Dynamics of stagnant Taylor bubbles in vertical upward pipe flow with Venturi obstruction and non-Newtonian liquids

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ABSTRACT

Experiments were carried out to study the dynamics of large gas bubbles which were captured by a Venturi restriction in vertical pipes with Newtonian (water) and polymer liquids ("PAC" – Poly Anionic Cellulose). Such a setup allows observations of large bubble under nearly static conditions over long times. In particular this study has focussed of the surrounding liquid draining around the bubble, as well as the downstream wake behind the Taylor bubble. The flow profile in the wake is crucial for the capture of smaller bubbles and thus causing the large bubble to "feed" on the smaller bubbles.

INTRODUCTION

In many practical multiphase flow processes situations may arise when obstructions in the pipe prevent gas bubbles from passing and thus making them stagnant. This can occur in chemical engineering process flows and also in drilling processes, typically when liquid is flowing downwards as with "Underbalanced Drilling" (UBD) and "Managed Pressure Drilling" (MPD) with gas being mixed with the drilling mud to reduce mud weight and the hydrostatic pressure gradient.

In previous papers by the authors, the dynamics of large ("Taylor") gas bubbles in vertical pipelines have been investigated in various contexts[12,13,14]. This paper focuses on large gas bubble kept stationary downstream of a Venturi with downward flowing liquid.

The work is motivated by methods and challenges during drilling and operations of petroleum wells. In some cases reservoir natural gas flows uncontrolled and with high pressure into the well, e.g. as in a "gas kick" or with influx of H_2S. Then there would be a need to force the gas back, down into the well and reservoir. This method is often referred to as "Bullheading". In other cases it is better to let the gas bleed in a controlled way up to the drilling platform. However, it is possible that the gas bubble movement is hindered by components of the drill string, which narrows the inner flow area in the drill string or the surrounding annulus space. Any type of internal flow obstructions, like valves and instrumentation equipment could locally increase the liquid velocity. If the downward liquid speed exceeds the gas bubble rise velocity the, such obstructions will hinder or even stop gas bubbles from migrating upwards. This can mask unwanted counter current gas-liquid flow, and over time lead to substantial gas accumulation downstream of the obstruction. A detailed outcome of such local accumulations is unpredictable, but is in general expected to induce enhanced flow fluctuations and pressure fluctuations. An example is shown in Fig. 1. The decrease in both internal drill-

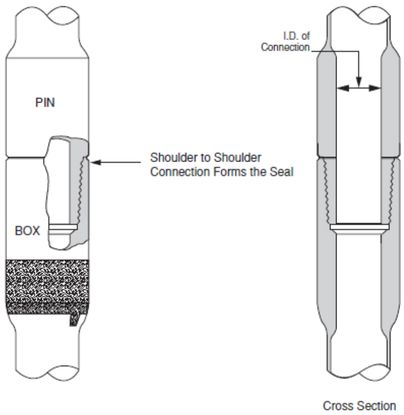

Figure 1: Tool joint parts of the drillstring makes contractions similar to Venturis.
(http://petroleumsupport.com/wp-content/uploads/2013/11/tool-joints.png

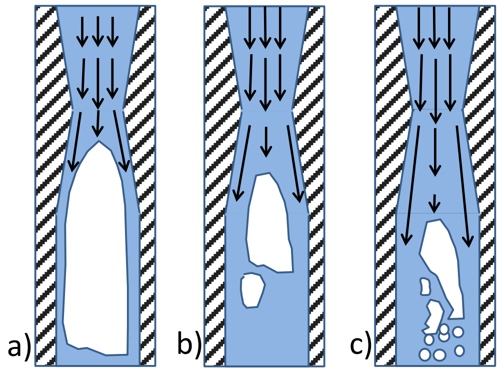

Figure 2: A large gas bubble trapped in a divergent expanding pipe flow field. The position of the bubble is self-regulating for a fixed liquid flow rate.

pipe area and outside annulus space area may affect the movement of large gas bubbles both places.

Another background for carrying out this experimental study is the challenge of studying the dynamics large gas bubbles over longer time intervals. During natural movement they can only be followed for short times under given flow and pressure condition. Or it might be necessary to use a whole array of sensors and cameras along the pipe. The idea here was to set up a counter-current downward liquid flow which would balance the gas bubble rise velocity. To do this in a straight vertical pipe is very difficult, since the liquid flow velocity will easily be too low or too high to keep the bubble balanced. If the flowrate is too low the bubble will flow upwards and escape out at the top. In the case of too high flowrate the bubble(s) will be forced downwards and eventually flow around to other pipe with upward liquid flow and drain out there.

A simple way to overcome the stability issue is to introduce a divergent pipe section so that the liquid velocity decreases from the top as shown in Fig.2, with a Venturi to be inserted in the pipe.

THEORY

Large gas bubbles with a bullet shape, often called Taylor bubbles, have a rise velocity U_{T0}:

$$U_{T0} = 0.35\sqrt{g \cdot D} \qquad (1)$$

With liquid flow imposed, the total rise velocity U_T is:

$$U_T = U_{T0} + U_L \qquad (2)$$

Here D is the pipe diameter and U_L the liquid velocity at the nose of the bubble, with positive direction upwards. If U_L is downwards (negative) and equal to U_{T0}, the bubble becomes stagnant.

However, in a divergent field like in Fig.1, depending on the liquid flow velocity the Venturi may focus the velocity profile[7], so that the centreline velocity deforms the Taylor bubble and may eventually cause a breakup. In this case of fragmentation into smaller bubbles, the rise velocity is even smaller than for the Taylor bubble. Consequently the bubbles may therefore be transported downwards and up into the neighbour pipe. Therefore the rheology of the liquid becomes very important, since it influences the velocity profile in the Venturi. The rheology also determines the drag and impact momentum on the Taylor bubble, and thereby the geometry and the stability of the bubble. Finally, with the shear thinning liquids used in these experiments, the rheology controls the rise velocity of small bubbles, since the effective viscosity is much higher for low shear rates.

A literature review shows that very few relevant articles published have been published on the topic of stationary bubbles in non-Newtonian vertical pipe flow. Impact of velocity profile upstream the bubble Newtonian flow is well described in Polonsky[1]. Counter-current flow of liquid and Taylor bubbles have been studied by Benattalah[2] for small diameter pipe, and by Fabre[6] et al. Fabre[6] also discusses symmetry breaking of Taylor bubbles. Clanet[5] studied rise velocities of slug bubble in arbitrary cross sections. Delfos[3] et al described bubble breakup at the rear of the Taylor bubble. Rise velocities were analysed by Viana[4] and Santos[9] as shown in Fig.3. Scammel[11] studied heat transfer of Taylor bubbles in co-current flow. Very little is studied regarding non-Newtonian flow. Turian[8] studied single phase non-Newtonian flow friction in restrictions. Wenyuan[10] et al studied rise velocity and dynamics of a range of bubble sizes. Agu[7] et al did numerical simulations of non-Newtonian flow also in a Venturi. Further references for Taylor bubbles in non-Newtonian vertical flow are given to our earlier works[12, 13, 14]. These papers also serve as a general background for this work. Finally we refer to the MSc thesis by Potokin[15], which has been carried out in parallel with this present paper.

EXPERIMENTAL

The flow rig is shown in Fig. 4. Water is initially at the same level in the two vertical pipes. But when the pump starts, liquid from the left pipe (i.d. = 4cm) is pumped into the bigger pipe (i.d. = 8cm) and a flow starts as indicated by arrows. The overflow is controlled by a submersible DC voltage bilge pump (0-12Volt), giving 1.3 L/s maximum at 12 V for water.

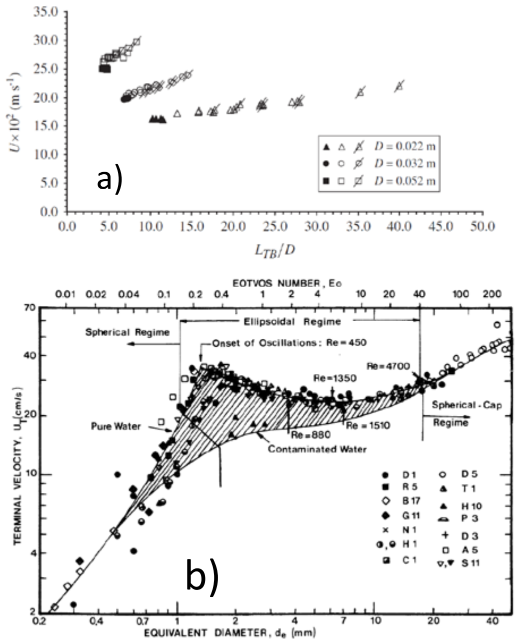

Figure 3: a) Taylor bubble rise velocity as a function of bubble length (from Santos[9])
b) Bubble rise velocity as a function of bubble diameter (from Clift[16])

The liquid flows through a flow straightener before entering into the Venturi. When steady liquid flow has been established, gas is injected below the control valve shown in Fig.4. Both water and PAC polymer solutions were used for the experiments. The concentrations used were 1, 2, 3 and 4 g PAC per litre water.

A number of images of the bubble flow were recorded in “high speed” mode at 120 frames per second by means of a Samsung EK-GC200 camera.

Venturi

The Venturi was made from acrylic, carefully milled and polished inside to have a fairly good optical quality as can be seen from the experiment pictures. The throat is slightly elongated as shown in Fig. 5. The Venturi was set and sufficiently held in place by careful clamping on the outer pipe.

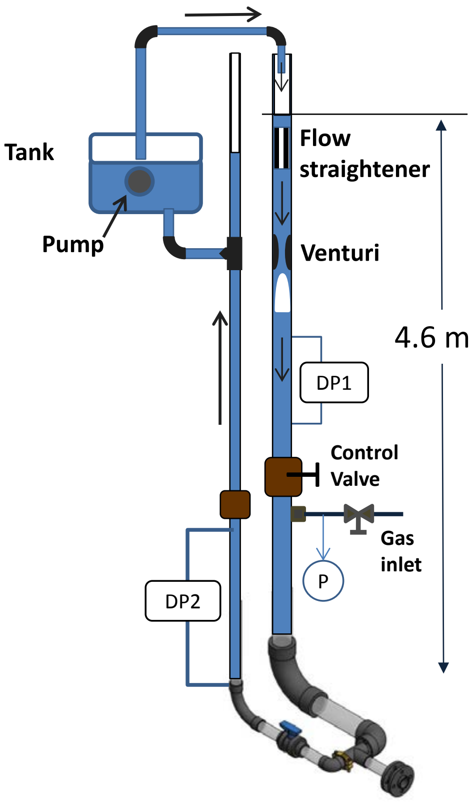

Figure 4: Experimental setup of the flow rig

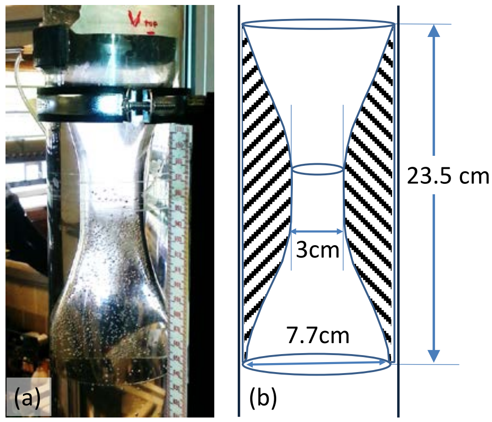

Figure 5: The Venturi placed inside the pipe. a) Picture b) Drawing and dimensions

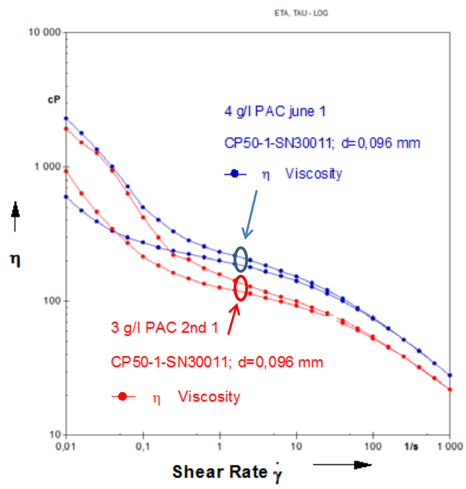

Figure 6: Rheology of PAC solutions 3 and 4 g/L. Substantial hysteresis was found, and will be further investigated.

<u>Rheology measurements</u>

For the polymer flow experiments PAC mixtures were made in concentrations of 1, 2, 3 and 4 gram per litre water. Viscosity versus shear rate for only 3 and 4 g/L is shown in figure (PAC 3-4 gpL). The curves in Fig. 6 show substantial hysteresis, but due to lack of time with the paper it remains to check the tests in a long series of increasing and decreasing shear rate.

<u>Pump calibration</u>

The DC pump was calibrated against a magnetic flowmeter, with a fairly linear and repeatable characteristic of flowrate versus voltage as long as the back pressure was atmospheric - as in our experiments.

For the polymer flows the effective viscosity is higher and the pump delivery is somewhat reduced.

The calibration curves for water and PAC 4g/L are shown in Fig. 7.

With PAC the return flow in the return channel was so slow for the highest flow rates that chamber “A” was emptied at the pump inlet and consequently could not be measured, as indicated in Fig.7.

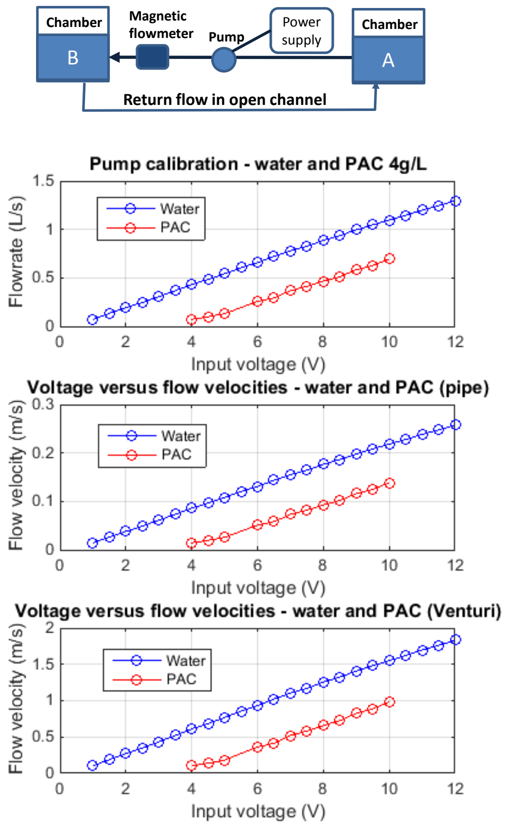

Figure 7: Pump calibration for water and PAC. Pump flow rate and velocity in the pipe and in the Venturi throat as a function of voltage.

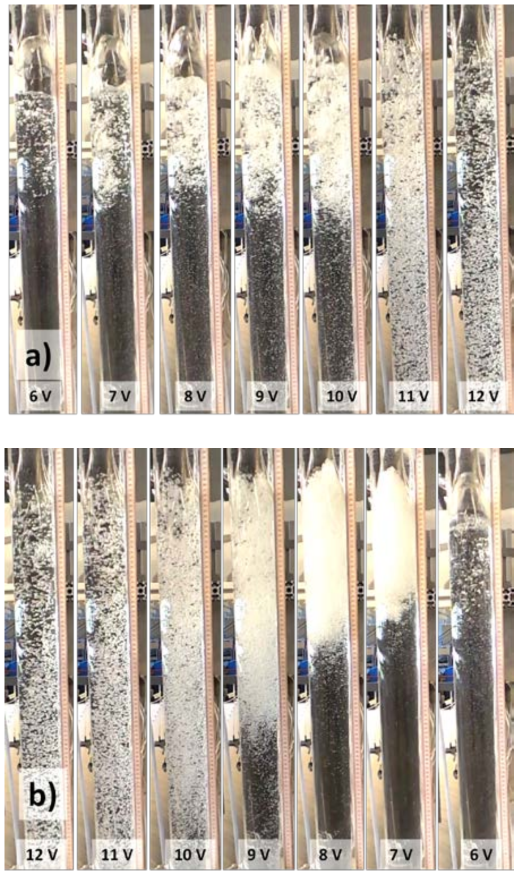

Figure 8: Bubble breakup process in water experiments for a) increasing flowrate (6-12 V) and in b) decreasing flowrate (12-6 V)

ANALYSIS

Flow experiments were carried out for water and the four polymer solutions with PAC 1-4 g/L. Water experiments are shown in Fig.8. Stable flow was established and then a large gas bubble was injected below the open control valve. When it reached the Venturi it would either escape up if the flow rate was small, or be captured below the Venturi for higher flow rates. For 6 Volt the downward flow velocity in the big pipe is around 0.12 m/s and in the Venturi throat 0.88 m/s. The upward Taylor bubble is approximately 0.3 m/s. Thus it is bigger than the flow velocity in the pipe, but less than in the Venturi throat, and it will be captured.

For voltages less than 5, the Taylor bubble reached the throat. There it became deformed, was unstable and eventually broken up. Fig.8 shows the same initial bubble for a) increasing voltage (and flowrate) and in b) for decreasing flow. There is a slight hysteresis in this up and down process. The population of small bubbles that have been established for the highest flowrates lasted for several minutes before coalescence and separation had restored the original state. Thus the hysteresis would be less if longer relaxation time had been allowed in the sequence. Also the breakup process appeared to be quite radial symmetric.

Experiments with PAC solutions

For the PAC 1g/L solution the summary of the tests are shown in Fig. 9. This series of images is organized with same flowrate (voltage) in each pair for easier comparison of hysteresis effects. The recordings were as for water.

That is, first the voltage was increased from 6 to 12 (up) and then reduced (down). This series is perhaps the most interesting in the sense that it resembles the water tests in the breakup process, but in this case the viscosity is also considerably higher. The smaller bubbles are therefore more easily transported downwards from the Taylor bubble, over to the left pipe where the gas drains out at the top. The pairs of images in figures Fig.9 shows quite clearly, that on return to the same flowrate, some air has been lost. The smaller bubbles are therefore more easily transported downwards from the Taylor bubble, over to the left pipe where the gas drains out at the top.

For PAC 3g/L a summary is shown in Fig. 10. For this high concentration of PAC the Venturi flow mainly deforms the bubble, and it becomes highly asymmetric. There is nearly no fragmentation or loss of gas.

For PAC 4g/L this deformation process continues, as seen in Fig. 11 for 7V and 9.5 V. The bubble is more distorted, eventually is deeply split, and may be cut in two as seen in Fig.12. A video of the process in Fig. 11 and 12 is very instructive and can be obtained from the authors.

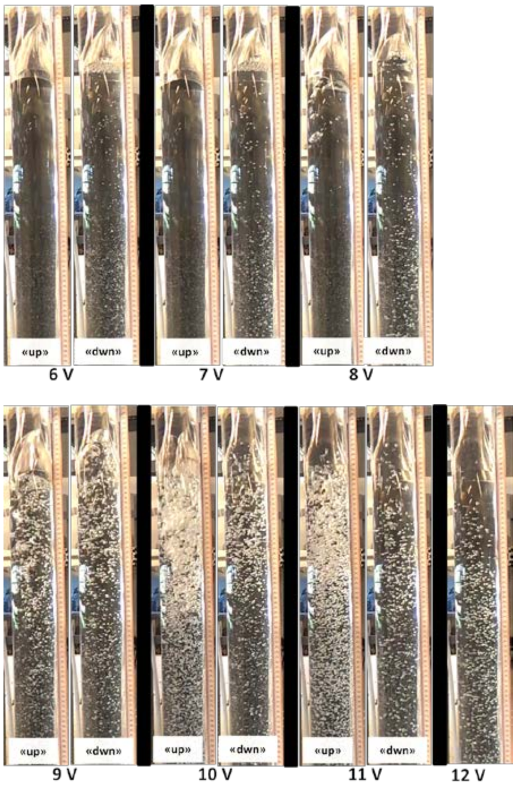

Figure 9: Breakup process for PAC 1g/L. Voltage/flowrate (6-12 V) arranged as pairs for increase (up) and decrease (dwn).

DISCUSSION AND CONCLUSIONS

There is substantial difference in the behaviour of the slug bubble in the Newtonian (water) case and in the polymer (PAC) cases. The experiments with water show some important effects.

As the flowrate increases as in Fig.8 a), the Taylor bubble seems to become gradually fragmented, with a fairly radial symmetric velocity profile around the Taylor bubble. Only a small asymmetry is seen for water. When the flowrate is decreased again there seems to be some hysteresis, since the bubble fragmentation remains. Very few of the bubbles are transported down and around to the other pipe.

For PAC 1 g/L the fragmentation process is fairly similar to only water. However in this case, the small fragmented bubbles are transported all the way down and around.

While the tests with water shows a large degree of symmetry in flow profile, bubble movement and also in the turbulent breaking of the Taylor bubble, this is not so for the non-Newtonian case. Asymmetry is apparent both in flow and bubble shape.

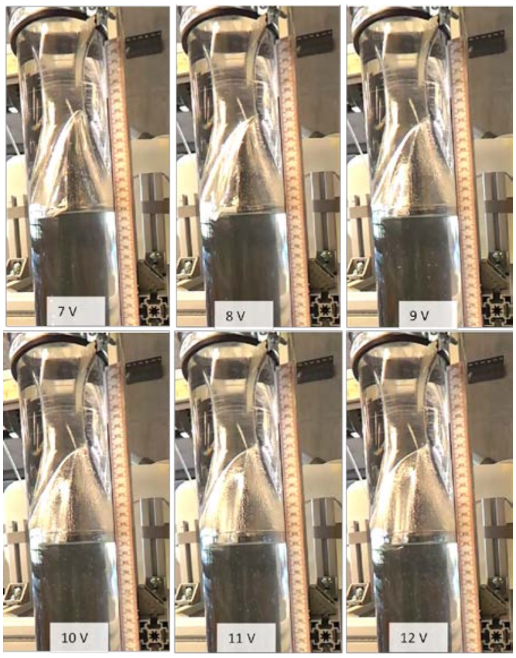

Figure 10: For PAC 3g/L the big bubble does not break but is more and more distorted for voltage/flowrate (6-12 V).

For the higher concentrations of PAC, above 1g/L, the Taylor bubble and the liquid flow interact and together break the symmetry. The liquid flow is forced to one side and the gas bubble to the opposite side. This is sketched in Fig. 13. The stresses are indicated by arrows. Another clearly observed effect is that much less fragmentation is found in these PAC experiments (PAC 2-4 g/L).

Future work

The rheology measurements revealed substantial hysteresis. This will be followed up to check if the polymer has become aerated during mixing, and to investigate long term effects.

The velocity profile in the Venturi throat seems to be influenced by the bubble. Thus there is most likely a back-coupling to the upstream flow with similarity to a previous paper[13] by the authors. This will be investigated further using PIV and flow visualisation.

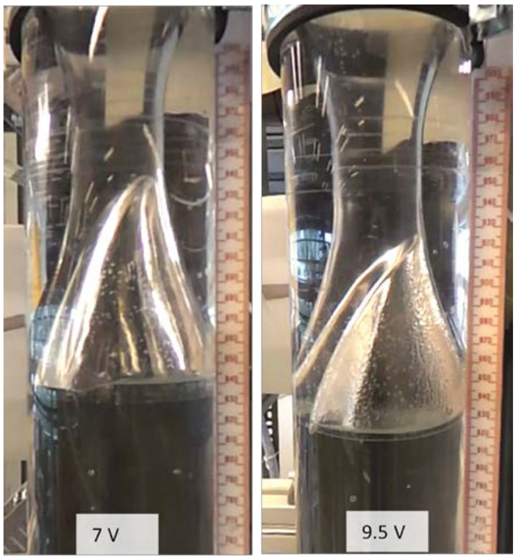

Figure 11: For PAC 4 g/L the big bubble does not break but is more and more distorted for voltage/flowrate (6-12 V).

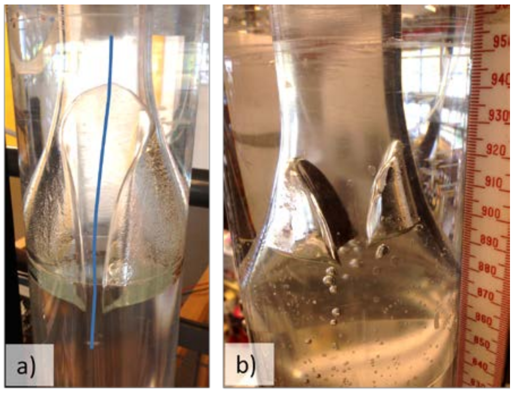

Figure 12: a) PAC 4 g/L bubble seen into the deep split at 12V pump power. The flow direction is indicated by the long arrow. The bubble may eventually be cut into two pieces b) A similar distribution often arises when air is injected from the top. It then flows down as smaller bubbles from the top and coalesce into larger bubbles in the wake.

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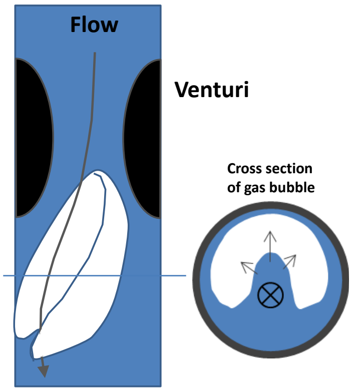

Figure 13: The bubble is shifted and deformed by the asymmetric velocity profile which "self-organizes" with the bubble

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