STARTUBE: A NOVEL TUBE DESIGN FOR BUBBLE TOLERANT INTERCONNECTION IN FLUIDIC SYSTEMS

T. Metz[1], W. Streule[1], R. Zengerle[1] and P. Koltay[1]

[1]*Laboratory for MEMS Applications, Department of Microsystems Engineering (IMTEK), University of Freiburg, Germany*

ABSTRACT

For the first time we present a new tubing geometry for the bubble tolerant interconnection of fluidic systems. The tube has a star shaped profile, forcing bubbles into its centre by capillary forces. The StarTube is save from being clogged by bubbles as liquid can bypass in the side channels of the tube. The mobility of bubbles is increased decisively as their contact line perpendicular to the movement direction is minimized. A model established for the prediction of bubble configuration shows that the simplest design which leads to a centred bubble requires six grooves and contact angles of $\theta < 20°$.

Keywords: Bubble, Tube, Pipe, Star, Capillary, StarTube

1. INTRODUCTION

Gas bubbles in fluidic connections induce resistance due to contact line effects, with pressure losses in the order of the capillary pressure [1]. The losses accumulate for multiple bubbles. Conventional connections transport bubbles with the flow to positions where they can disturb the operation. Sometimes so called "bubble traps" are used to isolate bubbles and to enable liquid to pass. The presented StarTube is a unique solution enabling trapping of bubbles as well as increasing bubble mobility in the flow.

2. WORKING PRINCIPLE

The star-shaped profile of the StarTube is built up from a circular pattern of rectangles (Fig. 1a.). Gas bubbles are forced into the centre of the tube by capillary forces (Fig. 2a). A centred bubble enables the liquid to bypass in the outer channels formed by the fingers of the profile. The reduced contact line perpendicular to the flow direction maximises bubble mobility. An obstacle across the centre of the tube can hold back bubbles (Fig. 7). This realizes an efficient bubble trap.

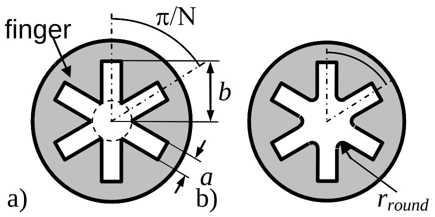


Fig. 1: Cross section of the StarTube: N rectangles forming the grooves and a cavity in the centre. The situation for rounded edges is shown in (b).

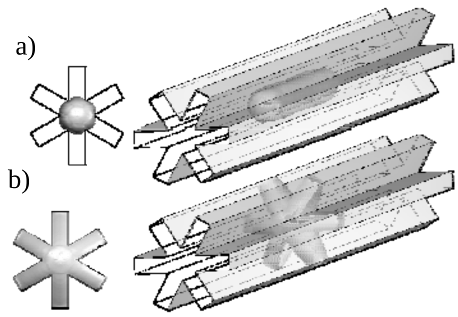


Fig. 2: Simulations of bubbles in a StarTube (N=6, b/a=3). Depending on contact angle and geometry a bubble either adopts a (a) centred ($\theta = 0°$) or (b) clogged ($\theta = 50°$) configuration.

2. THEORY

The configuration a bubble attains in a StarTube - centred (Fig. 2a) or clogging the whole cross section (Fig. 2b) depends on the details of the geometry and the contact angle θ. Conditions for centred bubbles can be determined by considering the capillary pressure p_{cap} which is constant all over the surface of the bubble. In the centred position p_{cap} must be lower then the maximum capillary pressure p_s the side channels can exert (Fig. 3). The surfaces of a long bubble in the side channels can be regarded as cylindrical. The maximum pressure p_s it can produce is given by the contact angle and the channel width a, as

$$p_{side} = \sigma \frac{1}{r_s} = \sigma \frac{2\cos\theta}{a}, \qquad (1)$$

where r_s is radius of the cylindrical surface in a side channel. On the other hand, the capillary pressure of the bubble p_{cap} is defined by the bubbles caps. A centred bubble in the StarTube has wall contacts only along the edges and the capillary pressure is given by [2]

$$p_{cap} = \sigma \frac{S}{A}. \qquad (2)$$

S denotes the circumference and A the area of the cross section of the bubble. In the limit of the maximum capillary pressure, the cross section is given by a series of N arcs with radius r_s (Fig. 3). Thus p_{cap} can be evaluated as a function of N and q for this case and compared to p_{side}. If p_{cap} is smaller than p_{side} the bubble is centred. This leads to a condition for centred bubbles, relating the number of fingers and the contact angle of a StarTube:

$$N > \pi \left(\arctan\left(\frac{2\cos^2\theta}{\pi - 2\theta + 2\cos\theta\sin\theta} \right) \right)^{-1}. \qquad (3)$$

Eq. 3 must be fulfilled in order to obtain centred bubbles in a StarTube. The solid line in Fig. 4 represents the case when both sides of Eq. 3 are equal. Only StarTubes with parameters above the curve lead to centred bubbles. It can be seen that these require more at least six fingers. Computational Fluid Dynamics (CFD) Simulations and experiments confirm the model (Fig 4). Simulations were performed with a volume of fluid method, that accounts for surface tension and contact angles (ESI-CFD ACE+ [3]).

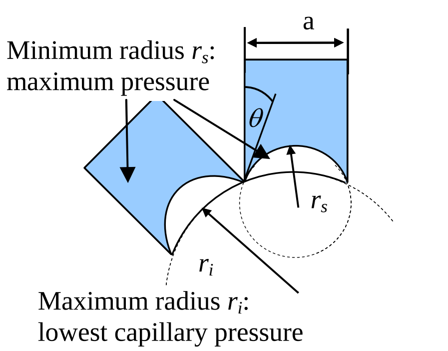


Fig. 3: Part of the cross section of a StarTube. The bubble surface forms arcs in the cross section. Contact angle at the edges can vary what leads to varying arc radii's.

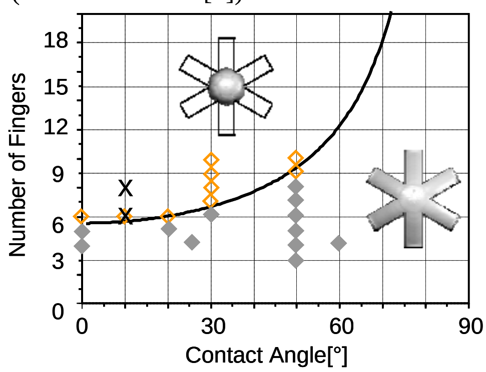


Fig. 4: Necessary number of fingers for functional StarTube. Performed simulations and Experiments are marked: ◇ centred bubble; ◆ clogging bubble; x fabricated tubes (centred bubbles).

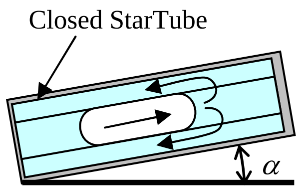


Fig. 5: Experimental setup of buoyancy

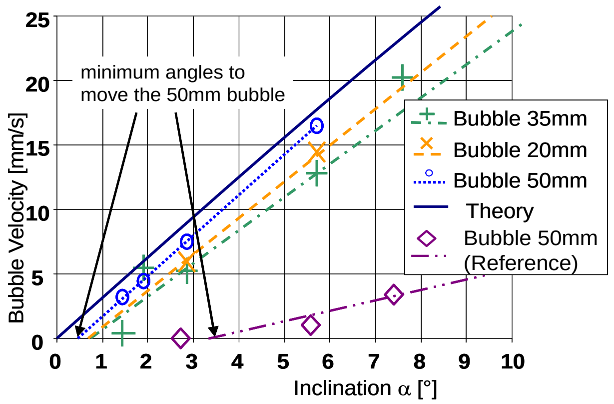
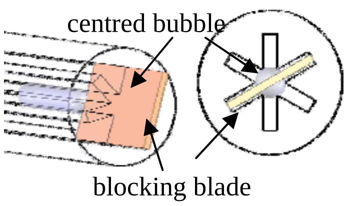


Fig. 6: Observed and theoretical predicted velocities of bubbles moving in inclined StarTube. (a=1100 µm; b=2.5 mm; N=8; r_{round}~250 µm)

3. EXPERIMENTS

StarTubes were fabricated in PDMS, one with six side channels (a=500 µm, b=2.5 mm, N=6, r_{round}~250 µm) and one with eight (a=1100 µm, b=2.5 mm, N=8, r_{round}~250 µm). They were made hydrophilic by HMDSO plasma deposition, leading to a contact angle θ<10°. Bubbles brought into the tubes were centred as predicted. The increased mobility of gas bubbles in the StarTube has been proven by buoyancy experiments as sketched in Fig. 5. In comparison to a circular PDMS tube. The minimum necessary inclination angle to move a bubble is about eight times smaller in the StarTube than in the conventional tube (Fig. 6).

Fig. 7 shows a bubble trap realized by introducing a small blade across the centre of a StarTube.



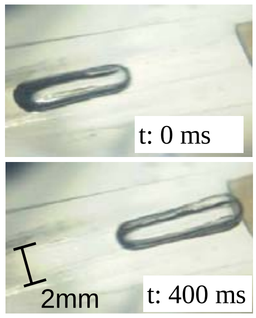


Fig. 7: StarTube (N=6) with a crossing blade to hold back a centred bubble.

5. CONCLUSION

The increased bubble mobility in the StarTube was successfully proven and a theoretical assessment was presented which enables the design of such tubes. The StarTube has a great potential of application in µTAS, it can be used within systems and for connection by external tubing, to form bubble traps and to avoid clogging.

ACKNOWLEDGEMENTS

This work was funded by the German Science Foundation (DFG) under project ZE 527/3.

REFERENCES

[1] H. Wong, C. J. Radke, and S. Morris, "The Motion of Long Bubbles in Polygonal Capillaries .2. Drag, Fluid Pressure and Fluid-Flow" *J. o. Fluid Mechanics*, 1995

[2] D. Langbein, Capillary surfaces : shape, stability, dynamics, in particular under weightlessness, Book, Springer, 2002.

[3] ESI-CFD,CFD-ACE+ Modules Manual, Huntsville, 2006