a greater rate of flow into it. In other words the arm filled with bubbles should have a lower hydrodynamic resistance than the arm that is completely liquid filled. From equation (2) it can be seen that bubbles will indeed lower the resistance to flow when \(0.4h/l_BCa_i^{1/3} > 1\). When this condition is satisfied by the lead bubble of a train as it flows into one of the arms of the symmetric loop, every single bubble following it will also flow into the same arm as each bubble entering the arm will serve to reduce the resistance to flow in that arm. This criterion can be rewritten in terms of the speed of the incoming bubble train as the speed of the lead bubble as it flows into one of the arms of a completely liquid filled symmetric loop is half that of the incoming train \((Ca_i=0.5 Ca)\),

\[
Ca_c = 2\left(0.4\frac{h}{l_B}\right)^3 \quad (3)
\]

Equation (3) is seen to describe with reasonable accuracy our experimentally measured speeds of transition to filter regime (Figure 1g)

CONCLUSION
In conclusion we have shown how there are easily accessible regions in the parameter space defined by bubble length and speed were resistance to flow in a microchannel is reduced by the presence of bubbles. When this parameter space is accessed by the lead bubble of a monodisperse bubble train as it flows into a symmetric loop, all bubbles of the train are directed into one of the arms and the train filters. The findings presented here should provide not only a additional perspective in developing facile strategies to regulate digital microfluidic flows through complex networks but also provide insights into dynamics of multiphase flows in porous media or physiological systems.

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REFERENCES

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