Structure of stationary gas slug in an annular channel

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Abstract. Experimental study of liquid flow structure around a stationary gas slug in an annular channel was performed. The channel consisted of two concentric pipes with the diameters of 32 and 10 mm. Slug was produced in a downward liquid flow in an annular channel. Wall shear stress distribution was measured in both walls of the channel using an electrodifusional technique. It was shown that the shape of the slug in the annular channel differs significantly from that in a circular pipe. The distribution of wall shear stress along the slug was presented for different angular positions in the channel.

1. Introduction
Slug gas-liquid flows in pipes and channels are among the main flow regimes which exist at definite ratios of liquid and gas flow rates. Most of the studies of slug flows were performed in circular pipes of different diameters. Studies of slug flows in channels of different geometries were presented only in several papers. Two-phase flows in vertical non-circular channels (including annular) were studied in [1]. Data on void fraction in two phase flow in vertical and inclined annular channels were presented in [2]. The flow pattern transition in a two-phase flow in the annular channel was studied in [3]. The flow regime was identified by the analysis of signals from a specially designed impedance probe. An analytical model for cap bubble flow was presented. An experimental study of interface area transport in upward two-phase flow in annular channel was performed in [4]. The flow regime was identified using visual observations. Radial distribution of void fraction was measured using the local conductivity probe. Most studies of the two-phase flow in annular channel focused on flow pattern transition and measurements of gas phase characteristics. The flow structure of liquid phase was considered in [5]. Wall shear stress was studied during single slug motion in a channel.

In order to obtain more detailed information on the flow structure of liquid, surrounding the gas slug, studies of stationary gas slug in vertical circular pipes were performed in [6, 7]. Such slugs were produced in downward liquid flow at definite liquid velocity. There are no studies of stationary slugs in annular channels in the literature.

This paper presents experimental study of stationary gas slug in an annular channel. Measurements of mean and fluctuating wall shear stress were performed on both walls of the channel.

2. Experimental technique
The test section of experimental setup is shown schematically in Fig. 1. The test section was a vertical pipe (1) of 32 mm inner diameter. A central pipe (2) with an outer diameter of 10 mm was mounted coaxially inside this vertical pipe. Three spacing grids (3) were mounted to keep the relative position of the inner pipe. Liquid was supplied to the test channel through the system of flow rate measurement. The flow in the test section was downward. A capillary tube of 1 mm inner diameter (4) was inserted into the test channel to supply air. The outlet orifice of the tube was the position of the
nose of stationary gas slug. The downward end of the capillary tube was shifted along the pipe axis to provide measurements. Similar technique was used in [6, 7] to produce stationary gas slug in circular pipes.

**Figure 1.** Scheme of test channel: 1 – outer pipe; 2 – inner pipe; 3 – spacing grids; 4 – capillary tube; 5 – wall shear stress probe.

**Figure 2.** Photos of stationary slug.

**Figure 3.** Channel cross section.
The tested liquid was distilled water with the addition of potassium ferri- and ferrocyanide and sodium hydroxide. The liquid temperature was maintained at 30°C by an automatic system. The test gas was air.

Wall shear stress measurements were performed using an electrodifusional technique [8]. Wall shear stress probes were mounted in the outer and inner pipes. The sensitive element of the probe was a 0.05 mm thick platinum foil cemented into the pipe wall and polished flush with it. The size of the electrode exposed to the flow was 0.05*1 mm. The probes were calibrated in the single flow in the annular channel. The wall shear stress was calculated from the liquid flow rate using the Blasius correlation. The correlation of probe current vs wall shear stress obtained from calibration was used for measurements in the slug flow.

3. Results of experiments
The stationary gas slug was produced in the annular channel at average liquid velocity of 0.33 m/s. Liquid velocity was significantly higher than the velocity of slug rise in the quiescent liquid. For the used annular channel this velocity was 0.16 m/s. It was not possible to produce the slug at velocities lower than 0.33 m/s due to the slug instability. Fig. 2 shows photos of stationary gas slug. The slug did not occupy the total cross section of the channel. Fig. 3 shows schematically the cross section of the channel. Most part of the channel section is occupied by the gas slug. There is also a section occupied by liquid bridge. Similar structures were observed in the upward slug flow in annular channels [4, 5].

Circumferential angle \( \phi \) shows the position of the measuring points.

![Figure 4](image-url)

Figure 4. Mean wall shear stress a – \( \phi =0^\circ \), b – \( \phi =80^\circ \), c – \( \phi =180^\circ \).
Fig. 4 shows results of wall shear stress measurements vs distance along the slug. Here $\tau_W$ is the time averaged wall shear stress in the measuring point. The origin of coordinate $x$ is in the slug nose (the orifice of the capillary tube). Measurements are performed for different values of circumferential angle $\varphi$ (Fig. 3). Wall shear stress at the outer wall monotonously increases with $x$ at all angles. Similar behavior was observed in experiments with stagnant gas slug in the downward flow in a pipe [7]. In the case of circular pipe all the liquid is transferred into the annular film flowing along the pipe wall. The liquid accelerates under gravity which results in increasing wall shear stress with increasing $x$. In the case of annular channel, part of the total flow rate is converted into the film. Wall shear stress distribution at the outer wall only weakly depends on the angle $\varphi$. For the case of inner wall the behavior is different. The values of wall shear stress at inner and outer walls are close only for $\varphi = 0^\circ$ (region of liquid bridge). In the region of gas slug ($\varphi = 80^\circ$ and $\varphi = 180^\circ$) wall shear stress at the inner wall is significantly lower than at the outer wall. The values of $\tau_W$ are approximately the same for $x > 20$mm which shows stabilization of liquid film thickness.

Figs 5 and 6 show wall shear stress fluctuations at outer and inner walls. Here, relative wall shear stress fluctuation $\varepsilon = \tau_W' / \tau_W$, where $\tau_W'$ is r.m.s. value of wall shear stress fluctuations. The level of fluctuations is approximately the same for the outer wall (of the order of 0.1). The behavior of fluctuations on the inner wall is more irregular. The values of $\varepsilon$ are almost constant for the angles $\varphi = 0^\circ$ and $180^\circ$ (positions of liquid bridge and gas slug). For $\varphi = 80^\circ$ the values of $\varepsilon$ are significantly higher. This value of angle $\varphi$ corresponds to the boundary between gas slug and liquid bridge. The position of this boundary is fluctuating, so this point is alternative in both structures. As can be seen from Fig. 4, the values of wall shear stress on inner wall are significantly different for $\varphi = 0^\circ$ and $\varphi = 180^\circ$. Therefore, the measuring point for $\varphi = 80^\circ$ is in zones of either high or low wall shear stress. This type of intermittency provides high values of wall shear stress fluctuations.
Results of measurements show the complex structure of liquid flow around a stationary gas slug in the annular channel.

**Conclusions**

An experimental study of stationary gas slug in an annular channel has been performed. The shape of the gas slug in the annular channel differs significantly from the shape of the classical Taylor bubble in the circular pipe. The slug loses its axisymmetric shape.

Measurements of mean and fluctuating wall shear stress were performed for different distances from the slug nose on both outer and inner walls of the channel. It has been shown that wall shear stress on the outer wall weakly depends on the circumferential angle. The behavior of wall shear stress on inner wall is significantly different for the regions of gas slug and liquid bridge.

In the region of gas slug the wall shear stress on outer wall is significantly higher than on the inner wall.

Results obtained demonstrate a complex structure of gas slugs in annular channels and can be used for developing CFD models of slug flows.

**Acknowledgments**

The study was performed under state contract with IT RAS III.22.7.3 (AAAA-A18-118051690120-2).

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