Secondary instability of waves in annular two-phase flow with and without entrainment

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\textbf{Abstract.} Spatio-temporal evolution of disturbance waves and ripple waves in annular gas-liquid flow was studied using high-speed modification of laser-induced fluorescence technique. Both flow regimes with and without entrainment were studied. It was shown that all the ripples in regimes with entrainment arise due to instability of back slopes of the disturbance waves, and their further evolution is predefined by the point of appearance. In regimes without entrainment two types of waves were detected, where waves of one type arise due to instability of back slopes of waves of the other type. Thus, similarity of wavy structure of flow regimes with and without entrainment was established.

1. Introduction

Presence of intensive gas shear drastically changes wavy structure of liquid film in comparison to that of gravitationally falling films. The film surface under strong gas shear is covered by small scale ripple waves (also called “ripples”). According to generally accepted point of view \cite{1}, ripples are omnipresent at film surface, at any liquid Reynolds numbers. At higher liquid Reynolds numbers, the disturbance waves appear. The latter are characterized by high amplitude (several times greater than thickness of the residual liquid layer between waves); large longitudinal size (several centimeters); large transverse size (in channels with inner diameter less than 3 cm disturbance waves form full ring around the circumference of the channel); high velocity (several m/s).

The area of flow parameters where the investigators observed high-amplitude waves approximately coincides with the regime area where entrainment of liquid from the film surface occurs. The tiny liquid droplets are torn off the film surface and entrained into the core of gas stream. According to observations of Woodmansee & Hanratty \cite{2}, the droplets tearing-off happens due to scattering of ripples on crests of disturbance waves by the intensive gas shear. Woodmansee & Hanratty \cite{2} proposed a model of appearance of ripples based on simple assumption of Kelvin-Helmholtz instability. An attempt to develop this approach was recently performed by Holowach et al. \cite{3}.

Nevertheless, no experimental investigation of ripples appearance process was performed. Such investigation requires the simultaneous measurements of local film thickness at large number of points along the longitudinal section of the channel with high spatial resolution and sampling frequency. The most efficient attempt of such measurements was made by Sekoguchi & Takeishi \cite{4} using measuring
system that consisted of large number of conductivity probes, separated by distance of 5 mm. Unfortunately, this was not sufficient to reach the necessary resolution.

At low liquid Reynolds numbers no entrainment occurs at any high gas velocities. It is commonly supposed that no disturbance waves appear at the film surface in absence of entrainment, and only ripples exist. Asali & Hanratty [5] tried to predict the ripples frequency in such regime, on the assumption that the frequency is equal to frequency of waves of maximum growth. The comparison has shown that experimental wavelength is approximately two times higher than wavelength predicted by theory.

The goal of present work is to investigate the appearance and further evolution of ripples in regimes with and without entrainment in details.

2. Experimental setup and measurement technique

Experiments were performed in vertical Plexiglas cylindrical channel with the inner diameter of 15 mm and the length of 1 meter, at distances 1-20 and 50-70 cm below the inlet. Liquid film was formed on channel wall using a slot distributor with the gap width of 0.5 mm, gas entered the channel through a co-axial tube of slightly smaller diameter.

Channel was made with square outer side to decrease optical distortions. Continuous green laser with the wavelength 532 nm and power 50 mW was used as the light source. Laser beam was converted into a vertical light sheet aimed at the region of measurements. Rhodamin-6G in concentration 30 mg/l was used as fluorescent matter. Fluorescent light was registered by the 10-bit CCD camera with linear (2048*1 pixels) matrix. Camera was aimed at the region of measurements with the focus on the nearest inner wall of the channel. Distance from camera to channel wall was 450 mm. Camera was equipped with low-pass orange filter. Axes of camera and laser were placed at a small angle to each other on horizontal plane. This allowed avoiding registration of light emitted by the film flowing on the remote wall of the channel. The sketch of experimental setup is given in Fig. 1.

All experiments were conducted in the measurement area with the length of 20 cm with spatial resolution 0.1 mm. Width of measurements area was equal 0.1 mm, and the thickness of laser sheet was about 1 mm. Exposition time was 150 μs and registration frame rate - 2000 fps. Registered image brightness was converted into local film thickness using calibration curve obtained in a set of in situ calibration tests.

Flow regimes characterized by the presence of disturbance waves and liquid entrainment were investigated. Liquid Reynolds number Re (defined as ratio of volumetric liquid flow rate per unit...
perimeter of the tube to the kinematic viscosity of liquid) varied in the range of 140-350 for regimes with entrainment and 40-60 for regimes without entrainment; superficial gas velocity $V_g$ varied in the range of 22-58 m/s (that corresponds to gas Reynolds number range 22000-58000). Distilled water was used as working liquid.

3. Experimental results

The picture of ripples generation in regimes with entrainment is shown in Figure 2. The sequence of instantaneous distributions of local film thickness is shown in reference system moving with the velocity of disturbance wave (3.5 m/s) – a large amplitude wave in the center of the frame. Ripples denoted by 1, 2 and 3 can be seen on the disturbance wave’s surface. Ripples 2 and 3 have just appeared, and they are generated at the back slope of the disturbance wave. Our analysis of experimental data shows that all the ripples are generated only at the back slopes of disturbance waves, and, thus, only a part of film surface is unstable to ripples generation.

Returning to the Fig. 2, we can see that ripple 2 was generated closer to the crest of disturbance wave, and the ripple 3 – farther from the crest. In the following moments of time it can be seen that amplitude of ripple 2 will grow to rather high values and the ripple will travel faster than the parent disturbance wave. After reaching the front of the disturbance wave, it will disappear – either slowly or sharply – which can be seen on the example of ripple 1. This disappearance occurs due to scattering of the ripple by the gas shear, described in [2], contributing to the entrainment.

Figure 2. Evolution of ripples on disturbance wave. Re=350, $V_g$=36 m/s.
Ripple 3 appears farther from the crest of parent disturbance wave and lags behind it. Gradually it reaches the residual layer after the parent disturbance wave and travels along it with approximately constant speed until being overtaken by the following disturbance wave. The similar sequence for the regimes without entrainment is shown in Figure 3. Despite that all the waves were expected to be ripples, we can mark out some waves that are faster, higher longer than the rest of the waves – similar to disturbance waves in entrainment regimes. Reference system in Fig. 3 is moving with velocity of such a fast wave in the center of the frame (1 m/s). It can be seen that smaller waves, denoted by 1 and 4, are generated at the back front of this fast wave. After inception, waves 1 and 4 travel slower than the parent wave. Such smaller waves are promptly absorbed by the following fast wave (absorption can be seen for waves 2 and 3). So, in the regimes without entrainment, only a part of film surface – back slopes of the fast waves – is unstable to smaller waves generation.

![Figure 3](image)

**Figure 3.** Generation of secondary waves by a primary wave in regime without entrainment. Re=40, Vg=36 m/s.

Thus, despite essential difference in amplitudes, wavelengths and velocities, the wavy structure in regimes with and without entrainment is rather similar. In both regimes two types of waves exist, that
we will call “primary waves” and “secondary waves”. The primary waves are characterized by high velocity and long lifetime, and the secondary waves are the short-living waves that arise only on the back slopes of primary waves. In regimes with entrainment primary waves are known as “disturbance waves”, and the secondary waves are known as “ripples”. In regimes without entrainment all the waves – primary and secondary ones – were previously called “ripples”.

In regimes with entrainment fast and slow secondary waves exist: the former move faster than primary waves and disappear on their fronts, contributing to liquid entrainment; the latter move slower than primary ones and are promptly being absorbed by the following primary wave. In regimes without entrainment only slow secondary waves exist. This difference explains the transition to entrainment – no secondary waves can reach fronts of primary ones to be ruptured by the gas shear in regimes without entrainment.

To investigate further the processes of secondary waves generation, the statistical study of inception regions of secondary waves was performed. The coordinate of inception $x_i$ was defined as the distance between point of inception and beginning of the primary wave. Since amplitude and length of primary waves may vary greatly at the same flow parameters, this distance was normalized by dividing it to the length $\lambda$ of the primary wave. $\lambda$ was defined as the distance between the points where slopes of primary wave cross the thickness of substrate. The latter was defined as the most probable value of film thickness. No less than 30 secondary waves of each sort were processed for each set of flow parameters. The relation $x_i/\lambda$ is the dimensionless coordinate of waves inception, which will be dealt further.

![Figure 4. Example profiles of primary waves (a, b) and distributions of secondary waves inception coordinates (c, d). (a, c) – Re=350 (entrainment regime); (b, d) – Re=40 (without entrainment). Vg=36 m/s. Crosses denote slow secondary waves, circles denote fast secondary waves.](image-url)
Figures 4 (a) and (b) show the examples of profiles of thickness of primary waves in regimes with and without entrainment, respectively. Point where the dimensionless coordinate is equal to zero corresponds to the beginning of the primary wave, point where the dimensionless coordinate equals to 1, corresponds to the end of the primary wave. Figures 4 (c) and (d) show the examples of distribution of inception coordinates of secondary waves in regimes with and without entrainment.

It can be seen from Figure 4 (c) that there exists some kind of separation point at the distance of 0.65 \( \lambda \) in regimes with entrainment. Fast secondary waves appear closer to primary wave’s front, and slow secondary waves appear closer to primary wave’s tail. So, the areas of secondary waves inception represent different adjoining parts of the primary wave’s back slope.

From Figure 4 (d) it can be seen that no fast secondary waves exist in case of regimes without entrainment. The area of slow secondary waves generation is similar to the area of generation of all secondary waves in regimes with entrainment.

The relative areas of fast and slow secondary waves inception in case of entrainment do not change essentially with gas velocity growth (Fig. 5 (a)).

![Figure 5](image)

**Figure 5.** Dependence of the average dimensionless coordinate of secondary waves inception on the gas velocity. (a) – Re=350 (entrainment regime); (b) – Re=40 (without entrainment). Crosses denote slow secondary waves, circles denote fast secondary waves.

Figure 5 (b) shows corresponding data for flow regimes without entrainment. As it was noticed above, no fast secondary waves were observed for such regime; areas of slow secondary waves generation are rather close to that of entrainment regimes and their behavior with changing gas velocity is the same.

4. Discussion and conclusions

Several essentially new observations were made in present work. First, the similarity of wavy structure in regimes with and without entrainment was found: it was shown that in regimes without entrainment two types of waves exist, differing in length, amplitude, velocity, etc. Moreover, it was shown that the smaller waves are always generated by the larger waves. New terms “primary waves” for larger waves and “secondary waves” for smaller waves were introduced to simplify further investigation.

Second, it was shown that only a part of film surface in annular gas-liquid flow (the limited parts of back slopes of primary waves) is unstable to secondary waves generation in regimes with and without entrainment. These observations prejudice mechanism of ripples generation based on simple Kelvin-Helmholtz instability model, proposed by previous investigators.
Third, it was shown that in regimes without entrainment all the secondary waves move slower than parent primary waves, but in the regimes without entrainment some kind of bifurcation of the process of primary wave’s back slope evolution takes place. Depending of the relative coordinate of initial disturbance (whether it is close or farther to the crest of parent primary wave than certain separation point), it may suffer two different scenarios of evolution, one of which leads to entrainment and the other doesn’t.

Such separation can be explained under the assumption of existence of eddy motion inside the primary wave in regimes with entrainment. Such eddy for gravitationally falling films was predicted in many theoretical works (e.g., [6]). In case of eddy existence, the stagnation point appears at the back slope of the wave, separating the wave’s back slope into two parts: one of these parts moves faster than the whole wave, and the other moves slower. In this case, external pressure in the vicinity of stagnation point can be regarded as the destabilizing force, leading to secondary waves inception.

According to simulation of [6], under certain values of wave’s amplitude no eddy exists under the wave’s hump and there is no stagnation point at the wave’s back slope. Thus, no parts of wave move faster than the whole wave. This picture corresponds to our observations on the absence of fast secondary waves in regimes without entrainment. Moreover, the amplitude of primary waves in regimes without entrainment is essentially smaller than that of primary waves in entrainment regimes, and the absence of eddy wouldn’t contradict to the model [6]. Of course, this is only one of possible explanations.

References
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