Quantitative analysis of transverse non-uniformity of liquid film at the initial stage of annular-dispersed flow

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Abstract. The process of formation of disturbance waves in annular gas-liquid flow was studied using three-dimensional configuration of brightness-based laser-induced fluorescence technique in two ducts of different geometry in the proximity of the inlet. The process was found to consist of three stages: formation of initial two-dimensional high-frequency waves; fragmentation into localised chaotic 3D-waves and formation of large-scale quasi-2D disturbance waves. A method of quantitative characterisation of the degree of transverse coherence of film surface was developed and used to estimate the coordinates of the borders of the three stages. All the stages occur closer to the inlet at higher superficial gas velocities and lower liquid flow rates. It was found that the shape of the duct does not exert significant influence of the distance of existence of two-dimensional initial waves, whilst the disturbance waves are formed closer to the inlet in the circular duct.

1. Introduction
Annular flow is a common regime of two-phase gas-liquid flow occurring at high gas flow rates. In this flow regime liquid phase travels as a film along the duct walls together with gas stream flowing through the core of the duct. At high gas and liquid flow rates part of liquid is torn from the film surface and travels in form of droplets inside the gas core. In such a case the interface is always covered by large-scale disturbance waves coexisting with small-scale ripple waves. The entrainment occurs mainly due to disruption of ripples on top of disturbance waves by the gas stream (see [1]).

The disturbance waves appear not far from the inlet. Frequency of disturbance waves decreases with downstream distance due to coalescence of disturbance waves in [2], whilst their velocity grows with distance and is stabilised far from the inlet in [3]. Average characteristics of disturbance waves far from the inlet were studied in a large number of experimental works; many of them are summarised in the review paper by Azzopardi [4].

The process of disturbance waves formation is less studied. It was found by Zhao et al. in [5] that prior to disturbance waves formation the film surface is covered by low-amplitude high-frequency initial waves. Alekseenko et al. [6] applied spatiotemporally resolved measurements of film thickness to observe that the disturbance waves are created due to coalescence of the initial waves. These measurements were performed in two-dimensional representation, i.e., along one longitudinal section of the duct.

Clark et al. in [7] found that presence of gas stream enhances formation of large quasi-two-dimensional waves on film surface. Nevertheless, the film surface in annular flow remains essentially three-dimensional. The disturbance waves, being the most two-dimensional waves in such a system, are of limited transverse size (see [8]) and they are non-uniform by amplitude in transverse direction [9]. Zhao et al. in [5] observed that the transverse coherence of disturbance waves increases with...
downstream distance. Thus, studying the process of disturbance waves formation only in frames of 2D approach might lead to loss of important information.

The first qualitative results on formation of disturbance waves in 3D space were obtained by Alekseenko et al. (see [10]). It was found that the initial waves are two-dimensional with flat fronts normal to flow direction and covering the whole width of the duct. At some distance from the inlet the initial 2D waves are broken into small-scale localised 3D waves, which are very different by shape and size. The 3D waves undergo multiple acts of coalescence, which leads to formation of large-scale quasi-two-dimensional disturbance waves.

In the present work, a new method of quantitative estimation of the degree of three-dimensionality of film surface is proposed. The method is applied to the obtained fields of film thickness to study the downstream evolution of two-dimensionality of film surface at the initial stage of annular flow.

2. Experimental setup and measurement technique

The experiments were conducted in two vertical ducts of different geometry: in a circular pipe with inner diameter of 11.7 mm and in a rectangular duct with cross-section of 50 mm by 5 mm (Fig. 1). The length of each of the ducts was about 70 cm. The liquid was supplied onto the duct walls through a tangential slot distributor with width of 0.5 mm. In the circular duct liquid film covered the whole inner surface of the pipe; in the rectangular duct only one of the wider walls was covered by liquid. The wetted perimeter was approximately the same in both cases. The advantage of the rectangular duct consists in absence of optical distortions caused by the duct's curvature and in possibility to observe the whole wetted area. The latter is not true for the circular duct, in which only 1/4 of wetted perimeter can be observed by a single camera. The main disadvantage of the rectangular duct is presence of the side walls which might slow down the disturbance waves.

![Figure 1. 3D-BBLIF method in circular (a) and rectangular (b) ducts.](image)

Adiabatic air-water flow at nearly atmospheric pressure was studied in both cases. Superficial gas velocity, $V_g$, and liquid Reynolds numbers, $Re_L$, were used as flow parameters. $Re_L$ was defined as:

$$Re_L = \frac{Ql\nu}{\nu^2}, \quad Re_L = \frac{Q(l\nu)}{\nu^2}$$

for circular and rectangular duct, respectively. Here $Q$ is volumetric liquid flow rate, $\nu$ - kinematic viscosity of liquid (water at working temperature of 16°C has viscosity of $1.15\times10^{-6}$ m$^2$/s), $d$ - inner pipe diameter, $l$ - width of the wider wall of the rectangular duct.
To measure the local film thickness, 3D-configuration of brightness-based laser-induced fluorescence technique was applied. This method enables one to make measurements of film thickness resolved in both longitudinal and transverse coordinates and in time with high spatial and temporal resolution. Small amount (10 mg/l) of Rhodamine 6G dye was dissolved in working liquid. For excitation of fluorescence, liquid was illuminated by a continuous 2 W laser with wavelength of 532 nm. The laser beam was spread into a spot illuminating the whole region of interrogation (RoI). Brightness of re-emitted fluorescent light was measured by high-speed camera Photron Fastcam SA5 equipped with orange optical filter to cut-off the reflected laser light. The size of the RoI, spatial resolution, sampling frequency and the range of flow parameters for both ducts are given in Table 1.

The measured brightness of fluorescent light, $I(x,y,t)$, can be converted into the local film thickness, $h(x,y,t)$, where $x$ is longitudinal coordinate, $y$ - transverse coordinate and $t$ is time. $I$ and $h$ are related as follows:

$$I(x,y,t) = C(x,y) \cdot [1 - e^{-\alpha h(x,y,t)}] \cdot [1 + K \cdot e^{-\alpha h(x,y,t)}] + D(x,y).$$

Here $\alpha$ is coefficient of absorption of the laser light by the fluorescent dye, which is measured separately; $K$ is the coefficient of reflection of the laser light from water-air interface, which is equal 0.02 at moderate interface slopes; $D(x,y)$ is the dark level of camera and $C(x,y)$ is the compensation matrix, created to compensate the non-uniformity of laser illumination and to create a reference value of brightness corresponding to a reference value of film thickness.

### Table 1.

|                        | Circular duct | Rectangular duct |
|------------------------|---------------|------------------|
| Longitudinal size of RoI (mm) | 80            | 200              |
| Transverse size of RoI (mm)   | 12            | 50               |
| Spatial resolution, mm/pixel | 0.1           | 2                |
| Sampling frequency (kHz)     | 10            | 1                |
| Liquid Reynolds numbers     | 140-400       | 140-400          |
| Gas velocity (m/s)          | 22-57         | 14-43            |

3. Results and discussion

As mentioned above, the process of disturbance waves’ formation consists of three stages, characterised by different degrees of two-dimensionality (see [10]):

Stage 1. Formation and development of the initial 2D waves;
Stage 2. Decay into 3D waves.

Stage 3. Formation of quasi-2D disturbance waves.

Figure 2 shows the waves typical for these three stages marked on instantaneous fields of film thickness in circular (a) and rectangular (b) ducts.

**Figure 2.** Graphical representation of instantaneous shape of film thickness obtained by 3D-BBLIF method in circular (a) and rectangular (b) ducts. $Re_l=220$, $V_g=26$ m/s.
Automatic identification of these three stages requires a method of quantitative estimation of two-dimensionality (or "transverse coherence") of film surface. This method was derived on the basis of cross-correlation analysis. Similar approach was employed by Zhao et al. in [5], who used cross-correlation between the signals of conductance probes placed around the circumference of the pipe.

Present experimental data are obtained in form of 3D matrices, \( h(x, y, t) \). The film is considered to be fully two-dimensional when all the temporal records of film thickness, obtained at the same \( x \) coordinate but different \( y \) coordinates, are identical. Vice versa, absence of correlation between such records would correspond to complete three-dimensionality of film surface. The degree of two-dimensionality is then obtained in form of a 3D matrix \( b(x, y_i, y_j) \), which was defined as maximum value of normalised cross-correlation function between the two temporal records of film thickness, obtained at the same downstream coordinate, \( x \), and different transverse coordinates, \( y_i \) and \( y_j \):

\[
b(x, y_i, y_j) = \max_{\tau} \left( \frac{\sum_{t=1}^{T} h(x, y_i, t) h(x, y_j, t - \tau)}{A} \right).
\]

Here \( T \) is duration of a whole record, \( \tau \) - variable temporal delay between the two records and

\[
A = \max \left( \sum_{t=1}^{T} h(x, y_i, t)^2, \sum_{t=1}^{T} h(x, y_j, t)^2 \right).
\]

Variation of \( \tau \) was introduced in order to minimise possible influence of constant time shift between the two records, i.e., the case when the waves are two-dimensional but slightly inclined to the horizon. Such distortion of the wave fronts is expected to occur next to the side walls of the rectangular duct. Normalisation by \( A \) in this form was introduced to compensate for the difference in the amplitudes of the waves. Thus, the present approach enables us to minimise the influence of both curved/inclined wave fronts and persistent change in waves' amplitudes across the waves and to focus on the transverse size of the waves.

For a fixed value of \( x=x_0 \), \( b(x_0, y_i, y_j) \) is a square matrix symmetrical relative to the main diagonal; each element of this diagonal is equal 1. The value of \( b \) decreases with the distance from this line; the rate of decrease depends on two-dimensionality of the film. Fig. 3(a) shows an example of \( b \)-matrix at constant \( y_i=24 \) mm together with 3 profiles \( b(y_j) \) obtained at different values of \( x \) (Fig. 3b). The rate of decrease is rather low close to the inlet, where the initial waves are approximately two-dimensional (see Fig. 3b at \( x=6 \) mm). In the range of 3D-waves (\( x=50 \) mm in Fig. 3b) \( b \) reaches low values very quickly. After the disturbance waves are formed (see \( x=180 \) mm in Fig. 3b) the values of \( b \) at larger \( dy = |y_j - y_i| \) grow again. For further analysis, a constant value of \( dy \) was selected so that \( b \) in the region of 3D-waves would be about 0.1 for all flow regimes. At the same time, \( dy \) must be small enough to allow analysis of maximum number of pairs of records, \( \{y_i, y_j\} \). The optimum value of \( dy \) in such a case should be equal to maximum transverse size of the 3D-waves, \( L \), which was found to be about 5 mm (see Fig. 3b for \( x=50 \) mm).

**Figure 3.** Effect of the distance between the correlated records (\( y_i=24 \) mm) on \( b \) value. (a) The whole set of \( x \)-coordinates; (b) Three selected profiles \( b(y_j) \) at different stages. \( Re_{x}=220, V_g=26 \) m/s.
Figure 4 shows examples of downstream evolution of two-dimensionality coefficient at constant dy=5 mm (i.e., section of b-matrix defined as \( b(x, y_i, y_{i+5}\text{mm}) \)) for two flow regimes. This matrix is quite uniform across \( y_i \) coordinate (see Fig. 4a-b), so the average of this matrix over \( y_i \) was used for further analysis. At moderate gas velocities (see Fig. 4a,c) a prominent peak of two-dimensionality is observed near the inlet, corresponding to the Stage 1; transition to Stage 2 (the fragmentation of 2D-waves into 3D-waves) is accompanied by decrease of two-dimensionality to the value of about 0.1. At the Stage 3 the transverse coherence is recovered gradually with downstream distance, denoting the formation of disturbance waves and their growth in transverse direction. The picture is similar in the case of high gas velocities (Fig. 4 b, d), except for two moments. First, the initial peak is nearly absent in this case, which means that the initial waves are broken into 3D-waves almost immediately. Second, the third stage (recovery of transverse coherence due to formation of disturbance waves) occurs much closer to the inlet as well.

![Figure 4](image1.png)

**Figure 4.** (a, b) The effect of \( y \)-coordinate at constant \( dy \) for the whole set of \( x \)-coordinate. (c,d) Dependence of cross-correlation averaged over \( y \) on \( x \). (a,c) - \( Re_L=220, V_g=26 \text{ m/s}, (b,d) - Re_L=400, V_g=43 \text{ m/s}. \) Rectangular duct.

![Figure 5](image2.png)

**Figure 5.** Measured \( x \)-coordinates of the end of Stage 1 (a) and beginning of Stage 3 (b) in rectangular (squares) and circular (circles) ducts.
Based on dependencies \( b(x) \) it is possible to identify the borders between the Stages 1-2 and 2-3 for each combination of flow rates. The borders were defined as the points where linear extrapolations of particular areas of \( b(x) \) dependencies cross the level \( b=0.1 \). The first selected area was the steep negative slope just behind the maximum of two-dimensionality of the initial waves. The second area was the steepest positive slope right after the shallow plateau around the value \( b=0.1 \).

The measurements results are shown in Fig. 5. The spatial length of Stage 1 decreases with increasing gas velocity; it reaches large values of \(-100 \text{ mm} \) for the lowest \( V_g \) (Fig. 5a). There is an effect of \( Re_l \) as well: the lower is \( Re_l \), the faster 2D-waves are disrupted into 3D-waves, but this effect is weak in comparison to that of gas velocity. The most interesting thing is that the data for both ducts lie on the same line; the difference does not overcome the difference due to liquid flow rate. The whole set of data can be approximated by a single dependence \( x \sim V_g^2 \) (see the solid line in Fig. 5a). Thus, the shape of the duct does not strongly affect the process of disruption of 2D waves.

The coordinate of start of Stage 3 also decreases with gas velocity and increases with liquid Reynolds number (Fig. 5b). In the rectangular duct, the effect of \( Re_l \) is less expressed, being comparable to the uncertainty of the method; at the same time, the effect of \( V_g \) is prominent in the used \( V_g \) range. The data obtained in circular duct at the highest gas velocities, seem to satisfy the general trend observed in the rectangular duct, though the effect of \( Re_l \) is much more evident in this region whilst the effect of \( V_g \) nearly disappears. The most striking difference is that the formation of disturbance waves starts much earlier at moderate \( V_g \) in the circular duct. This may be explained by the effect of the side walls of the rectangular duct, slowing down the disturbance waves.

4. Conclusions

The process of formation of disturbance waves in annular gas-liquid flow was studied using brightness-based laser-induced fluorescence technique in three-dimensional approach. The measurements were performed in two ducts of different shape in a wide range of air and water flow rates. The process of disturbance waves formation consists of three stages, which differ, in particular, by three-dimensionality of film surface. A method of quantitative characterisation of degree of transverse coherence of liquid film was developed to identify the stages automatically. It was found that the length of each stage of the process decreases with gas velocity but increases with liquid flow rate. The length of the area of existence of initial 2D-waves was found to be nearly independent on the duct's shape. At the same time, formation of disturbance waves may occur closer to the inlet in the circular duct in the range of moderate gas velocities.

Acknowledgments

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