StarTube: A Tube with Reduced Contact Line for Minimized Gas Bubble Resistance

Tobias Metz, Wolfgang Streule, Roland Zengerle, and Peter Koltay*

Laboratory for MEMS Applications, Department of Microsystems Engineering (IMTEK), University of Freiburg, Georges-Koehler-Allee 106, 79110 Freiburg, Germany

Received April 16, 2008. Revised Manuscript Received June 16, 2008

In this work we introduce a novel tubing design for multiphase flow that minimizes gas bubble resistance. The design termed "StarTube" has a lamella-like wall structure and was developed to prevent clogging by gas bubbles. This is performed by forcing gas bubbles into the center of the tube by capillary forces, allowing liquid to bypass in the outer grooves. It was found that the mobility of gas bubbles in such a tube is increased more than 1 order of magnitude. The reason is that the contact line perpendicular to the direction of flow is minimized, reducing resistant effects related to the contact line—in particular, contact angle hysteresis.

Introduction

Gas bubbles in fluidic systems and interconnections are a widespread problem in microfluidics and at the interface between microfluidic devices and macroscopic systems. Bubbles occur when reservoirs are connected or exchanged, e.g., to print heads or medical dosage systems. They can also appear as a product during process operation, e.g., in direct methanol fuel cells[1] or due to degassing of dissolved gases in any fluidic system. Gas bubbles add capacitive effects and pressure losses to the flow in channels. The pressure losses scale with the capillary pressure $\Delta p \sim \sigma r^{-1}$ (surface tension σ; channel radius r) and thus increase with miniaturization.[2,3]

Reasons for the pressure losses are hydrodynamic effects in the vicinity of the contact line[3] and contact angle dynamics and hysteresis.[4] Contact angle hysteresis is the static difference in contact angle between an advancing and a receding contact line. For a bubble in a tube, the front meniscus is bound by a receding contact line while at the back an advancing contact line is placed. Contact angle hysteresis induces a threshold force F onto a gas bubble.[5] It must be surmounted to move a bubble at all. The force scales with the variation between advancing contact angle θ_{adv} and the receding contact angle θ_{rec}, proportional to the capillary pressure $F \sim \sigma r^{-1}(\cos\theta_{\mathrm{adv}} - \cos\theta_{\mathrm{rec}})$.[4,5]

At a moving contact line further a dynamic change in contact angle can be observed leading to a dynamic resistance. This effect is still a topic of research and different laws for the relation between velocity and contact angle are discussed.[6,7] The proportion of contact angle hysteresis and contact angle dynamics depends strongly on the actual surface, roughness, and chemistry.[8] In any case contact angle hysteresis dominates for the smallest velocities, in particular, when a bubble starts moving and the velocity is nearly zero. Both effects are related to the contact line at the caps of a bubble and are independent (in the absence of surfactants) of the length of the bubbles.[9,10]

Contact angle hysteresis can be measured with a droplet sitting on a surface by evaluation of the minimum angle necessary to move the droplet by gravity when tilting the surface. From hydrophobic surfaces it is known that roughness increases the contact angle (superhydrophobicity) and can decrease hysteresis considerably;[8] therefore, droplets move much more easily on these surfaces (lotus effect).[11] In experiments and simulations it has already been found that the resistant force is stronger perpendicular to roughness in the form of lateral grooves than along those grooves.[8,12]

The presented StarTube exploits this effect and applies it to bubbles in tubes to minimize their resistance to the flow. The StarTube has grooves in the side walls that minimize the contact line perpendicular to the direction of flow. Effects associated with the contact line are reduced and the mobility is increased. Gas bubbles can be removed from the tube by small forces even in the direction opposite to the main flow, e.g., by buoyancy against liquid flow from a reservoir with bubble flow back into the reservoir. To achieve this behavior the star-shaped geometry was designed in a way that capillary forces prevent a bubble from moving into the grooves.

Working Principle of the StarTube

The star-shaped profile of the StarTube is built up from a circular pattern of rectangles (Figure 1a.). Gas bubbles are forced into the center of the tube by capillary forces (Figure 1b). The centered bubble position ultimately enables the liquid to bypass a bubble in the outer channels formed by the fingers of the profile. In theory the contact line perpendicular to the flow direction should be zero. In reality fabrication always leads to a small rounding and therefore a small part of the contact line is left. Nevertheless, the reduced contact line improves bubble mobility significantly.

* Corresponding author. Contact: peter.koltay@imtek.uni-freiburg.de, Tel: +497612037282, Fax: +497612037322.

(1) Litterst, C.; Eccarius, S.; Hebling, C.; Zengerle, R.; Koltay, P. J. *Micromech. Microeng.* **2006**, *16*, S248–S253.
(2) Gravesen, P.; Braneberg, J.; Jensen, O. S. J. *Micromech. Microeng.* **1993**, *3*, 168–182.
(3) Bretherton, F. P. *J. Fluid Mech.* **1961**, *10*, 166–188.
(4) Wong, C. W.; Zhao, T. S.; Ye, Q.; Liu, J. G. *J. Electrochem. Soc.* **2005**, *152*, A1600–A1605.
(5) Schaffer, E.; Wong, P. Z. *Phys. Rev. E* **2000**, *61*, 5257–5277.
(6) Bracke, M.; De Voeght, F.; Joos, P. *Prog. Colloid Polym. Sci.* **1989**, *79*, 142–149.
(7) Hoffman, R. L. *J. Colloid Interface Sci.* **1975**, *50*, 228–241.
(8) de Gennes, P. G. *Rev. Mod. Phys.* **1985**, *57*, 827–863.
(9) Probstein, R. F. *Physicochemical Hydrodynamics: An Introduction*; Wiley-Interscience: Chichester, 2003; pp 305−351.
(10) Fuerstman, M. J.; Lai, A.; Thurlow, M. E.; Shevkoplyas, S. S.; Stone, H. A.; Whitesides, G. M. *Lab Chip* **2007**, *7*, 1479–1489.
(11) Cassie, A. B. D.; Baxter, S. *Nature* **1945**, *155*, 21–22.
(12) Jia, X.; McLaughlin, J. B.; Ahmadi, C.; Kontomaris, K. *Int. J. Mod. Phys. C* **2007**, *18*, 595–601.

10.1021/la801194j CCC: $40.75
Published on Web 08/01/2008

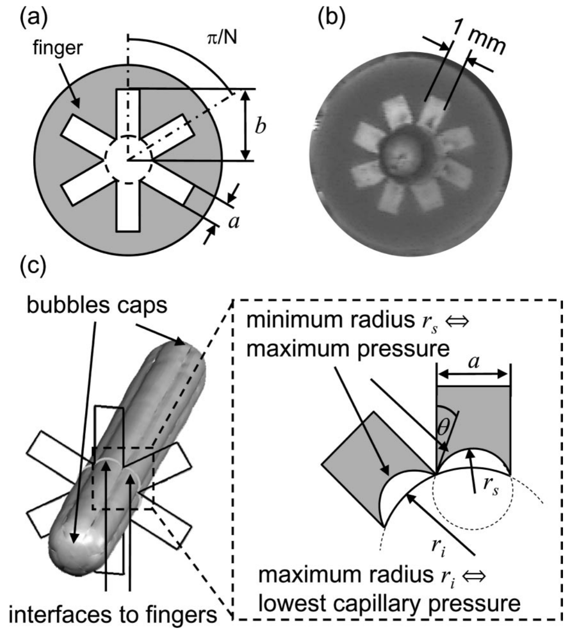

Figure 1. Setup and working principle of the StarTube. (a) Cross section of the StarTube: N rectangular grooves forming the fingers and a cavity in the center. (b) Photograph of a bubble centered in a StarTube ($N = 8$; contact angle $\theta = 0°$; $b = 2.5$ mm; $a = 1$ mm). (c) Setup of a bubble in the StarTube.

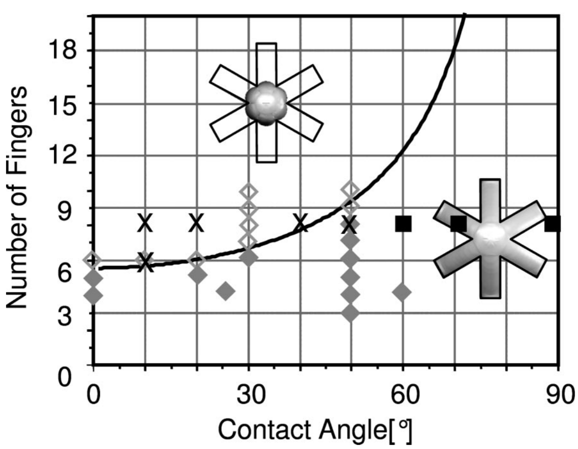

Figure 2. Theoretical prediction whether a bubble is centered or clogs the channel completely. Diamonds show validations by CFD Simulations (filled = clogged, open = centered). Crosses and quads mark performed experiments using different mixtures of propyl alcohol and water (x = centered, quad = clogged, deviation in measured contact angles $\Delta\theta \sim \pm 5°$).

Bubble Positions

The configuration a bubble might attain in a StarTube—centered or clogging the whole cross section (Figure 2)—depends on the number of grooves and the contact angle θ. Conditions for centered bubbles can be determined by considering the capillary pressure p_{cap} which must be constant over the entire surface of the bubble. In the centered position, p_{cap} must be lower than the maximum capillary pressure p_{side} the side channels can exert (Figure 1c)

$$p_{side} > p_{cap} \tag{1}$$

Otherwise the enclosed gas would also enter into the side channels. The surfaces of a long bubble in one of the side channels can be regarded as cylindrical (Figure 1c). The maximum pressure p_{side} the surface can sustain is given by the contact angle and the finger width a, as given by eq 2

$$p_{side} = \sigma \frac{1}{r_s} = \sigma \frac{2\cos\theta}{a} \tag{2}$$

On the other hand, the capillary pressure of the bubble in the central section p_{cap} can be calculated by the integral theorem on capillary surfaces (eq 3)[13,14] if its shape is known

$$p_{cap} = \sigma \frac{S}{A} \tag{3}$$

In eq 3 S denotes the circumference and A the area of a bubbles cross section. In the limit of the maximum capillary pressure, the cross section is given by a series of N arcs with radius r_s (Figure 1c). Thus, p_{cap} can be evaluated analytically using eq 3 as a function of N and θ for this case and compared to p_{side} according to eq 1. This leads to a necessary condition for centered bubbles, relating the number of fingers and the contact angle of a StarTube

$$N > \pi\left(\arctan\left(\frac{2\cos^2\theta}{\pi - 2\theta + 2\cos\theta\sin\theta}\right)\right)^{-1} \tag{4}$$

Eq 4 must be fulfilled in order to obtain centered bubbles in a StarTube. It does not depend on the actual dimension of the tube—as long as gravity does not decisively deform the bubble shape. Computational fluid dynamics (CFD) simulations and experimental results as presented in Figure 2 confirm this model. The solid line in Figure 2 represents the case when both sides of eq 4 are equal. Only StarTubes with parameters above the graph lead to centered bubbles. At least six fingers are required to force a bubble in a central position. Simulations were performed with a volume of fluid method, that accounts for surface tension and contact angles (ESI-CFD ACE+ (ESI-Group http://www.esi-group.com/)). The deviation between experiments and theory can be explained by the finite radii at the edges in the extruded tube.

Fabrication

The experiments in this work were performed with a StarTube made from PDMS. The tube with eight fingers and a width a = 1 mm and a depth b = 2.5 mm was fabricated by extrusion (Fabricated by MG-Silikon a St. Gobain Company, Lindau, Germany). For quantitative experiments with water (viscosity $\eta = 1 \times 10^{-3}$ Pa; $\sigma = 72.5$ N m^{-1}), the extruded tube was treated with HMDSO plasma, leading to a temporary advancing contact angle around 20° (AQUACER from P PLASMA ELECTRONIC GmbH, Neuenburg, Germany). Though the dimensions of the samples were relatively large, all effects were found as suggested by theory.

Measurement of the Bubble Resistance

As pointed out, contact angle hysteresis leads to a threshold force on bubbles in tubes. Here we document a bubble rise experiment that shows that the threshold resistance is more than 1 order of magnitude smaller in the StarTube than in a conventional circular tube. The mean velocity of a gas bubble driven by buoyancy in an inclined tube was derived by measuring the time a bubble needs to pass a defined distance.

In the StarTube, liquid can move in the outer grooves in the opposite direction from that of a gas bubble. Thus for the StarTube an experiment was set up with a closed tube including a gas bubble. In contrast, a closed circular tube does not allow a gas bubble to move at all, as liquid cannot bypass the bubble and

(13) Finn, R. *Equilibrium Capillary Surfaces*; Springer-Verlag: Stanford, 1986.
(14) Langbein, D. *Capillary surfaces: shape, stability, dynamics, in particular under weightlessness*; Springer: Berlin, 2002; pp 41−178.

the circular tube used for reference measurements was set up as a closed loop.

In the experiments the viscous pressure loss of the moving liquid must be balanced by the buoyant pressure $\Delta p_{buoyant}$ induced by the bubble

$$\Delta p_{buoyant} = \Delta p_{visc} \quad (5)$$

For a tilted StarTube with tilt angle α this can be rewritten to

$$\rho g \sin \alpha l_{bub} = 2\eta \, l_{bub} \frac{U^2}{A_{liq}^{\ 2}} \frac{A_{bub}}{A_{liq}} v_{bub} \quad (6)$$

where U is the circumferential length of the star-shaped profile and A_{bub} and A_{liq} are the areas in the profile occupied by the bubble and the liquid, respectively. In eq 6 the viscous pressure loss Δp_{visc} is calculated by the law of Hagen-Poiseuille for laminar flow.[15] The bubble velocity v_{bub} is a linear graph for a given bubble length when plotted against the buoyant pressure that is defined by the height difference along the bubble $l_{bub} \sin \alpha$. It would be a unique graph for all lengths when plotted against sin α.

In the loop formed by the conventional tube (diameter 3 mm, ~30 cm length) the viscous pressure drop Δp_{visc} can be calculated similarly and depends on the length of the tube but not on the bubble length l_{bub}. Therefore, the bubble velocity is a unique linear function of the height difference over the bubble $l_{bub} \sin \alpha$.

Experiments were performed for different bubble lengths for the StarTube and the circular tube. Measured velocities are plotted against the height difference over the bubble $l_{bub} \sin \alpha$ in Figure 3. The graphs are extrapolated toward zero bubble velocity. In addition, a theoretical graph for a gas bubble of length 50 mm is shown calculated by eq 6 with a slight deviation between theory and experiment that lead from the simplicity of the model for the laminar flow. The results in Figure 3 allow one to estimate the resistant force onto the gas bubbles induced by contact angle hysteresis given by the minimum height $l_{bub} \sin \alpha_{min}$ necessary for a bubble to start moving. From the derived values (Table 1) it can be found that for the StarTube the resistant effect is more than 1 order or magnitude smaller than for the conventional tube. The reason is that the contact line perpendicular to the direction of movement is minimized in the StarTube.

(15) Sigloch, H. *Technische Fluidmechanik*; VDI Verlag: Düsseldorf, 1996; pp 1−496.

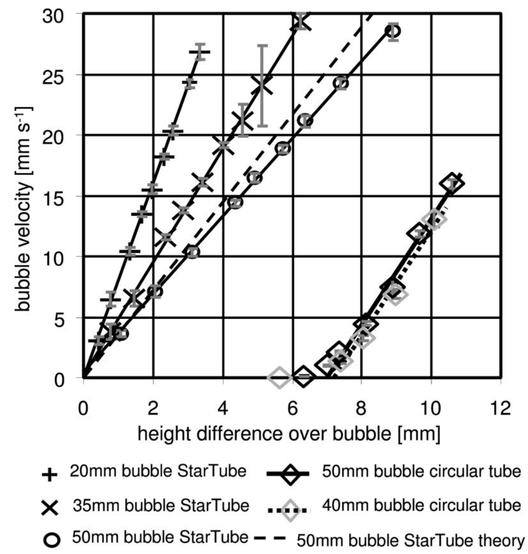

Figure 3. Bubble velocities measured in bubble rise experiments.

Table 1. Derived Threshold Height $l \sin \alpha_{min}$ until Bubbles Start to Move

	Star Tube			circular tube	
bubble length l_{bub} [mm]	20	35	50	50	40
$l \sin \alpha_{min}$ [mm]	<0.1	<0.1	<0.1	7.05	7.23
quality of regression [%]	99.9	99.9	99.9	99.0	98.2

Conclusions

The presented StarTube is a novel tubing design for multiphase flow with a rich field of application for fluidic interconnections, in particular, between microfluidic devices and the environment. It has been shown how the StarTube predictably separates gas bubbles from the liquid flow and prevents clogging. At least six fingers are necessary to achieve a centered position. The resistance of gas bubbles is decisively reduced in the StarTube. This is attributed to the reduced contact line resistance of gas bubbles achieved by minimizing the contact line perpendicular to the direction of movement only.

Acknowledgment. This work was supported by the Deutsche Forschungsgemeinschaft (ZE 527/3).

Supporting Information Available: Additional figures available. This material is available free of charge via the Internet at http://pubs.acs.org.

LA801194J