Correlations between velocity and size of bubbles trapped by gas-sheared liquid film

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Keywords: bubble size and velocity, sheared gas-liquid flows, Laser Induced Fluorescence

ABSTRACT
At high enough gas and liquid flow rates, the surface of gas-sheared liquid films are covered by a complex system of waves of different scales. Disruption of ripples on top of disturbance waves by a strong gas shear leads to creation of droplets that entrained into the core of gas stream. In addition, gas may be entrapped by film surface in form of bubbles of various sizes. In this work, the study of gas-sheared liquid film was performed in horizontal rectangular duct using high-speed brightness-based LIF technique. This technique directly measures the thickness of the liquid layer to a resolution of 0.040 mm over a 50mm by 20 mm area simultaneously at speeds of 10 kHz using a high speed camera and pulsed laser set up. Nine experiments were carried out at three liquid Reynolds numbers and three gas Reynolds numbers. In previous work it was demonstrated that the droplet impact entrained gas in the base film and that the number of the bubbles was relate to the flow conditions. In this work the speed of the bubbles is compared to the local film height and the bubble sizes to investigate how these affect the speed of the bubbles. It is shown that the bubble act as traces and so velocity ranges can be determined that change as the film thickness changes.

1. Introduction
The entrainment of gas into a liquid in sheared flow, such as annular flow in pipes, is of interest to a range of industrial areas. The entrainment of the gas can strongly influence flow characteristics, enhance chemical reactions and influence heat transfer. The droplets are created by the disruption of ripples on top of the disturbance waves by a strong gas shear (Woodmansee and Hanratty, 1969, Alghoul et al., 2011a). These droplets impact on the surface of the liquid and can generate bubbles. It has also been suggested (Rodríguez and Shedd, 2004) that a second mechanism of gas entrainment occurred by the breaking of the disturbance waves similar to the action of bubble entrainment in the ocean. Breaking surface waves in the ocean generate bubbles over a range of sizes. The sizes and number of the bubbles are dependent on the turbulent
fragmentation. Larger bubbles are less probable because of fragmentation due to turbulent shear stress (Deane and Stokes, 2002). Below a critical bubble Webber number of around 3-4.7, which is related to the Hinze scale of the turbulence, the bubbles are more likely not to be sheared and are sustained by surface tension effects. (Rodríguez and Shedd, 2004) also suggested that there is a limit to bubble density and this was confirmed by (Hann et al., 2015).

This study is a continuation of work previously presented into the droplet impact, generation of bubbles and final bubble size distribution (Hann et al., 2015, Cherdantsev et al., 2015). Previous work using this technique determined that addition to the breaking mechanism, significantly more bubbles were produced by the impact of fast droplets at low impact angles (Cherdantsev et al., 2015). It has been identified that furrow impacts most often occur on the base film and these impacts can generate up to 50 bubbles in a single impact. Figure 1 shows an example of the height of the film before and after a furrow impact. In (Hann et al., 2015), the bubble size distribution and relation to the local film height was discussed. In this paper the data is reanalyzed to obtain the velocity of the bubbles and this is compared to the local height of the film and the bubble size.

**Figure 1:** The top image shows the film heights in the moments before the impact of a droplet. The bottom image shows the stream of bubbles generated by the impact of the droplet 3 ms later.
2. Methodology

The experimental analysis and procedure are similar to those used by (Alghoul et al., 2011b) and (Cherdantsev et al., 2014). In this experiment the Brightness-Based Laser Induced Fluorescence technique was used to measure the thickness of the film. The camera was located below the system and the laser shone through the base film to measure the local height. Here, a smaller region was studied to obtain more detail (51 mm longitudinally and 20 mm transversely). Thus, spatial resolution was improved to 40 µm per pixel, enabling us to resolve much smaller bubbles and droplets. Flow rates corresponding to gas superficial velocities of 25, 30 and 35 m/s and liquid Reynolds numbers of 220, 360 and 520 were selected for the study as there was more drop deposition activity. In this the Reynolds number was defined as the volumetric liquid flow rate per unit width of the duct divided by the kinematic viscosity of liquid. For each combination of flow rates three records with duration of 0.2 s each were obtained.

Figure 2: Schematic showing the configuration of the shearing rig and associated measurement system.

An example of the type of images that BBLIF is capable of is shown in Figure 1. These images have been converted from intensity values using the procedure outlined in (Cherdantsev et al., 2014) so that the intensity value is the height of the film. The two selected close-up regions in Figure 1 show ripples on the surface that have a droplet impact crater and secondary droplets formed due to the impact of a larger droplet impacting on the film. The bottom image shows that there are a number of bubbles generated by the impact of the drop. The use of the BBLIF technique makes these bubbles easier to identify and discriminate from droplets compared to
standard imaging techniques, due to their darker interior (due to less liquid present) and bright ring.

The following procedure is used to identify the bubbles:

- The image was segmented into low and high frequency component using the median of the image taken over a 50x50 square. This estimated the mean film height as the median and identified the high frequency components associated with the bubbles, droplets and other features and the difference between the original and the median image.

- The high frequency image of the bubble contained a depression surrounded by a brighter ring as shown in Figure 3. Unfortunately this is only true for bubbles larger than 2x spatial resolution (about 80\(\mu\)m), so smaller bubbles are ignored in this analysis. The images were quantized to limit the effect of noise and then a watershed analysis was used to detect the depressions associated with bubbles. For each of these watershed regions, the equivalent diameter and centroid was recorded.

- Regions with large eccentricity or over a certain size were filtered out as being associated with the space between bubbles or optical distortions.

- The velocity of the droplets was measured using a particle tracker algorithm that used the centroid of the identified bubbles. This used the Hungarian linker and the munkres function to identify if a bubble pair exists in adjacent frames. A size discriminator was also implemented to ensure only a bubble of comparative size was matched between image pairs. If no pair existed, in adjacent frames, then the bubble was marked as false and was not counted as a true bubble.

This final step was used as a final filter to ensure only real bubbles were counted. Only features existing in adjacent frames were counted in the final analysis. Therefore the outcome of this analysis were that for each frame we recorded the centroid of all valid bubbles, the local height of the film at each location of a valid bubble, and the velocity of each valid bubble. As can be seen from Figure 3 this clearly identified most of the bubbles larger than 2 pixels in size. Obviously it undercounted the smallest bubbles, so these are ignored in the further analysis. It should be noted that the number of smaller bubbles increases with gas velocity and liquid Reynolds number.
Figure 3: Example of the stages of the analysis algorithm: (a) small segment of larger image with identified bubbles present. (b) high pass median filter of the data (50x50) (c) quantized image to minimize over-segmentation in the watershed (d) low pass median filtered data showing variation of the base film.

3. Results

The distribution of the magnitude of the velocity of each verified bubbles, for all 9 cases that were studied, can be seen in Figure 4. It is expected that the velocity of the bubbles will correlate with the velocity of the fluid, so the height of the bubble in the fluid column is expected to affect the velocity. Some bubbles will be trapped in the slower moving base film while others will be travelling inside the faster moving disturbance wave leading to the bimodal distributions, especially at higher air velocities. Since the frequency and speed of disturbance waves will increase with increasing $Re_L$ and $Re_G$, the shift in the location of the faster peak can be associated with this effect.

Figure 4: The distribution of velocities of the bubbles changes as the $Re_L$ and $Re_G$ increases.
Increasing number of disturbance waves strengthens the higher velocity peak.

The bimodal nature of the velocity of the bubbles can be seen more clearly in a slice plot of the change in the velocity distribution with time (Figure 5). The times of the faster bubbles correlate clearly with the times of the passing of the disturbance waves.

**Figure 5:** This shows that the velocity distribution changes at key points during the time of capture. These correspond to the presence of disturbance waves. The sharp discontinuities are due to this being three 0.2 s segments stitched together. This is for \( Re_G = 94674 \) and \( Re_L = 520 \).

**Figure 6:** The bubble velocity distributions at times \( t_1 \) and \( t_2 \) corresponding to the location of a
disturbance wave and base film respectively. Flow parameters are $Re_g = 94674$ and $Re_L = 520$.

The noise level in individual distributions is quite high, so to understand the effect that the disturbance wave has on the bubble size and velocity distributions, a POD filter was used to identify the strongest modes making 95% of the energy and the distributions were reconstructed only using these modes. The results of the specific POD filtered velocity distribution at times $t_1$ and $t_2$, corresponding to the disturbance wave and the base film respectively as indicated in Figure 5, are shown in Figure 6. This demonstrates the major difference between the velocity of the base film and the velocities in the disturbance wave. Bubbles in the base film are only moving at around 0.5 m/s, while bubbles in the disturbance wave are moving at around 1.5 m/s. This relates to a gas velocity of 35 m/s.

**Comparison of bubble diameter, velocity and film height**

![Acceleration of bubble on crest](image1)

![Deceleration of bubble in trough](image2)

**Figure 7**: x-t diagram showing the acceleration and deceleration of a bubble as the local film height varies.

In the previous work it was noted in passing that the tracks of bubbles accelerated and decelerated depending on the local film height. An example of this can be seen in Figure 7, where the gradient of the bright streak in this x-t plot increases and decreases in relation to the thickness of the local film present.

The measurement analysis provides three salient parameters; bubble size, velocity, and the local height of the film around the bubble. These will be compared in this section to investigate this behavior in more detail. To determine if the bubble velocity is related to the bubble diameter, the probability of particular size/velocity pairs are plotted for the data in Figure 8.
**Figure 8:** The probability of particular bubble size/velocity pairings. The construction line is \( v_{\text{mean}} \). It can be observed that there is a minimum velocity for larger bubbles. Probability is presented as a logarithm to emphasis lower probabilities.

This figure demonstrates several features. Firstly small bubbles can travel at any velocities. Secondly, as bubbles get larger, their minimum velocity increases non-linearly. It can be seen that the largest bubbles are travelling at around the modal velocity of the velocity distribution. Since these bubbles are most probably contained within the fluid of the disturbance wave, their velocity will be a mean velocity of the fluid rather than a peak velocity. What is also clear is that
larger diameter bubbles occur in all nine cases, but the number of them is significantly more as the liquid quantity and gas velocity increase.

**Figure 9**: The probability of bubble velocity to local film thickness pairings. Construction lines are the mean film thickness and \(v_{\text{mean}}\). Colour shows the log (probability) to emphasize the lower probabilities.

Figure 9 demonstrates the relationship between the bubble velocity and film thickness. The construction lines are the mean film thickness and the mean velocity of the film. Since the bubbles act as tracers, particularly the small ones, this gives an indication of the velocity of the film through the depth. As \(Re_L\) increases, the bubble velocity range in the disturbance wave
does not vary by significant amount. As $Re_G$ increases, the bubble velocity range in the disturbance range increases. Increasing $Re_G$, increases the volume of fluid present in the system, which increases the maximum film thickness and hence the number of bubbles at higher velocity in the disturbance waves.

The bubbles act as tracers, so the velocity measurements give an indication of the film velocity profile through the film. The upper level of the distributions should therefore represent the Universal Velocity Profile based on the law of the wall of the film such as that measured by (Ashwood et al., 2015).

$$u^+ = \begin{cases} 
    y^+ & \text{for } 0 < y^+ < 5 \\
    7.2 \ln(y^+) - 6.6 & \text{for } 5 < y^+ < 30 \\
    7.38 \ln(y^+) - 7.1 & \text{for } 30 < y^+ 
\end{cases}$$

For the base film where the film is thinnest, the upper level of the distribution is linear as would be expected for a laminar boundary layer. The bubbles will take slower velocities in this flow if they are imbedded in the boundary layer. There is also a minimum velocity which is dependent on the bubble size (compare to Figure 8). As the local film thickness increases the bubbles will move into the turbulent region and so demonstrate a logarithmic relationship. Increasing the gas velocity increases the slope in the laminar layer since the wall shear stress increases. Increasing the Reynolds number of the liquid increases the volume of fluid present and hence the film thickness, so the wall shear stress also decreases. Identification of the wall shear stress might allow the normalization of these distributions and it could be that they would be similar when presented in law of the wall units.

4 Conclusion

In this paper, a gas sheared flow has been investigated using the BBLIF technique. The technique makes the identification of bubbles easier than visualization. The velocity of the identified bubbles is calculated using a Hungarian linker technique. Analysis of the velocity shows that large bubbles are convected in the disturbance waves, while smaller bubbles congregate in both the base film between the disturbance waves, and in the disturbance waves. It is shown that the velocity of the bubbles is consistent with them being trapped in the boundary layer flow, with a minimum velocity that is dependent on the bubble size (and hence how close they can get to the wall).
Acknowledgements. The work was supported by the UK EPSRC Program Grant MEMPHIS (EP/K003976/1) and a joint project of Royal Society and Russian Foundation for Basic Research (15-58-10059-KO_a).

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