Study of development of disturbance waves in annular gas-liquid flow.

Andrey V Cherdantsev1,2, Mikhail V Cherdantsev1, Sergey V Isaenkov1 and Dmitriy M Markovich1,2

1Kutateladze Institute of Thermophysics, 1 Lavrentiev ave, 630090 Novosibirsk, Russia
2Novosibirsk State University, 2 Pirogov str, 630090 Novosibirsk, Russia
cherdantsev@itp.nsc.ru

Abstract. Downstream development of disturbance waves properties in annular regime of gas-liquid flow was conducted in adiabatic air-water downwards flow in a vertical pipe with inner diameter of 11.7 mm. The measurements were conducted using brightness-based laser-induced fluorescence technique. Instantaneous distributions of local thickness of liquid film along one longitudinal section of the duct over the first 45 cm from the inlet were obtained with sampling frequency of 10 kHz. Based on these spatiotemporal plots, dependence of local average velocity of disturbance waves on downstream distance was obtained for a wide range of gas and liquid flow rates. Three main stages of flow development were identified: a stage prior to formation of disturbance waves, a stage of constant acceleration of disturbance waves and a stage of deceleration nearly compensating the initial acceleration. Transitions to both second and third stages occur closer to the inlet at higher gas velocities and lower liquid flow rates. The initial acceleration is defined by the effect of the gas shear; it grows in parabolic manner with superficial gas velocity and shows weak dependence on liquid flow rate. The deceleration is supposed to occur due to entrainment of liquid from disturbance waves.

1. Introduction
In annular regime of gas-liquid flow high-velocity gas stream flows through the central part of the duct; the walls of the duct are covered by liquid film. The liquid can be entrained from film surface into the gas core in form of droplets. The liquid film is covered by large-scale disturbance waves separated by thin residual layer and small-scale ripple waves covering both the residual layer and the disturbance waves. The disturbance waves play important role in annular flow: they carry the major fraction of liquid, affect shear stress and heat and mass transfer in the flow and generate the ripples on their rear slopes (Alekseenko et al., 2008). The ripples, in turn, contribute to the shear stress by increasing the interface roughness (Schubring & Shed, 2011) and, being torn into droplets by the gas stream at the tops of the disturbance waves, contribute to liquid entrainment. In order to create physically based models predicting pressure drop and liquid entrainment in annular flow it is necessary to accurately predict the properties of the disturbance waves. Such modelling requires basic assumptions on waves properties and behaviour which may be obtained via comprehensive experiments.
Large amount of experimental data on average velocity, height and frequency of disturbance waves at different flow rates and physical properties of the phases was collected in previous years. The majority of these experiments were conducted at large distances from the inlet, where the flow is believed to be stabilised. In particular, it was shown (Hall Taylor et al., 1963) that far from the inlet the disturbance waves travel with constant speed over long distances. But the disturbance waves are formed close to the inlet (Zhao et al., 2013) and their properties change significantly with downstream distance, $x$, at the first meters of the duct length. In particular, their frequency decreases with $x$ due to numerous acts of irreversible coalescence (Hall Taylor & Nedderman, 1968) and their velocity undergoes complex evolution with strong initial acceleration and weaker subsequent deceleration (Wolf et al., 2001). The number of experimental works devoted to studying disturbance waves evolution is small and, as a rule, the measurements were conducted by pointwise methods in a small number of downstream positions of the probes. The disturbance waves should be modelled starting from their appearance and subsequent development, since these processes define their properties downstream.

In the recent work by Alekseenko et al. (2015) the process of formation of disturbance waves was studied using field measurements of film thickness at the first 100 mm of the pipe length. It was found that the disturbance waves are formed due to coalescence of high-frequency initial waves. The disturbance waves were found to accelerate after formation, but studying their further development was restricted by the short length of the region of interrogation. In the present work, the investigated longitudinal section of the pipe was expanded to 450 mm from the inlet to study the further stages of waves development.

2. Experimental setup and measurement technique
The experiments were conducted in adiabatic air-water flow at near-atmospheric conditions. Downward annular flow was organised in a vertical acrylic resin pipe with inner diameter of 11.7 mm and length of 650 mm. The scheme of the experimental setup is shown in Fig. 1(a).

![Figure 1](image_url)  
Figure 1. (a) Scheme of the experimental setup. (b) Scheme of the inlet.

Liquid circulated in a closed hydrodynamic loop. Prior to the experiments it was pumped from the receiving tank into the pressure tank located 3 metres above the pipe entrance. During the experiments the pump was switched off and liquid went into the distributor under hydrostatic pressure. The distributor ensures uniform wetting of the pipe walls by the working liquid, which is introduced as a film through a ring-shaped 0.5 mm thickness slot between the inner surface of the pipe and the outer
surface of gas-feeding tube (Fig. 1b). Liquid flow rate was controlled with a float rotameter. The gas was introduced from the centralised line of compressed air through the thin-walled steel tube mounted coaxially with the main pipe. Gas flow rate was controlled by an orifice meter connected to U-manometer. The gas-liquid mixture leaving the pipe entered swirl separator. After separation the liquid phase entered the receiving tank and the air went to the atmosphere.

Liquid Reynolds number, \( Re_L \), was defined as volumetric liquid flow rate divided by wetted perimeter of the pipe and by kinematic viscosity of the liquid. \( Re_L \) values of 140, 220, 300 and 400 were used. Superficial gas velocity, \( V_g \), defined as volumetric gas flow rate per cross-section of the pipe varied in the range from 22 m/s to a maximum of 100 m/s at \( Re_L = 140 \). Due to restrictions of the rig pressure, maximum \( V_g \) was 90 m/s for \( Re_L = 220 \), 80 m/s for \( Re_L = 300 \) and 57 m/s for \( Re_L = 400 \). According to Webb & Hewitt (1975) and Alekseenko et al. (2015) in this range of \( Re_L \) the selected range of \( V_g \) ensures presence of disturbance waves.

Film thickness was measured using brightness-based laser-induced fluorescence technique. Fluorescent dye Rhodamine 6G was dissolved in working liquid in small (15 mg/l) concentration. For excitation of fluorescence a continuous 2W laser with wavelength 532 nm was used. The laser beam is converted into a narrow vertical light sheet illuminating a longitudinal section of the pipe with length of 450 mm starting from the inlet. Rhodamine 6G absorbs the laser radiation and re-emits it in red spectral domain. The brightness of the re-emitted light depends on the thickness of liquid layer. This brightness is measured by high-speed camera equipped with orange optical filter to avoid registration of reflected and scattered laser light. The camera sampling frequency was either 10 or 20 kHz depending on gas velocity. Exposure time was 40-60 \( \mu \)s. A line of 1000 camera pixels was "seeing" the region of interrogation, which yielded spatial resolution of 0.45 mm per pixel. For each combination of gas and liquid flow rates a record with duration of 2 seconds was obtained. Brightness of re-emitted light, \( J \), is related to film thickness, \( h \), as:

\[
J(x) = C(x)(1 - e^{-\alpha h}) (1 + Ke^{-\alpha h})
\]

Here \( C(x) \) is a compensation matrix, \( \alpha \) is the absorption coefficient, \( K \) is coefficient of reflection from water-air interface, which is equal 0.02. \( \alpha \) is measured separately by comparing brightness of fluorescent light emitted by liquid in two slots of known thicknesses. \( C(x) \) can be constructed based on in situ measurements of time-averaged brightness of liquid layer with known average thickness. A simple example of such reference signal is thin \((Re_L=40)\) film falling under action of gravity; thickness of such film is described well by the Nusselt solution.

3. Results and discussion

An example of spatiotemporal film thickness matrix, \( h(t,x) \), is shown in Fig. 2 in graphical representation. Local brightness of each pixel of this image is linearly proportional to local film thickness measured at given \( \{x,t\} \)-point. White corresponds to film thickness equal to or more than 1 mm. Each string of such a matrix represents an instantaneous distribution of film thickness along the downstream coordinate, \( x \). Each column represents a temporal record of film thickness obtained at fixed downstream coordinate. Waves are visible in this image as bright inclined lines, with local slope of a line to the \( t \)-axis corresponding to the instantaneous velocity of the wave.

At the very inlet (the leftmost part of the image) regular small-amplitude waves of very high frequency can be observed. Due to coalescence of these initial waves the disturbance waves are formed (Alekseenko et al., 2015). The disturbance waves are characterised by large longitudinal size, amplitude, speed and lifetime; they are separated by thin base film layer; their crests are covered with ripples moving faster than the waves themselves. Spatiotemporal trajectories of the disturbance waves are curved upwards in the beginning, which means that the speed of the waves grows downstream. In the rightmost part of the image the trajectories are almost straight, which indicates nearly constant speed. The number of disturbance waves gradually decreases with \( x \) due to waves coalescence. Acts of coalescence can also be observed in Fig. 2 as intersections of two waves' trajectories after which only one wave travels further.
Using spatiotemporally resolved data, average velocity of waves can be easily measured at every x value by calculating the cross-correlation function (CCF) for neighbouring temporal records of film thickness, \( h(t, x \pm \delta x) \), where \( \delta x \) is the length "seen" by one camera pixel; this length is equal to 0.45 mm. The velocity is then estimated as \( 2\delta x/\delta t \), where \( \delta t \) is the temporal delay corresponding to maximum of CCF. To increase accuracy of the measurements, the vicinity of the CCF maximum was interpolated by a parabola, and location of its maximum was used as a more precise estimation of \( \delta t \). Afterwards it corresponds to the average velocity of the disturbance waves: though small-scale ripples coexist with disturbance waves on film surface, they are of much smaller amplitude and their contribution into CCF is negligible.

Figure 2. Fragment of spatiotemporal plot of film thickness, \( h(t, x) \), for \( Re_L=220, V_g=36 \) m/s.

Figure 3. Dependence of average velocity of the waves on downstream distance. \( Re_L=400 \).
The obtained dependencies $V(x)$ for one $Re_l$ are shown in Fig. 3. At the initial stage a short high-amplitude peak in the velocity plots can be observed. This peak describes the velocity of the initial waves prior to formation of disturbance waves. According to Alekseenko et al. (2016), the initial waves are two-dimensional at first, but after some distance they undergo fragmentation into localised 3D waves. The latter coalesce to form quasi two-dimensional disturbance waves. Thus, at the 2D stage the initial waves undergo acceleration (the growing part of the peak); the fragmentation into 3D waves is accompanied by decrease in the speed of the waves.

![Figure 4](image)

**Figure 4.** (a) Search for linear stage in the dependence $V^2(x)$. (b) Difference between the linear extrapolation shown by the dashed lines in Fig. (a) and the measured squared velocity. $Re_l=400$.

![Figure 5](image)

**Figure 5.** (a) Borders of the three regions of waves development. (b) Acceleration in time at the stage of constant initial acceleration.

After the stage of constant acceleration, waves' speed continues to grow, but at significantly lower rate. Figure 4(b) shows the difference between the constant-acceleration prediction and the measured values of $V^2(x)$. This difference also linearly grows with $x$; at higher gas velocities the growth starts closer to the inlet and the rate of growth is larger. Wolf et al. (2001) who observed deceleration of the disturbance waves relatively far from the inlet, related it to liquid entrainment, which leads to thinning
of liquid film. This idea seems reasonable since the dependencies shown in Fig. 4(b) are very similar to the dependencies of entrained fraction on $x$ (see, e.g., equation 23 in Kataoka et al., 2000). Nonetheless, we suppose that the way entrainment affects the waves speed is more complex than just integral thinning of liquid film. Since the entrained droplets are "extracted" directly from the disturbance waves, the entrainment may lead to decrease in the area of interaction between the gas stream and a disturbance wave, and thus reducing the effective drag force.

To summarise, three stages of waves development can be identified based on present experimental data: (1) the region of initial waves prior to formation of the disturbance waves; (2) the region of constant acceleration of disturbance waves; (3) the region of reduced acceleration due to liquid entrainment. The borders of the three regions are shown in Fig. 5(a). Both regions (1) and (2) shorten at higher gas velocities and lower liquid flow rates. The measured values of constant acceleration at in the region (2) for the whole investigated range of gas and liquid flow rates are shown in Fig. 5(b). at grows with $V_g$ in a parabolic manner, and it does not show any strong dependence on $Re_L$.

4. Conclusions

Development of waves in downward annular gas-liquid flow was studied using brightness-based laser-induced fluorescence technique. Spatiotemporal evolution of film thickness and local velocity of waves was studied over first 45 cm of a vertical pipe with inner diameter 11.7 mm. Three stages of waves evolution were identified. At the first stage, initial high-frequency waves appear on film surface. These waves undergo strong acceleration followed by deceleration. Based on previous observations in three-dimensional space (Alekseenko et al., 2016) we suppose that the velocity increases while the initial waves conserve two-dimensionality and decreases after the 2D-waves are fragmented into small 3D-waves. At the second stage the large-scale disturbance waves appear and move with constant acceleration, which grows in parabolic manner with gas velocity without strong dependency on liquid flow rate. At the third stage the acceleration suddenly drops to very small values. The reason of such a sharp decrease in acceleration is supposedly related to start of liquid entrainment from the tops of disturbance waves leading to decrease in waves amplitudes and hence the effective drag force exerted on waves by the gas stream. The length of each stage decreases with gas velocity and increases with liquid flow rate. It is very likely that downstream the region of interrogation used in the present work one more stage of waves development can be observed, related to start of deposition of liquid droplets from the gas core onto film surface and consequent stabilisation of waves velocity. This assumption requires experimental validation through spatiotemporal measurements of film thickness conducted farther from the inlet.

References
[1] Alekseenko S V, Antipin V A, Cherdantsev AV, Kharlamov S M and Markovich D M 2008 Microgravity Sci. Technol. 20 271
[2] Alekseenko S V, Cherdantsev A V, Cherdantsev M V, Isaenkov S V and Markovich D M 2015 Int. J. Mult. Flow 77 65
[3] Alekseenko S, Cherdantsev A, Cherdantsev M, Isaenkov S and Markovich D 2016 MATEC Web Conf. 84 00001
[4] Kataoka I, Ishii M and Nakayama A 2000 Int. J. Heat Mass Transfer 43 1573
[5] Hall Taylor N S, Hewitt G F and Lacey P M C 1963 Chem. Eng. Sci. 18 537
[6] Hall Taylor N S and Nedderman R M 1968 Chem. Eng. Sci. 23 551
[7] Schubring D and Sheed T A 2011 Int. J. Heat Fluid Flow 32 730
[8] Webb D R and Hewitt G F 1975 Int. J. Mult. Flow 2(1) 35
[9] Wolf A, Jayanti S and Hewitt G F 2001 Chem. Eng. Sci. 56 3221
[10] Zhao Y, Marikides C N, Matar O K and Hewitt G F 2013 Int. J. Mult. Flow 55 111

Acknowledgments
The work was supported by Russian Science Foundation (project RSF 16-19-10449).