Movement of gas slug in annular channels with different diameter ratios

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Abstract. The motion of gas slugs in annular channels was studied experimentally. The outer tube diameter was 32 mm. The inner tube diameter varied from 4 to 25 mm. The gas slugs were produced by injecting air through a capillary tube. The shapes of gas slugs were studied by high-speed videos. The paper presents data on the rise velocity of gas slugs in the channels, and wall shear stress measurements, performed by electrodifusional technique. The probes were mounted on both walls of the channel. The evolution of wall shear stress during slug passage was recorded.

1. Introduction
Gas-liquid slug flow in pipes and channels is one of the main flow regimes which exists at definite ratios of liquid and gas flow rates. The characteristic feature of slug flow is the existence of gas inclusions occupying almost the entire channel cross-section. A lot of papers consider slug flows in pipes. In vertical pipes of circular shape, the slugs have an axisymmetric shape. Several papers consider slug flows in channels of different shapes, see for example [1]. It was shown that the shape of the gas slug in the 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 a 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 an annular channel was studied in several papers. The flow regime was identified based on 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 an annular channel was performed in [4]. The flow regime was identified based on visual observations. Radial distribution of void fraction was measured using a local conductivity probe. Most studies of two-phase flow in the annular channel were concentrated on flow pattern transition and measurements of gas-phase characteristics. The flow structure of the liquid phase was considered in [5]. Wall shear stress was studied during a single slug motion in a channel.

The paper presents experimental data on the shape of gas slugs and liquid flow during gas passage in annular channels with a different diameter ratio of inner and outer tubes.

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 experimental setup is described in detail in [8].
The test section was a plastic tube 32 mm inner diameter. A central tube was mounted inside it concentrically to produce an annular channel. Inner tubes of different diameters were used, namely, 4, 6, 10, 20, and 25 mm. So the hydraulic diameter of the annular channel varied from 28 to 7 mm.

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 [5, 6]. Wall shear stress probes were mounted in the outer and inner pipes. The sensitive element of the probe was a platinum foil 0.05 mm thick 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 wall shear stress on inner and outer walls was calculated according to the recommendations of [7]. The correlation of probe current vs wall shear stress obtained from calibration was used for measurements in the slug flow.

Air from a pressure vessel was injected into the flow through a capillary tube. The volume of gas injected was controlled by a quick closing valve operating by an electronic circuit.

3. Results of experiments

Visual observations and high-speed videos of gas slug passage were performed in channels with different inner tubes. Typical still photos of gas slugs in the channels are shown in Fig. 1. In all cases, the slugs have an asymmetric shape. The region of the gas slug does not occupy the whole cross-section of the channel. There is the region of the liquid bridge through which the liquid flows around the slug. This region remains even in the channel with a small inner tube diameter.

![Figure 1. Photos of gas slug in annular channels. a - Dinn = 4 mm, front view; b - Dinn = 25 mm, front view, c - Dinn = 25 mm, side view](image)

The rise velocity of gas slugs was determined from the videos. Results of measurements are shown in Fig. 2. The rise velocity of gas slugs in still liquid almost does not depend on the inner tube diameter. The velocity is the same as in the circular tube with the diameter of the outer tube of the annular channel. A slight increase of rise velocity was detected only for the smallest Dh.
Figure 2. The velocity of gas slug in the annular channel.

Fig. 3 shows the evolution of wall shear stress on inner and outer tubes during gas slug passage. X is the distance from the slug nose. The values of wall shear stress increase monotonously with increasing X on both walls of the channel. However, the values of $\tau_w$ on the inner wall are lower at $D_h = 22$ mm. This difference becomes less with decreasing $D_h$. In the case of $D_h = 7$ mm the values of $\tau_w$ on both walls are practically the same.

Figure 3. Wall shear stress in the annular channel depending on the distance from the slug nose.

It can be seen from Fig. 3 that at high values of X the values of $\tau_w$ do not depend on the distance from the slug nose. This means that the liquid films on both walls of the channel become stabilized. The thickness of liquid films can be estimated from the values of $\tau_w$.

Visual observations of the slug motion show that the slugs rotate around the channel axis during their motion along the channel. This makes it impossible to measure the distribution of wall shear stress around the channel circumference. To obtain this distribution, experiments with stationary gas slugs were performed. The slug was “suspended” in the downward liquid flow in an annular channel.

Typical distributions of wall shear stress in the gas bubble region are shown in Fig. 4. Here, $\phi$ is the circumferential angle, $\tau_{m}$ is time-averaged wall shear stress on the inner tube. The length of the gas bubble was 200 mm. Measurements were performed for different distances X from the bubble nose (gas injection point). The values of angle $\phi$ from 0 to about 80 correspond to the region of the liquid plug, angles from 80 to 180 correspond to gas bubble.
Figure 4. Wall shear stress in the inner tube around gas slug in annuli.

The distributions of wall shear stress over the pipe circumference are very nonuniform. High values of $\tau_{w}$ were detected in the range of angles $\phi$ from 0 to about 80. This is the region of the liquid bridge. Significantly lower values of $\tau_{m}$ are in the range of angles from 80 to 180 in the region of the gas bubble.

Conclusions
The motion of gas slugs in annular channels was studied experimentally. The channels had different diameters of the inner tube, the hydraulic diameter changed from 7 to 28 mm.

In all cases, the gas slug had an asymmetric shape. This differs the slug flow in annular channels from that in a circular pipe. The gas slug does not occupy the whole cross-section of the channel. The relative flow of liquid was split into film flows along channel walls and bridge flow in the region, free of the bubble. The evolution of wall shear stress along the slug was measured. Lower values of wall shear stress were obtained on the inner wall of the channel. The difference between inner and outer walls becomes less with decreasing hydraulic diameter.

The distribution of wall shear stress around the channel circumference showed that a significant portion of the liquid flow rate flows in the liquid bridge around the gas slug.

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

The work is fulfilled in the framework of the state contract with IT SB RAS

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