Formation and evolution of disturbance waves in annular flow

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ABSTRACT

Investigation of the initial stage of annular gas-liquid flow is performed in a number of configurations, including upward and downward flow in circular pipes and in a rectangular duct. In all cases the inlet was organised as a tangential slot. Field measurements of local film thickness are performed using brightness-based laser-induced fluorescence technique. Measurements were resolved along both longitudinal and transverse coordinates and in time with high spatial and temporal resolution. It was shown that the disturbance waves are created in the very vicinity of the inlet via coalescence of initial high-frequency waves appearing due to Kelvin-Helmholtz instability. These waves are strictly two-dimensional and highly regular but they are promptly broken into small three-dimensional horseshoe-shaped waves. The length over which the initial waves are coherent decreases with superficial gas velocity. Further downstream the 3D waves undergo multiple coalescence forming large-scale quasi two-dimensional disturbance waves, able to generate fast and slow ripples on their rear slopes. Thus, degree of two-dimensionality, characterised by cross-correlation between the film thickness records in different longitudinal sections of the duct, strongly decreases in the beginning and then gradually recovers. Once formed, the disturbance waves are accelerated by the gas shear with constant acceleration in time. Further downstream, acceleration decreases. The latter is supposed to occur due to entrainment of liquid from tops of disturbance waves, resulting in losing amplitude and, hence, velocity by the disturbance waves. Direct comparison between the underpredicted velocity and rate of entrainment was performed, confirming the above hypothesis. Acceleration and velocities were compared for different flow configurations and analysis of influence of flow orientation and size and shape of the duct was performed. It was shown that for large enough gas velocities the effect of flow orientation and pipe diameter was small, but the corners of the rectangular duct slow down the formation and development of the disturbance waves.

1. Introduction

In annular flow liquid film flows on the inner wall of the pipe sheared by high velocity gas stream flowing in the center of the pipe. In such a flow large-scale disturbance waves are formed on film surface. The disturbance waves are important since they carry the major fraction of liquid (e.g., Han et al. 2006); increase pressure drop in the channel (e.g., Schubring et al. 2010); are necessary for entrainment of liquid (e.g., Hewitt & Hall Taylor 1970); enhance heat transfer
and initiate nucleate boiling in heated pipes (Barbosa et al. 2002). On these reasons, the disturbance waves are being studied intensively for over 50 years. Recent experimental investigations with high spatial resolution techniques showed that the disturbance waves are much more complex than waves travelling on falling films. Hewitt et al. (1990) noticed that the disturbance waves resemble shallow plateaus covered with high-amplitude ripple waves. Such appearance is also distinguished in a number of modern experimental data (Alekseenko et al. 2008, Schubring et al. 2010, Farias et al. 2012, Zadrazil et al. 2014). Ripples covering the surface of the disturbance waves, are generated at the rear slopes of disturbance waves and move faster than the parent disturbance wave (Alekseenko et al. 2008). Disruption of such ripples is the main mechanism of liquid entrainment from film surface into the core of gas stream (Woodmansee & Hanratty 1969, Azzopardi 1983, Cherdantsev et al. 2014, Pham et al. 2014).

New experimental information on structure of disturbance waves indicates that new understanding of disturbance waves is required to create new models which would be able to adequately describe and predict disturbance waves. A promising way to better understand the nature of the disturbance waves is to study the process of their formation. In early literature, two hypotheses were proposed explaining how the disturbance waves are created. Hanratty & Hershman (1961) and later Andreussi et al. (1985) supposed that the disturbance waves are created due to instability of film surface to long-wave perturbations. Martin & Azzopardi (1985) supposed that the disturbance waves appear due to turbulent bursts in the liquid phase. Experiments by local conductivity probes (Zhao et al. 2013) showed that near the inlet, before the disturbance waves appear, the film surface is covered by high-frequency small-amplitude waves. In recent paper of our group, Alekseenko et al. (2015), longitudinal film thickness profile near the inlet of 15 mm i.d. pipe was obtained using laser-induced fluorescence technique. It was found that disturbance waves are formed due to multiple coalescence of initial high-frequency waves that appear due to Kelvin-Helmholtz instability. This does not contradict to the idea of Hanratty & Hershman (1961), since instability to long perturbations (or, putting it the other way, stability of the long-wave perturbations) is necessary for existence of disturbance waves. Nonetheless, multiple coalescence of short waves is an efficient way to produce a large-scale perturbation of finite amplitude much faster than it would be created from growth of infinitely small long-wave perturbation. As for the turbulent bursts, it is really difficult to detect and measure them without being able to obtain instantaneous velocity fields inside the film with very good spatial resolution. Application of such methods to gas-sheared liquid films is only beginning (Zadrazil & Markides 2014). Anyway, the experimentally observed mechanism of disturbance waves formation did not require the existence of turbulent bursts.
The process of disturbance waves formation is also clearly distinguishable when downstream evolution of temporal spectrum of the signal is studied: amplitude of high-frequency peak corresponding to initial waves decreases simultaneously with growing of low-frequency peak corresponding to disturbance waves. Unexpectedly, frequency of initial peak was found to depend non-monotonically on gas velocity. This discrepancy is one of the reasons why the additional investigation of disturbance waves formation in full three-dimensional problem statement was required. Average velocity of disturbance waves was found to grow linearly with downstream distance over first 100 mm; nonetheless, further evolution of waves velocity remained unclear. Other authors report on velocity stabilisation (Azzopardi 1997) and even on local decrease of velocity in between acceleration and stabilisation stages (Wolf et al. 2001). The latter authors proposed that the acceleration occurs because of acceleration of the gas caused by static pressure gradient along the pipe and that deceleration occurs due to entrainment of liquid from film surface causing thinning of the film and hence slowing the disturbance waves down. Final stabilisation of velocity was believed to occur due to balance between accelerating and decelerating factors. The present work is expansion of the previous one in several aspects. First, it is aimed to find out how the process of formation of disturbance waves looks like in three-dimensional perspective. Second, downstream behaviour of waves velocity was investigated. Third, the relation between the waves evolution and integral flow parameters was studied.

2. Experiments

To study the effects of duct’s shape, length and size, several experiments were performed in different working sections. Besides the 15 mm pipe used in the previous experiments, another pipe with i.d. of 11.7 mm and a rectangular duct with cross-section 50*5 mm were used. The latter duct was used for 3D-experiments, which means the film thickness data were resolved over both longitudinal and transverse coordinates. Such configuration provides better optical access to the whole wetted width of the duct; besides, it gives opportunity to check if there is any effect of the duct’s curvature and corners. In all channels liquid film is formed by 0.5 mm tangential slot between the walls and a thin stainless steel plate. The experiments were performed with brightness-based laser-induced fluorescence technique (see, e.g., Alekseenko et al. 2012, 2015), which allowed us to obtain instantaneous distributions of local film thickness over either a section of a pipe or a rectangular area of a duct’s surface.
Example of the area of interrogation and layout of the measurement system relative to the rectangular duct is shown in Fig. 1.

![Diagram of the rectangular duct inlet and the area of interrogation.](image)

**Fig. 1** Scheme of the rectangular duct inlet and the area of interrogation.

Getting such distributions with high sampling frequencies enables us to study complete spatiotemporal evolution of individual waves on film surface and interaction of such waves. Besides, the shear stress and entrainment rate were measured for the two pipes. The former was measured with differential manometer through pressure taps flush-mounted into the pipe wall at different distances below the inlet; the latter was measured as difference in mass flow rate through two sampling probes bent towards the flow and located at different distances.

The details on the areas of interrogation in different channels are given in Table 1. In majority of the cases the downward flow was studied; upward flow was organised in 11.7 mm pipe.

**Table 1.** Summary of experiments in three ducts.

<table>
<thead>
<tr>
<th>Parameter \ duct</th>
<th>Pipe 15 mm</th>
<th>Pipe 11.7 mm</th>
<th>Rectangular duct</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>3-103 mm</td>
<td>500-620 mm</td>
<td>0-450 mm</td>
</tr>
<tr>
<td>Distance</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pressure drop</td>
<td>60-800 mm</td>
<td>400 &amp; 500 mm</td>
<td>None</td>
</tr>
<tr>
<td>Entrained fraction</td>
<td>120-800 mm</td>
<td>400 &amp; 500 mm</td>
<td>None</td>
</tr>
<tr>
<td>Dimensions of RoI</td>
<td>2D</td>
<td>2D, 3D</td>
<td>3D</td>
</tr>
<tr>
<td>Sampling frequency</td>
<td>10 kHz</td>
<td>10 kHz</td>
<td>1 kHz, 5 kHz</td>
</tr>
<tr>
<td>Spatial resolution</td>
<td>0.2 mm</td>
<td>0.45 mm</td>
<td>0.2 mm</td>
</tr>
<tr>
<td>Gas velocity range</td>
<td>15-57 m/s</td>
<td>27-58 m/s</td>
<td>18-100 m/s</td>
</tr>
<tr>
<td>Re liquid</td>
<td>140-400</td>
<td>140-350</td>
<td>140-400</td>
</tr>
<tr>
<td>Flow orientation</td>
<td>Downward</td>
<td>Downward, upward</td>
<td>Downward</td>
</tr>
</tbody>
</table>
3. Creation of disturbance waves in 3D space

Experiments in the rectangular duct were performed in order to understand how the process of coalescence of initial waves leading to formation of disturbance waves looks like in 3D-space. Fig. 2 shows comparison of x-t evolution in the 15 mm pipe (a) and two instantaneous frames in x-y representation of the data obtained with 5 ms interval in the rectangular duct, (b) and (c). In such images brightness is directly proportional to the local film thickness with white colour corresponding to film thickness of 1 mm.

![Image](image_url)

Fig. 2 (a) Spatiotemporal evolution of film thickness near the inlet in 15 mm pipe. $V_t = 22$ m/s. $Re_t = 220$ (reproduced from Alekseenko et al. 2015). (b, c) Instantaneous three-dimensional film thickness profiles. $Re_t = 220$, $V_t = 26$ m/s.

This figure shows that the process of initial evolution of film surface in annular flow is even more complex than it was described in 2D approach by Alekseenko et al. (2015). The initial Kelvin-Helmholtz waves are typically two-dimensional and very regular, with transverse size equal to that of the whole channel. They exist in such form for some distance, which decreases with increasing gas velocity. Eventually, each two-dimensional wave is disrupted by the gas flow...
into a number of localized solitary three-dimensional waves. The higher the gas velocity is, the larger is the number of 3D waves. For very large gas velocities, the 2D waves are broken immediately at the very inlet. This explains why the frequency of initial waves shows local drop when it reaches high gas velocities: in such a case the first peak in spectrum corresponds to 3D waves which are characterised by lower temporal frequencies. At larger gas velocities, break-up of each 2D wave is accompanied by a burst of entrainment.

After the disruption of the 2D waves, the 3D waves coalesce in large numbers to form the disturbance waves. It looks like coalescence of a couple of adjacent 3D waves provokes an avalanche of further coalescence, absorbing more and more 3D waves into the disturbance wave. Thus, the transverse size of disturbance waves at the stages of development grows and reaches the width of the duct by the end of RoI. Probably, it is so only because of the narrow width of the duct; according to experiments by Cherdantsev et al. (2014) in 161 mm width duct, there is a large fraction of localised disturbance waves at much larger distances from the inlet.

For quantitative characterisation of how the two-dimensionality of the waves increases downstream, five longitudinal sections of RoI were selected with step of 8 mm between them. Each section represents a matrix of film thickness values, \( h(y, x, t) \), where \( y \) is the section’s \( y \) coordinate. Then, for each pair of sections, for each longitudinal coordinate \( x \), two temporal records of film thickness were cross-correlated after subtraction of the mean film thickness. Similar approach was applied by Zhao et al. (2013) to film records obtained by conductance probes with different circumferential coordinates. Maximum value of cross-correlation function (CCF) was found within a small window of 20 ms. The normalized maximum value of CCF plotted vs \( x \) coordinate for three pairs of longitudinal sections is shown in Fig. 3.

It can be seen from Fig. 3(a) that the cross-correlation reaches very high values during the first several millimetres; then it decreases to minimal values observed at about 40-80 mm from the inlet. These two stages correspond to development of 2D waves and break-up into a number of 3D waves which are not correlated between each other. After this, the correlation grows with downstream distance indicating the development and transverse spreading of disturbance waves. Quite obviously, the cross-correlation is higher for the sections which are close to each other: there is nearly no cross-correlation between the two sections closest to the edges in Fig. 2(a). For higher gas and liquid flow rates (Fig. 3b) there is nearly no initial 2D waves (thus, nearly no peak in cross-correlation at the inlet), whilst the disturbance waves (and, hence, maximum cross-correlation) start to grow earlier.
Figure 3 Downstream evolution of maximum cross-correlation between pairs of longitudinal sections. (a) $Re = 220$, $V_g = 26$ m/s; (b) $Re = 400$, $V_g = 43$ m/s.

4. Downstream development of disturbance waves.

The dependency of average velocity of the waves on the downstream coordinate was found to be approximately linear within the range of distances of 40-100 mm below the inlet (Alekseenko et al. 2015). Nonetheless, it was supposed that this is actually square root dependence, whose nonlinearity is undistinguishable at the initial stage. This means that the acceleration of individual waves in time is constant and defined by the shear stress. To check this, the measurements were performed in a vertical pipe with diameter of 11.7 mm in a longitudinal section with length of 450 mm, starting from the inlet. Example of spatiotemporal evolution of waves in such a system is shown in Fig. 4. The two vertical stripes are related to connections of the pipe which slightly distort the view.
Figure 4 Spatiotemporal evolution of disturbance waves in 11.7 mm vertical pipe over first 45 cm from the inlet. (a) $Re_L=220$, $V_g=26$ m/s; (b) $Re_L=400$, $V_g=57$ m/s.

The disturbance waves obviously accelerate in these plots: slopes of their trajectories to $t$-axis increase with distance from the inlet (the left side of each image). Nonetheless, this slope becomes nearly constant in the half of $Rol$, which is farther from the inlet. Local average velocity was measured by cross-correlating pairs of temporal records of film thickness obtained by “probes” (i.e., pixels of the camera), separated by distance of 20 mm. Results of measurements of waves’ velocity depending on downstream distance are shown in Fig. 5(a) for both 15 mm and 11.7 mm pipes by solid and empty symbols, respectively, for the same $Re$. 
It could be seen that the disturbance waves are initially accelerated, but closer to the end of the RoI the velocity comes to saturation. Moreover, the local velocity even decreases downstream in 15 mm pipe. If the acceleration in time, $a_r$ was a constant, the velocity of disturbance waves would grow with distance in square-root manner, described by the following formula:

$$V(x) = \sqrt{V_0^2 + 2a_r(x - x_0)}$$  \hspace{1cm} (1)

Here $x_0$ is downstream distance at which the acceleration starts and $V_0$ is the velocity of waves at $x_0$. Solid lines in Fig. 5(a) show the approximation (1) based on the initial length where acceleration is roughly constant. Fig. 5(b) shows the difference between the expected values of velocity at certain distance predicted by formula (1) and the real experimental values. This "underachieved" velocity grows linearly with downstream distance. The higher is the gas velocity the closer to the inlet the growth of the discrepancy starts. This behaviour reminds very much the behaviour of the fraction of dispersed phase with downstream distance. Example of such behaviour is shown in Fig. 5(c) for slightly different conditions obtained in Cherdantsev (2006). In that work, the sampling probe was positioned at different downstream distances to measure local flowrate of the entrained droplets and hence local fraction of the dispersed phase. This fraction grows linearly with downstream distance over significant length of the pipe between the start of entrainment and achieving some balance between entrainment and deposition fluxes far from the inlet. Kataoka et al. (2000) proposed to describe this dependence using hyperbolic tangent function (see formula 22 in that paper). Linear growth of entrained fraction at the investigated range of distances denotes that constant amount of liquid is entrained per unit length.

In the light of similar behaviour of the entrained fraction and underachieved velocity, the idea of Wolf et al. (2001) on the role of entrainment in deceleration of disturbance waves after initial acceleration seems to be relevant. We should only state that the exact mechanism of this influence is most likely different from what was stated by these authors. Entrainment does not only makes the film thinner in average; it extracts liquid exactly from the tops of the disturbance waves (see the Introduction), making them to lose mass and, hence, amplitude. It is known that the velocity of individual disturbance waves linearly depends on their amplitude (example of such dependence is shown in Fig. 5d reproducing results by Cherdantsev, 2006), which is likely to be related to reducing the area of interaction of the wave with the gas flow in both transverse and longitudinal planes.
Figure 5. (a) Average velocity of the waves, obtained with cross-correlation method (solid and empty symbols) and constant-acceleration approximation of $V(x)$ dependence (solid lines). (b) Difference between the approximation and measured velocities from Fig. 5(a); (c) Downstream evolution of the entrained fraction (Cherdantsev 2006); (d) Relation between amplitude and velocity of individual disturbance waves (Cherdantsev 2006).

Comparison of the data for two pipes of different diameters near the inlet shows that velocities are the same. Besides, $V(x)$ dependencies far downstream in 15 mm pipe look like continuation of the dependencies for 11.7 mm pipe. At present, it is common to characterise the flow development in pipes by normalising the distance from the inlet by pipe diameter. The graph 5(a) shows that at least for waves’ velocity such normalisation would not work.
4. Conclusions

Formation and development of disturbance waves in annular flow was investigated using LIF method in various conditions. It was shown that prior to disturbance waves formation high-frequency initial waves appear due to Kelvin-Helmholtz instability. These waves are two-dimensional, but they are broken promptly into a number of 3D waves which undergo numerous coalescence downstream to form the disturbance waves. In terms of two-dimensionality of film surface it means that the two-dimensionality strongly decreases in the beginning after break-up of the initial 2D waves and it gradually recovers after disturbance waves are created. Thus, the mechanism of disturbance waves' formation, proposed by Alekseenko et al. (2015), is confirmed and expanded in the present work. Downstream evolution of waves velocity was analysed using the same technique in 2D approach, over long (450 mm and more) longitudinal distances simultaneously. It was shown that after initial stage of constant acceleration in time the disturbance waves start to lose acceleration and eventually even decelerate. Following argumentation of Wolf et al. (2001) it was shown that lack of acceleration is related to liquid entrainment from top of disturbance waves, leading to decrease in waves' amplitudes and consequent decrease in velocity.

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References


