Hydrodynamic structure of the flow around a stationary gas bubble in an annular channel

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Abstract. Characteristics of the slug gas liquid flow in an annular channel were studied experimentally. The channel had the diameters of outer and inner tubes of 32 and 10 mm. The liquid flow was downward. The stationary bubble (gas slug) was produced by injecting air through a capillary tube. Wall shear stress measurements were performed by electrodiffusional technique. The measured circumferential distributions of wall shear stress demonstrated a strong non-uniformity across the channel. The highest liquid velocity was in the region of bridge streamlining the bubble. The highest values of wall shear stress fluctuations are in the transition region between gas bubble and liquid bridge.

1. Introduction
Slug gas-liquid flow in pipes and channels is one of the main flow regimes, existing at certain ratios of liquid and gas flow rates. The characteristic feature of the slug flow is the existence of gas inclusions occupying almost all cross-section of the channel. A lot of papers consider slug flows in pipes. In vertical pipes of circular shape the slugs have axisymmetric shape. Several papers consider slug flows in channels of different shapes, e.g., [1]. It was shown that the shape of gas slug in annular channel differs significantly from the classical Taylor bubble typical for circular pipes.

Two-phase flows in vertical non-circular channels (including annular) were studied in [2]. Data on void fraction in two phase flow in vertical and inclined annular channels were presented in [3]. The flow pattern transition in two-phase flow in annular channel was studied in several papers. The flow regime was identified by the analysis of signals from a specially designed impedance probe. An analytical model for a cap bubble flow was presented. An experimental study of interface area transport in an upward two-phase flow in annular channels was performed in [4]. The flow regime was identified using visual observations. Radial distribution of void fraction was measured using local conductivity probe. Most studies of the two-phase flow in annular channel were concentrated 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 limited amount of studies of stationary slugs in annular channels in the literature. In [8] were presented the distribution of wall shear stress along the slug for different angular positions in the annular channel.
2. Experimental technique
An experimental setup was a flow loop closed for liquid. Liquid from a storage tank was pumped by a centrifugal pump to the test section. The liquid flow rate was measured by an orifice meter coupled with a differential pressure transducer.

The outlet orifice of the tube was in 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 at different positions along the bubble. Similar technique was used in [6, 7] to produce stationary gas slug in circular pipes.

The test liquid was distilled water with the addition of potassium ferri- and ferrocyanide and sodium carbonate. 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 electrodiffusional technique [7–9]. 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 0.05x1 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 values of wall shear stress on inner and outer walls were calculated according to recommendations of [10]. 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 inner tube of the annular channel was supplied with a rotating frame to provide the tube rotation. An automatic system ensured the tube rotation for given position, after that the acquisition of the probe current was performed. This allowed obtaining angular distributions of wall shear stress on the inner tube.

Wall shear stress measurements were performed for the values of mean liquid velocity of 0.24 m/s. The velocity of free rise of big bubble in the annular channel of this geometry was 0.16 m/s in stagnant liquid. It the case of downward liquid flow the gas bubble attached to the capillary was unstable at some range of liquid velocities of up to 0.16 m/s. For the $V_L = 0.24$ m/s the bubble was stable.

![Figure 1. Wall shear stress in annular channel for different distances from bubble nose](image)

$\tau_w$ is time averaged wall shear stress on the inner tube. The length of the gas bubble is 200 mm. Measurements are performed for different distances $X$ from the bubble nose (gas injection point). The values of angle $\varphi$ from 0 to about 80 correspond to the region of liquid plug, angles from 80 to 180 correspond to gas bubble.

The distributions of wall shear stress over the pipe circumference are very nonuniform. High values of $\tau_w$ are in the range of angles $\varphi$ from 0 to about 80. This is the region of liquid bridge. Significantly lower values of $\tau_w$ are in the range of angles from 80 to 180 in the region of gas bubble.
Similar angular distributions of wall shear stress are detected in the liquid flow behind the gas bubble. The distributions are qualitatively similar to those shown in figure 1. Low values of $\tau_m$ correspond to angles $\phi$ occupied by gas bubble. In the region of liquid bridge high values of $\tau_m$ are observed. The distributions become smoothed with increasing distance from the bubble.

Figure 2. Records of shear stress in inner wall for different angles, $X = 30$ mm, $V_L = 0.24$ m/s; a $\phi = 140$, b $\phi = 50$ deg.

Typical time records of instantaneous wall shear stress are shown in figure 2. Data are shown for different positions around the gas bubble. In the region of gas bubble there are relatively low fluctuations of wall shear stress. In the region of liquid bridge the frequency of fluctuations becomes higher, and the level of $\tau_m$ also significantly increases. A high level of fluctuations shown in figure 2b corresponds to the transition zone between gas bubble and liquid bridge. In this case the flow exhibits some kind of intermittency caused by the fluctuation of the position of side boundary of the gas bubble.

The values of relative wall shear stress fluctuations are presented in figure 3. Here, $\tau'_w$ is r. m. s. value of wall shear stress fluctuations. The vertical line shows the position of the bubble bottom. In the regions of gas bubble (a) and liquid bridge (b) the values of $\tau'_w/\tau_w$ are 0.1 to 0.15 for the values of $X$ corresponding to the gas bubble. For higher $X$ values, in the region of liquid plug after the bubble, the values of $\tau'_w/\tau_w$ increase significantly. This is connected with the vortex type flow after the bubble.

Figure 3. Relative wall shear stress fluctuations in annular channel.  
a – Gas bubble area. b – liquid plug area.

In the case of stationary gas bubble in the circular tube all the liquid flow rate is converted into an annular liquid film around the bubble. The characteristics of this film were studied in [11]. For the case of annular channel, the total flow rate is split in three components: liquid films on both walls of
the channel and the flow in the liquid bridge. Figure 1 shows that the values of \( \tau_w \) around the bubble are of the order of 2 Pa for all values of \( X \). This shows that the liquid film around the bubble is stabilized. The estimated thickness of this film is about 0.2 mm. So only small part of the liquid flow rate goes into liquid films. The most part of the liquid flows in the liquid bridge. However, both walls of the channel around the bubble remain wet.

**Conclusions**

The hydrodynamic structure of liquid around a stationary gas bubble in an annular channel has been studied experimentally. Both mean and fluctuating wall shear stress have been measured using an electrodiffusional technique. Distributions of flow parameters over the pipe circumference have been obtained for different distance from the bubble nose.

The stationary gas bubble does not occupy the whole cross section of the channel. The downward flow of liquid is split into film flows along channel walls and the bridge flow in the region free of the bubble. The values of mean wall shear stress are significantly higher in the bridge flow compared to that in the liquid film. So, the major part of the liquid flow rate passes in the region of the bridge flow.

The relative value of wall shear stress fluctuations is low in the region of liquid film. The highest values of fluctuations correspond to the boundary between liquid film and bridge flow due to flow intermittency.

The experimental data obtained show a significant difference of flow structure at the motion of big gas bubbles in circular pipes and annular channels.

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**References**

[1] Kelessidis V C and Dukler A E 1990 *Int. J. Multiphase Flow* **16**(3) 375–90
[2] Sadatomi M, Sato Y and Saruwatari S 1982 *Int. J. Multiphase Flow* **8** 641–55
[3] Hasan A R and Kabir C S 1992 *Int. J. Multiphase Flow* **18** 279–93
[4] Ozar B, Jeong J J, Dixit A, Julia J E, Hibiki T and Ishii M 2008 *Chemical Engineering Science* **63** 3998–4011.
[5] Nakoryakov V E, Kashinsky O N, Petukkhov A V and Gorelik R S 1989 *Experiments in Fluids* **7** 560–6
[6] Kockx J P, Nuewstadt F T M, Oliemans R V A and Delfos R 2005. *Int. J. Multiphase Flow* **31** 1–24
[7] Kashinsky O N, Kurdyumov A S and Lobanov P D 2008 *Thermophysics and Aeromechanics* **15**(1) 85–9
[8] Kashinsky O N and Kurdumov A S 2020 *Journal of Physics: Conference Series* **1677** 012061
[9] Nakoryakov V E, Timkin L S and Gorelik R S 2017 *Journal of Engineering Thermophysics* **26** 303–13
[10] Lawn C J and Elliott C J 1972 *Journal Mechanical Engineering Science* **14**(3) 195–204
[11] Ahmad W R, DeJesus J M and Kawaji M 1998 *Chemical Engineering Science* **53**(1) 123-13013