Splitting Mechanisms and Dynamics of Taylor Bubbles in Non-Newtonian Fluids in Annuli with Relevance to Gas-Kicks in Petroleum Wells

Rune W. Time and A.H. Rabenjafimanantsoa

University of Stavanger, Norway

ABSTRACT

In this work we describe experiments on slug flow involving Taylor bubbles rising in annuli. They are carried out with new flow rigs involving vertical annuli with different internal pipe configurations, most important being diameter ratios and axial geometry. The fluids used are water and PAC (polyanionic cellulose) in order to compare behaviour in Newtonian versus in non-Newtonian fluids. We also describe a new method to study the transition from continuous to split bubble using a gradually increasing inner pipe. High speed video is used to determine the bubble dynamics.

INTRODUCTION

Drilling of petroleum wells involves the risk of drilling into high pressure gas zones which may penetrate into the drilling fluid, causing blowouts and severe accidents. The last well known case was the accident with the Macondo well in the Gulf of Mexico in 2010. The incoming gas from the reservoir may be "disguised" when entering into the drilling mud if oil-based mud is used, while it is more easily detected if water based mud is used. At some position in the upward movement the pressure drops, so the gas will in any case re-appear as free gas and eventually create a large continuous bubble referred to as a Taylor bubble. In round pipes it has the shape of a long bullet, but in an annulus it will either fill around as shown in Fig. 1, or it will split to fill only a part of the annulus cross section, with liquid in the remaining part. Several example pictures are given later. The splitting mechanism is not fully understood, although the problem has been investigated since the 1980's. The rise velocity of the split Taylor bubble is considerably higher than for the round pipe at the same outer pipe diameter, and is also depending on the eccentricity of the inner pipe. For gas-kicks the rise velocity is crucial for the available time to carry out a controlled close down or out-circulation of the gas. Similarly, underbalanced drilling operates at lower pressure than reservoir pressure and makes the operation critical with regards to possible gas-kicks. The gas fraction in the drilling mud and thereby also the hydrostatic pressure gradient depends also on the bubble rise velocities. For gas injected together with the mud after the pump, there is a possibility of counter-current or stagnant flow of Taylor bubbles in the drill-string as seen in Fig. 2. When and if the gas fraction in the returning mud at some position up in the annulus is high enough to form Taylor bubbles the hydrostatic pressure gradient and the bottom-hole pressure, again is influenced by the bubble rise velocity

THEORY

The dynamics of Taylor bubbles in round pipe has been studied extensively[10,14].

But very little is done for annuli with non-Newtonian liquids like gas-kicks in drilling mud. Drilling fluids are nearly always designed to be non-Newtonian, shear thinning. This improves cuttings transport and at the same time gives less wall friction. Taylor bubbles were studied in non-Newtonian flow with circular pipes[2]. Pioneering work has been done on trying to model the splitting mechanism in Newtonian flows[8]. They concluded that the bubble always will split no matter how small the inner pipe is. Some concluded that even small inner pipes (filling 16% of the annulus outer radius) would split the bubble[7]. Several other have studied Taylor bubbles in annuli but again only for Newtonian fluids[1,4]. The distinction between full and split bubble is important because the dynamics in the two cases are quite different[6]. This leads to different rise velocities and thus different gas-liquid fractions. As may be seen in Fig. 1 from a paper forming the theoretical basis for a comprehensive numerical model[9], the Taylor bubble is assumed to fill the whole annulus around.

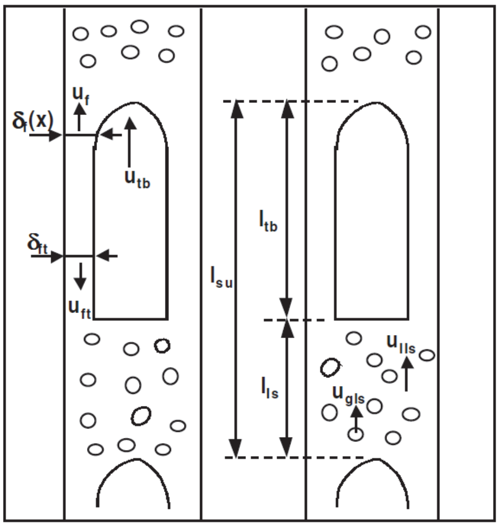


Figure 1. a) Slug flow structure of Taylor bubble in annulus. The Taylor bubble fills all around the annulus[9].

EXPERIMENTS

With reference to the existing literature it initially seemed unlikely that a Taylor bubble could rise in an annulus without splitting. However it seems unlikely that an infinitely thin inner string can cause such a splitting although similarly asymmetric Taylor bubbles exist even in circular pipes, as shown in Fig. 2.

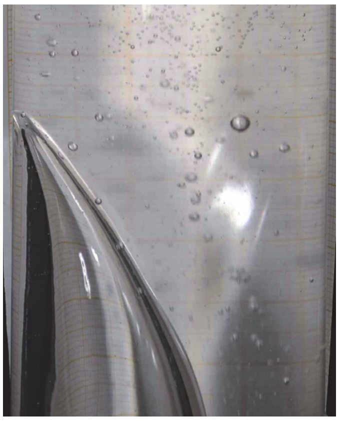


Figure 2. Precursor to a split bubble may be found even in circular pipes in counter-current flows. In this case a stagnant bubble is clinging to the wall with PAC200 flowing down.

Therefore a series of feasibility tests were carried out on different pipe geometries and inner strings. In small diameter pipes thin inner strings are used. They are susceptible to capillary forces and captured into the down-falling liquid film along the wall. For larger diameters (2 - 8 cm) the inner string is, if not clinging to the wall, at least exposed to oscillations from the Taylor bubble. Bearing in mind how easily the falling film becomes asymmetric, oscillations and mechanical properties of the inner string could be more important than considered in the existing literature.

Experimental setup

Two flows rigs have been used for this work. One is shown in Fig. 2. It is identical to the one used for a previous paper by the authors[11]. The annulus has a fixed outer diameter, while the inner pipe can be changed. In some of the experiments a telescopic inner pipe, a fish rod (brand Shimano, without rings) was used. This enabled a gradual increasing diameter with height. The purpose of such an arrangement was to study the breakup mechanism of the Taylor bubble changing from filling the annulus completely to splitting at larger inner pipe. Experiments with this setup are described in more detail later.

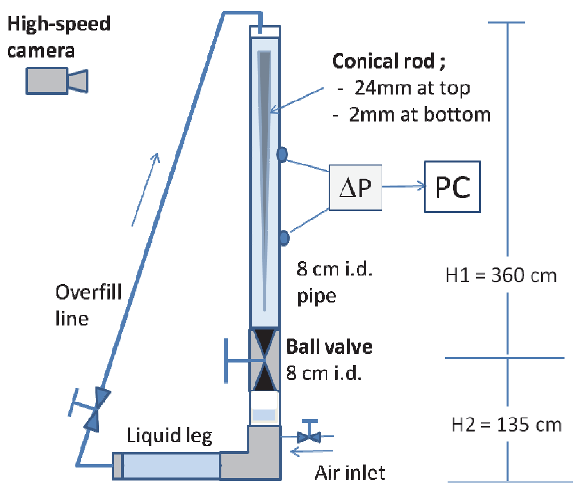


Figure 3. Experimental setup with 8 cm i.d. rise pipe and conical inner pipe. A nearly identical setup is used for constant gap annulus.

The other setup has a fixed annulus gap (1.5 cm) based on combining an 8 cm i.d. pipe with a smaller 5cm o.d. pipe used for the tests connected with Fig. 6 – Fig. 9.

<u>Fluid properties</u>

Water and two different concentrations of polyanionic cellulose (PAC) were used. These are “PAC200” with 2g dry powder per Liter of distilled water, and also “PAC 400” with 4g. The viscosity of the PAC solutions was measured using a rheometer of type Physica UDS 200 with cone plate configuration. PAC is chosen because of good optical transparency. The PAC solutions behave essentially as power-law fluids with parameters as given in Fig. 4.

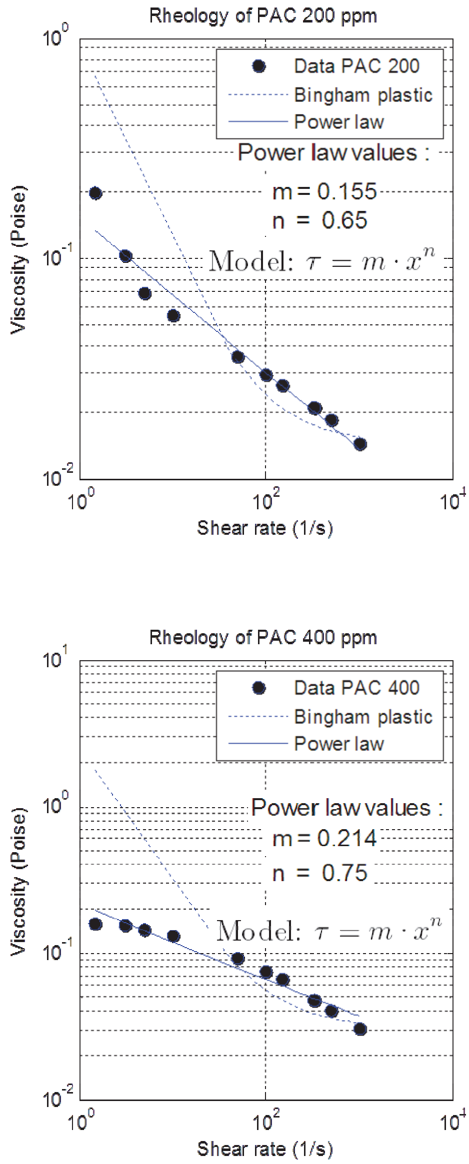


Figure 4. Rheology of PAC 200 and 400.

<u>Measurement techniques</u>

The bubble and film dynamics is determined both visually and using video. Also differential pressure is measured. This is also done in another accompanying paper[15] in these transactions. The optical quality of the liquid may change due to bubble entrainment over time, but is also exposed to biodegradation and may even start to form gel aggregates at air surfaces. This changes the interfacial tension and may perhaps influence some details of the splitting mechanism.

Instrumentation

The pressure sensors, of type Rosemount 3051C, have a range of 62mbar with time resolution 100 milliseconds. In addition a high speed camera was used (SpeedCam MiniVis e2) that records up to 2500 fps at full resolution 512x512 pixels. It can record up to 120.000 fps at reduced resolution. The camera has onboard memory for 8223 full frames at full resolution. Images are downloaded to computer via a GigaBit Ethernet cable by means of a dedicated communication program ("MotionBlitz", by Mikrotron).

Experimental procedure

Taylor bubbles were made by closing the ball valve and injecting gas under the valve while bleeding off the liquid in the pipe under the bubble, flowing it up to the top of the pipe. When the bubble had a given volume, the valve for the liquid outlet was closed and extra gas was injected to eventually pressurize the gas bubble. The experiment starts when the ball valve is suddenly opened and the Taylor bubble move up the annulus in the riser. Mainly the bubble shape, splitting or not splitting, was studied. But also the wake of the bubble, gas entrainment and gas fraction distribution axially is important for the overall slug pattern. Pressure recordings were used to determine average gas fractions in the pipe.

Time dependence in polymer experiments

When PAC was used as fluid it turned out that even though the Taylor bubbles are larger there are always avalanches of small bubbles in the wake of the bubble. Continuing the experiments with the same liquid, will at least for the PAC cases lead to accumulation of latent microscopic bubbles over time. This has several effects; such as decreasing the apparent liquid density, modifying the apparent viscosity, modifying the interfacial tension between gas and liquid, and also making the fluid more opaque.

A note on pressure measurements with polymers

An important impact of fluid ageing on pressure measurements was revealed. The pressure tap pipes were filled with the same fluid as in the pipe in order to have the same density as is the common solution if gas bubbles and particles should not enter the pressure tap pipes. After more than a week the experiments were repeated, but this time the response of the pressure sensors was reduced to around 10% of the original, and there was considerable time delay. Closer investigation showed that this was caused by gelling of the PAC inside the pressure taps. The gel took up most of the pressure variations as well as causing time delay by stress redistribution. The gel was replaced with tap water to avoid gelling. However since such measurement problem might arise also in others research it is considered worthwhile to investigate effect of gelling over time in long capillaries.

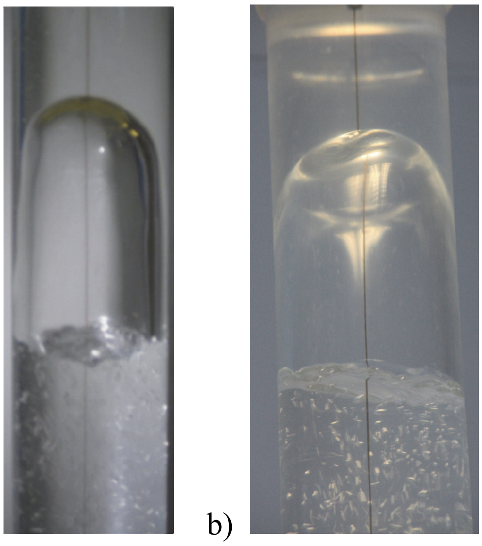
Gas entrainment in the wake

It was observed that as the Taylor bubble splits, the wake of the Taylor bubble is modified. The change of shape has been reported[5], but for only for round pipes.

The shape of the split bubble in a narrow annulus bears some similarity with a bent and wobbling "Delta wing" plane. In that analogy we observed most of the liquid oscillation and recirculation behind the "wing" tips. In this region there are irregular wakes resulting in gas entrainment into the liquid below, as may be seen in several pictures. For PAC the turbulent entrainment is less, on the other hand the Taylor bubble effectively captures bubbles following the countercurrent liquid in the down-falling film.

Feasibility tests with smaller pipes

Separate tests with six different pipes and annuli were tested ranging from 6mm i.d to 80 mm i.d. . For pipes less than 40 mm



a) b)

Figure 5. a) Taylor bubble rising in water inside an 8 cm i.d. pipe. A 0.6 mm string is stretched along the pipe axis to act as inner pipe. The bubble does not split in this case. b) Tilting or wobbling the pipe slightly does not cause splitting of the Taylor bubble, although a distinct central dip at the nose of the bubble can be seen.

i.d. the Taylor bubbles split. It was only for 80 mm pipe and a 0.6 mm inner string as in Fig. 5 that non-split bubble was observed.

<u>High speed video recordings</u>

In Fig. 7 and 8 are shown recordings with high speed camera on a split Taylor bubble just before reaching the top of stagnant water. The inner annulus is filled with coloured water (pink) for better contrast. The top level of the water is visible around 20% from the top of the image. As the bubble moves upward the liquid flows down in the split.

It accelerates as the split converges, and drags bubbles attached on the wall down with the flow. The bubble has the typical shape of a shirt collar.

The last image in Fig. 8 shows how the water interface at the top of the liquid column start to deform downwards and drain into the film.

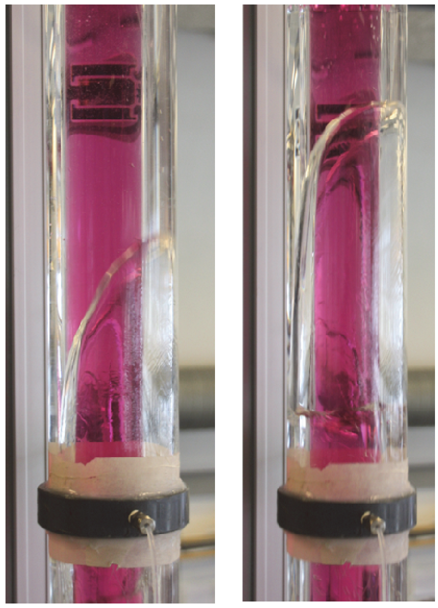


Figure 6. Sequence of a split Taylor bubble in water passing the pressure taps, seen sideways. The wake is asymmetrically deformed compared to a non-split bubble.

The film dynamics reflects another difference between PAC and water is the draining film as shown in Fig. 9. It appears that the film width in water reaches a final value faster than in PAC.

An explanation might be that the shear-thinning property of PAC causes the acceleration of the film to continue for a longer distance. Since volume flow is constant through any cross section of the film it will contract with increasing liquid speed.

<u>Experiments with telescopic inner pipe</u>

The 80mm pipe was also used in combination with a telescopic inner rod as mentioned initially.

A Shimano fish rod was used, 4 meter long, and with 19 segments with diameter ranging from 2mm to 24 mm. Also another type was tested with only 3 segments from 2mm to 20 mm over the same length, but the results are not included here.

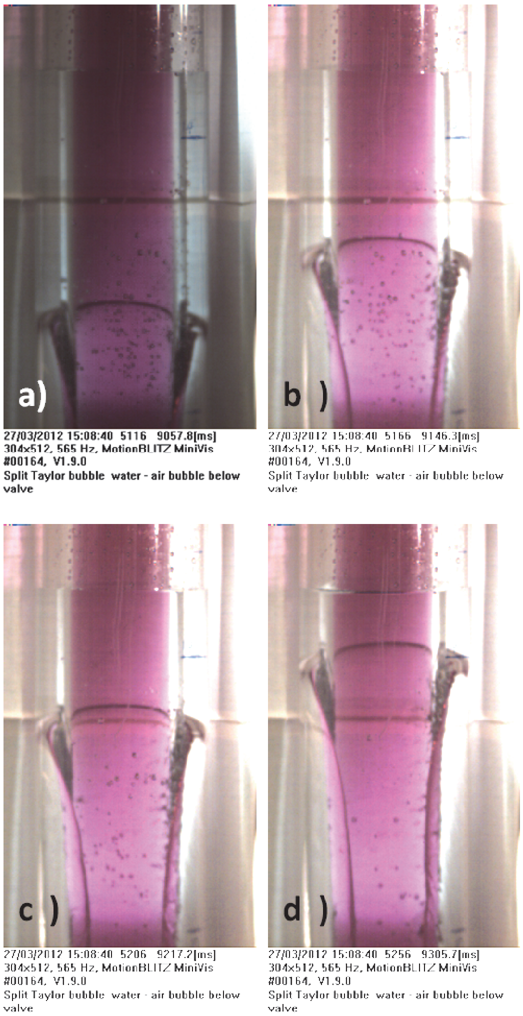


Figure 7. Sequences of bubble movement from high speed video recordings (565 frames per second) with water. The camera is directed towards the bubble split. Image a) in original color with the camera data text supplied. Images b) – d) with enhanced contrast. The vertical line in the middle of the image is from the background wall.

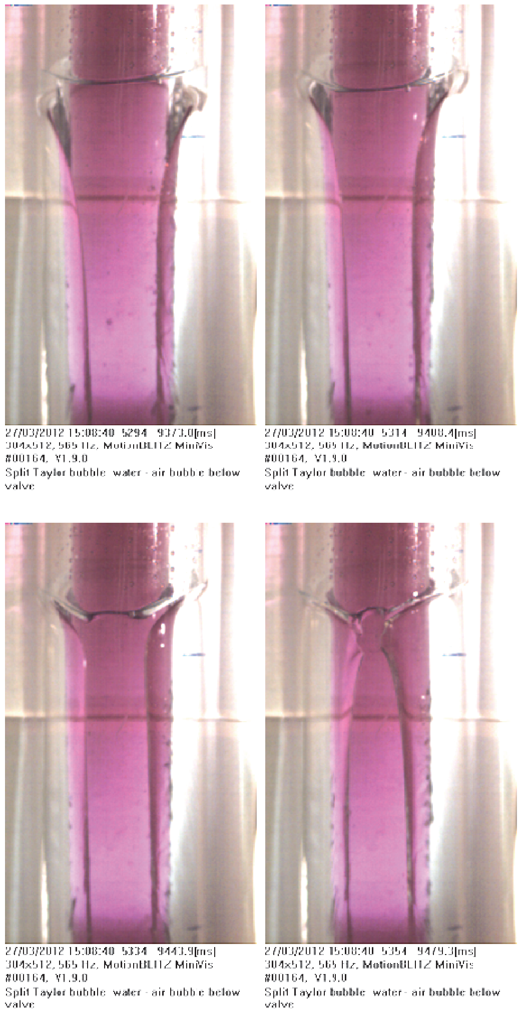
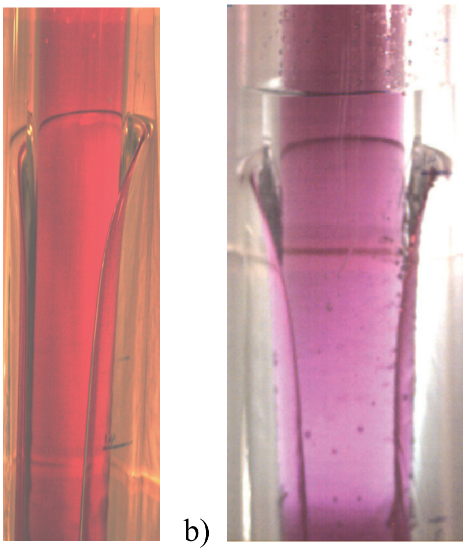


Figure 8. Later parts in the same sequence as Fig. 7. The upper water edge declines and drains down into the split and eventually until the bubble collapses. The top of the bubble breaks less than 100 ms after the last image here.

In Fig. 10 a) is shown how the bubble (in water) starts to develop a split around midway along the inner rod. But the split unexpectedly repairs in Fig. b., leaving only a wake on the film. The pairs of pictures in this event are perhaps giving the clearest illustration of the splitting mechanisms.
It is perhaps best described using a reference system following the Taylor bubble and then observe the liquid flow against and around the bubble nose. In Fig. 10 a) the liquid velocity profile has become asymmetric and the liquid flows with a dominant component from the rear side of the picture towards the camera side. The central rod acts as an obstacle, forcing the liquid to slow down, flow around it and reassemble on the lee side.



a) b)

Figure 9. Split bubble in PAC 200 shown in a) versus in water – image b). The width of the film in the split converges for a longer distance in PAC.

Flow from each side meets and reassembles on the lee into a forward flow. This slows the liquid and lifts the water film so that it clings between the rod and the outer pipe wall. In Fig. 10b) the velocity profile has become more symmetric and only a wake is left on the film, although at this section the rod is thicker. The wake waves in Fig. 10b) are similar to those observed behind a boats stern.

RESULTS AND DISCUSSION

These preliminary experiments indicate a splitting dynamics of the Taylor bubble which seem to involve several mechanisms. These involve interfacial tension, viscosity, gravity and pipe diameter.

First of all – it is established that it is possible to avoid splitting if the inner pipe is very thin. This is a moderation of the the comments that the Taylor bubble splitting will always occur in an annulus[7,8]. The presented tests show that "non-splitting" is possible both for Newtonian and non-Newtonian liquids.

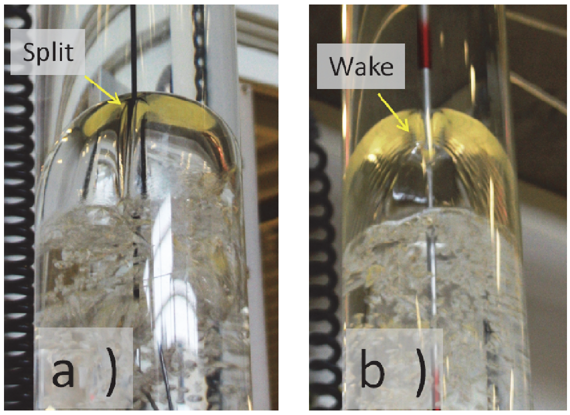


Figure 10. Sequence of the Taylor bubble in water with the 19 segment telescopic inner rod. In a) a clear split has developed. In b) one second later and higher up in the pipe only a wake remains on the downfalling film.

Differences between bubbles in pipes and annulus

It is well known for two-phase gas-liquid flow that a "completely vertical" Taylor bubble is more unstable than a slightly inclined (less than one degree). Seemingly the reason is due to coupled pressure and flow oscillations around the bubble exposed to sudden symmetry breaking. It is somewhat to a pencil held vertically resting on a table on its tip. In what direction will it fall if not held anymore. Moving away from the equilibrium is a self-amplifying process, since by Bernouilli's law an increase of velocity on one side leads to lower pressure, contraction of the annulus and splitting of the bubble. This again enhances the flow through the split and with even higher liquid velocity.

Fundamental mechanisms

Several mechanisms have been proposed as basic physical driving forces for splitting the Taylor bubble. Two of these are "minimum bubble area", and maximum slip velocity. The latter has never been proved, and can easily be shown to be invalid. Considering small bubbles - less than a millimetre - the rise velocity is proportional to the square of the diameter (in the "Stokes regime"). However, exceeding a diameter of one millimetre the bubble changes its shape, becomes elliptic irregular and has a rise velocity nearly independent of size, in fact it might drop a little. This continues up to the cm scale, when a spherical cap regime is reached; the precursor of the Taylor bubble. So, the rise velocity is not a *determining factor*. The alternative hypothesis; minimum surface area is somewhat different. This principle is well known in steady state thermodynamics.

However, fluid mechanics is dissipative thermodynamics and the fluid shear stress is intimately connected to the bubble dynamics.

<u>Instabilities due to initial oscillatory motion associated with a gas kick</u>

When the bubble is released from an overpressure as in a gas-kick, it will expand at the same time as it accelerates the overlying liquid. The mechanism is similar to a one-dimensional spring loaded with a mass M and released from a position away from equilibrium. In the fluid case the mass is reduced in a time dependent process, M(t). A special oscillation occurs which will also impose extra shear stress and velocity variations on the bubble. This may contribute to additional surface instabilities and enhance the bubble splitting.

In Fig. 10 is shown the position of the top liquid interface which is directly connected to the volume of the Taylor bubble. A small Matlab program was written to analyse series of images as in Fig. s 7 and 8 to detect the interface position along a given vertical line. It is a very simple one-parameter algorithm which tracks the dark interface. The simplicity naturally leads to some noise in level detection compared to if "human vision assistance" is involved. However analysing more than 2000 images is not feasible for human interpretation, while the program does the work in less than a minute.

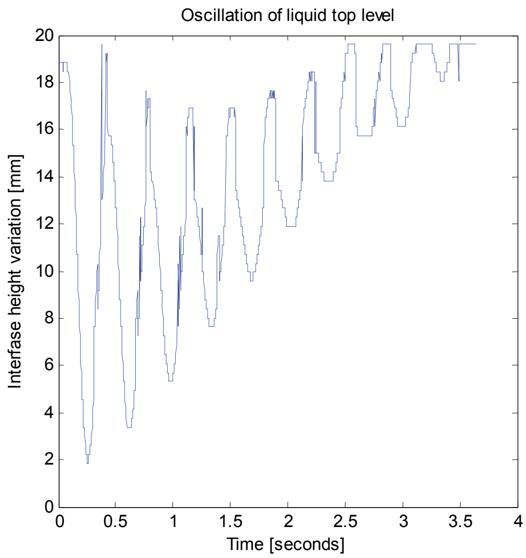


Figure 10. Oscillations and expansion of the bubble when released in a model gas-kick.

The figure shows that the interface initially drops when the bubble is released. This is due to the way the bubble is arranged in the present setup. It is initially kept under a closed ball valve, while draining out liquid to accommodate the bubble. The liquid is pumped up to the top of the vertical pipe. When the valve is suddenly opened the bubble is exposed to the overlying fluid, which is giving an extra 400 mbar bottom pressure due to the 4 m high liquid column. So it is initially compressed, then it decompresses. The oscillations are therefore inverse (up-down) of what is taking place in a real gas-kick, but otherwise the same.

Oscillation patterns as shown in fig. 10 could possibly also be used also to deduce the bubble velocity by the following argument: The increase of the liquid level is directly connected to the expanding bubble volume. The volume is again a function of the pressure via the equation of state, and the pressure is given by the depth in the liquid. Consequently the depth versus time can be deduced from the plot, and thereby the speed.

A possible Rayleigh Taylor instability

The study has also lead to a speculation on whether the splitting mechanism could be investigated using other geometries. For the limiting case that the annulus gap is very small one analogous setup would be flow between two parallel planes. In the case that the experiments start with an initial condition where a long bubble is placed at rest at the bottom of a vertically placed plane, the bubble will become unstable and fingering starts. This has been reported[13] and could be studied in a Hele-Shaw cell.

A possibly quite important difference may be that the annulus constitutes a simpel connected space, while the two-plate geometry is cannot be "simple connected", even if a pipe is used to convey pressure and some flow.

Effect of non-Newtonian liquid

In this work both Newtonian and non-Newtonian liquids have been used. The main differences seem to be on the viscous phenomena, while the fundamental impact of non-symmetry, gravity instability and interfacial instability are basically the same. Observations seem to indicate that PAC has a certain stabilizing effect on interfacial waves on the nose of the Taylor bubble and thus seem to delay the splitting a little.

However a counter effect is the shear thinning property which amplifies unstable velocity fields by reducing the apparent viscosity when the local velocity increases and the splitting sets in. This seems to be the dominating effect found in this work.

Remaining issues

It seems plausible from this work and others that the splitting of the Taylor bubble is connected to instabilities of the interface which is amplified by an asymmetry in the velocity and pressure fields. However, it was seen as in Fig. 10 that the split could disappear. So it remains to investigate the behaviour of a very long bubble, several meters. So far we have only found a few published works in the literature[14], which essentially summarizes works on Taylor bubbles in general. Other questions relate to rotating inner pipe (drill string), in which case it seems plausible to assume that a split bubble will set up a spiralling wrapping around the inner pipe. Yet another effect is behaviour of sideways movement of the inner string, a case which is to be followed up in future work.

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