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Multiphysical phenomenon of air bubble growth in polydimethylsiloxane channel corners under microfluidic negative pressure-driven flow

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ABSTRACT

The air bubbles can be used in a controlled fashion for multiphase microfluidics but also frequently plague microfluidic devices when unrestrained. However the phenomenon of the undesired air bubble growth in microfluidic channels has not been systemically studied yet. Based on a coupled-physics model, herein we try to explain the process of unwanted air bubble growth during microfluidic negative pressure-driven flow in polydimethylsiloxane (PDMS) channel corners with both theoretical and experimental approaches. The air bubble growth is the result of multiphase interactions among solid–liquid–gas contact, and it is mainly determined by interfacial air mass transfer and pressure variation of the flowing liquid. The intangible physics during the bubble growth is revealed and calculated through theoretical analysis. To validate the developed model, the air bubble growth rate variation range of 0.44×10^{-13} m^3/s to 3.4×10^{-13} m^3/s is observed under different experimental conditions. Both of the simulation and experiment data indicate that the rate of air bubble growth can be quantitatively correlated with the bubble location in the channel and the negative driving pressure. The reported studies can both benefit air bubble prevention and removal strategies while providing a theoretical framework for the systematic design of multiphase microfluidics where motive mass transfer exist.

1. Introduction

Multiphase microfluidic systems can enable high-efficiency chemical processing with limited reagent, time and power consumptions. Among the reported applications, gaseous bubbles and segments have been utilized for the purposes of rapid gas–liquid reaction and interfacial mass transfer by increasing the contact interface while reducing the mass transfer distance and axial dispersion [1–9]. Conversely, when random and uninhibited gas bubbles appear in a microfluidic channel they frequently lead to clogging of the channel, hindered liquid flow and even catastrophic failure of the entire device [10]. Although various air bubble filtration/removal strategies were developed [11–14] and related theories were studied [15], there are still plenty of phenomenon that need to be explained.

Polydimethylsiloxane (PDMS) has been the workhorse for microfluidic labs since the inception of soft lithography [16] due to its advantageous material characteristics that are greatly beneficial for biophysical research. However, these characteristics of PDMS also bring inconveniences to the device operation. For example, the high porosity and gas permeability of PDMS, which allows for higher mass transfer of gases, while proving beneficial for cellular growth [17,18] and degas driven flow [19], also increases the probability of unrestrained air bubble growth in the fluidic channels under certain conditions, such as a negative pressure environment.

Negative pressure-driven flow, as an alternative to positive pressure-driven liquid loading, can potentially allow larger flow velocities, by reducing interfacial pressure on the bonded surfaces which can in turn lead to device delamination [20], while simplifying device operation by employing only a single vacuum source for multiple devices/inlets [21] or by enriching the liquid actuation function with multiple vacuum sources connecting different outlets of a single chip [22]. These advantages of negative pressure-driven flow in PDMS devices though are limited by the high vulnerability of such devices to unwanted air bubbles during operation. However, the underlying physical mechanism of such phenomenon in microfluidic channel under negative

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pressure-driven flow has not yet been studied and further investigations are hence worthwhile.

In this report, we try to elucidate the undesired air bubble growth mechanism under negative pressure-driven flow in PDMS microfluidic devices with both theoretical and experimental methods. A multiphysical model is employed in the theoretical analysis followed by experimental observation and measurement of air bubble growth under different conditions to illustrate the undergoing processes. Quantitative correlations between air bubble growth rate and key parameters are then estimated based on simulation results and experimental data. These studies allow us to identify the critical factors influencing air bubble variations during negative pressure-driven liquid flow. We hope this report could benefit air bubble mitigation strategies for microfluidic devices and also the design of future multiphase microfluidic applications.

2. Undesired air bubbles in microfluidic negative pressure-driven flow

In normal conditions, the hydrophobicity of PDMS surface leads to unwetted flow of aqueous solutions. During liquid flow inside PDMS devices, the air bubbles could be often observed in the channel, as shown in Fig. 1. Under positive pressure-driven flow these entrapped air cavities can be pushed out of the fluidic channel into the PDMS bulk under the pressure gradient [23,24]. Conversely, under the continuing liquid flow pulled by negative pressure, these air bubbles keep growing larger, until they occupy the whole cross section and detach from the microchannel wall under the shear to form individual air segments, as shown in Fig. 1(a–d). These air segments take advantages of the pressure drop, which are supposed to be exerted on the liquid to drive the flow, to keep expanding, as shown in Fig. 1(e–g). The growing air segments (air bubbles) hugely increase the liquid flow resistance, and the flow would finally cease due to the unconquerable flow resistance in the microchannel, as observed in Fig. 1(h). Although not all of the fluidic actuation driven by negative pressure suffer from the harmful air bubbles blocking channels, there could be a considerable number of air bubbles to be perceived in hydrophobic PDMS channels during negative pressure-driven flow.

Air bubbles are observed in both PDMS channel corners and straight sections. In this paper, only the air bubble growth in channel corners, which is more frequently observed, is considered and illustrated by the developed theoretical model and experiments, the otherwise conditions are not involved.

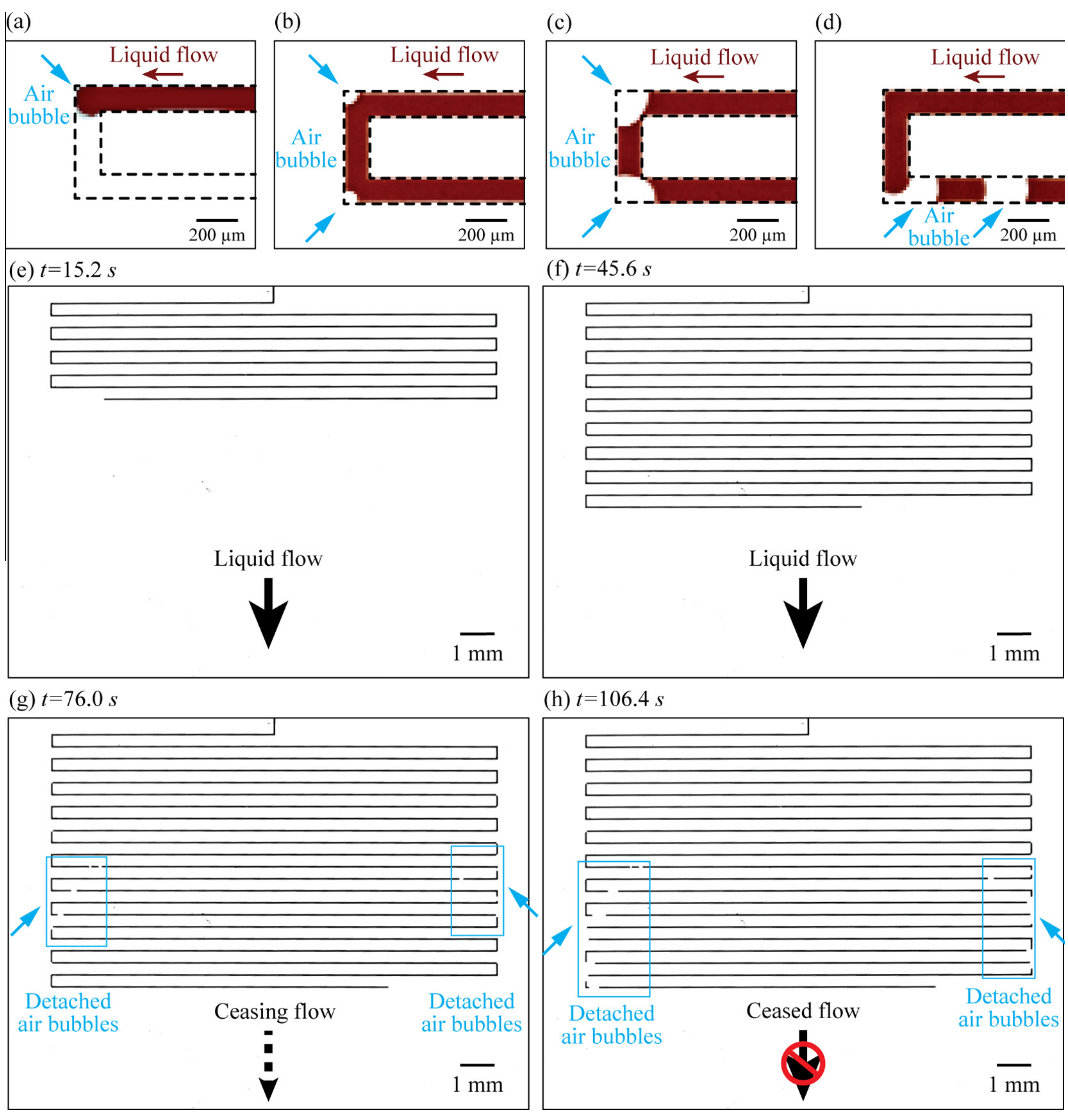

Fig. 1. Air bubble growth under negative pressure-driven flow. Experiment observation of air bubble (a) formation, (b and c) growth and (d) detachment in PDMS channel corners under negative pressure environment. (e–h) Liquid flow driven by negative pressure is plagued and blocked by growing air bubbles in the channel.