Dynamics of gas slugs in a vertical annular channel

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Abstract. Experimental studies of gas slug motion in an annular channel were performed. The channel consisted of two concentric pipes with the diameters of 32 and 10 mm. Experiments were performed for different values of liquid velocity. Slug velocity was measured using optical sensors. Wall shear stress measurements were performed using an electrodiffusional technique. It was shown that the shape of the slug in the annular channel differs significantly from that in a pipe. The distribution of wall shear stress along the slug was presented for different positions of the slug.

1. Introduction
Gas-liquid slug flow is one of the main regimes, existing at definite ratio of liquid and gas velocities. A lot of papers studied the characteristics of slug flow in vertical pipes. It was shown that the rise velocity of the gas slug does not depend on its length and can be determined from the rise velocity in stagnant liquid. Most of the papers considered characteristics of gas phase (slug length and velocity, frequency of slugs). A review of slug flow studies is presented in [1].

Liquid phase characteristics were studied in several papers. An electrodiffusional technique was applied for measurements of wall shear stress in slug flow in [2,3]. The conditional sampling technique was used to obtained liquid velocity profiles and wall shear stress distribution.

Most of the studies of slug flows were performed in circular pipes of different diameters. Studies of slug flow in channels of different geometries were presented only in several papers.

Two-phase flows in vertical non-circular channels (including annular) were studied in [4]. Data on void fraction in two phase flow in vertical and inclined annular channels were presented in [5]. The flow pattern transition in two-phase flow in annular channel was studied in [6]. The flow regime identification was made from 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 [7]. The flow regime was identified using visual observations. Radial distribution of void fraction was measured using local conductivity probe.

The studies of 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 not considered in these papers.

The purpose of the present paper is the study of slug flow in an annular channel. Liquid phase characteristics were measured by electrochemical technique.

2. Experimental technique
Experiments were performed on a flow loop closed for liquid. Liquid from a storage tank was supplied to the test section by a centrifugal pump. The liquid flow rate was measured by an orifice meter. The
test section was a vertical pipe with 32 mm inner diameter 1.8 m long. An inner tube with 10 mm outer diameter was mounted in this tube coaxially producing an annular channel. The hydraulic diameter of the channel was 22 mm. Gas was supplied to the liquid flow through a tube of 4 mm inner diameter. Gas was supplied from a vessel in which a constant pressure was maintained. A high speed electromagnetic valve was mounted at the outlet of the gas vessel. The valve was controlled by an electric signal. The length of the gas slug was changed by changing the length of the electric pulse.

The test 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 electrodiffusional technique. A wall shear stress probe was mounted in the outer pipe. 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 probe was calibrated in the single flow in the tube of 32 mm inner diameter. The central tube was removed during calibration. 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.

Two optical sensors were installed on the outer tube. Each sensor consisted of a laser module and a photodiode placed at the outer part of the tube. The distance between the sensors was 230 mm (along the tube). The sensors were used to determine the moments of slug passage in the tube cross section. The sensors were tuned in the following way. When the outer tube was filled with liquid, the laser ray came to the photodiode which corresponded to the upper level of the sensor. If the gas slug passed in the cross section of the sensor, the laser beam was deflected, the photodiode was not illuminated, and the sensor maintained the lower level of the signal. When these sensors were used in the annular channel, the sensors were tuned so that the laser ray did not touch the inner tube. These sensors were used to determine the moments of gas slug passage in the given cross section and also to determine the slug velocity.

3. Experimental results

Experiments were performed both in the tube and in the annular channel. The system of gas supply was the same in both cases. Experiments were performed for different values of superficial liquid velocity. For comparison, the case of zero liquid velocity (stagnant liquid) was also considered.

Figure 1 shows typical photos of gas slugs in the pipe and in the annular channel. The shape of the slug in the pipe was classical Taylor bubble [1]. Gas phase occupied most of the cross section of the pipe. The liquid flowed around the bubble producing an annular film. The shape of the slug was close to axisymmetric. In the case of annular channel, the shape of the slug was significantly different. The slug wrapped around the central pipe but it did not occupy the entire circumference. There was some narrow liquid bridge between adjacent borders of the slug. The angular position of this bridge rotated during slug motion along the channel. The shape of the cross section of the slug is schematically shown in Figure 2.

It was possible to define two positions of the slug as shown in the Figure. Position 1 corresponds to the gas part of the slug, position 0 corresponds to the liquid bridge.

Results of slug velocity measurements are presented in Figure 3 for both cases. There is a linear dependence of the slug velocity vs the liquid velocity. The coefficients in linear correlations are close for the pipe and for the annular channel. In the pipe, the velocity of slug depends on the velocity of liquid as \( U_s = 1.18 U_l + 0.22 \). In the annular channel, the velocity of slug depends on the velocity of liquid as \( U_s = 1.17 U_l + 0.25 \).

The wall shear stress probe was mounted in the annular channel between two optical sensors. During the experiments, the records of instantaneous wall shear stress in time were performed for all cases. The distribution of wall shear stress vs length was obtained using measured values of slug velocity. Results of measurements of wall shear stress distribution vs length (along the channel axis) are presented in Figures. 4 and 5. The zero position of the length corresponded to the head of the slug.
recorded by the optical sensor. The total length of the slug is marked in the Figures by red line. Results of measurements both in stagnant liquid and in the flow are presented. Measurements of wall shear stress were performed in both positions of the slug (Figure 2).

Figure 1. Photo of slug in a pipe and in an annular channel.

Figure 2. Scheme of slug in annular channel.

The values of wall shear stress decrease significantly during gas slug passage. This corresponds to the downward flow of liquid film around the slug. Minimum values of wall shear stress are attained at the slug bottom, after that the wall shear stress again attains positive values. High amplitude fluctuations of wall shear stress take place just after the slug in the liquid plug. The behavior of wall shear stress in the annular channel correlates well with similar measurements in a pipe [8]. The minimal values of wall shear stress are close for both cases in spite of strong flow asymmetry. However, the shape of the signal differs significantly in the region after the slug.

Figure 3. Velocity of rising slug in a pipe. a – pipe, b – annular channel.
Fig. 4. Wall shear stress under slug in annular channel, position 0.
   a – stagnant liquid, b – Ul = 0.25 m/s.

Fig. 5. Wall shear stress under slug in annular channel, position 1.
   a – stagnant liquid, b – Ul = 0.25 m/s.

Conclusions
An experimental study of slug dynamics in an annular channel was performed. The main features of the flow were obtained.

The shape of the gas slug in annular channel differs significantly from the shape of the classical Taylor bubble in a circular pipe. The slug loses its axisymmetric shape.

The rise velocity of slugs in annular channel can be determined using correlations in a vertical circular pipe both for stagnant liquid and for different liquid velocities.

Records of wall shear stress during slug passage were performed. It was shown that wall shear stress increases significantly during slug motion. The ensemble averaged wall shear stress evolution does not depend on the angular position of the slug.

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