Experimental study of the local structure of a bubble flow in a flat channel with sudden expansion

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Abstract. The hydrodynamic structure of the flow in a flat channel with sudden expansion was studied at constant flow rates of liquid and gas in the vertical flow at $Re = 6600$ and gas content $\beta = 0.03$. The measurements were carried out using the PLIF method; and with this view, fluorescent particles for PIV studies and the dye Rhodamine G were added to distilled water. An optical threshold filter was installed on the lens of the video camera. When processing images to obtain data on the local gas content, only bubbles falling into the plane of the laser beam were considered (the boundary glows, casting a shadow).

1. Introduction
An important problem in the creation of energy-efficient equipment is the study of passive heat transfer intensifiers. Often, for this purpose, devices with flow separation are used. Such devices are simple and reliable; therefore they are frequently used in various technical devices, including high-energy equipment and burner chambers.

One of the simplest examples of such equipment is channel or pipe with a sudden expansion. Due to intensive vortex formation after expansion, a significant intensification of heat exchange processes occurs. Despite a rather large amount of research, a number of questions are still open even for single-phase flow.

The effect of the sudden expansion of the channel on the flow structure and on the coordinate of boundary layer reattachment was studied in [1]. The influence of periodic disturbances directed into the main flow or near-wall region was considered [2]. Impacts were created using electromechanical or aerodynamic (jet) generators. The velocity profiles in a channel with a backward-facing step obtained using the PIV method were shown. In addition, data on turbulent fluctuations in a given current was presented. Our previous works [3, 4] related to determination of motion characteristics of bubbles in a channel with sudden expansion, but hydrodynamics of liquid phase in two-phase flow was not taken into account.

The purpose of this study is to measure the velocity distributions by means of PIV in order to obtain information about fluctuation characteristics of the flow. Pressure drop behind the sudden expansion of the flat channel is studied as well.

2. Experimental setup
The scheme of the test section is presented in figure 1. Experiments were carried out at liquid flow rate of $2.6 \text{ m}^3/\text{h}$ ($Re = 6600$). The experimental setup was a closed loop. The test liquid, i.e., distilled water, was pumped from the main tank through the flow measurement system and pressure water supply. For
flow measurement, an ultrasonic flow meter was used. Uncertainty of flow measurement was 2 percent of the measured value. The work area was a flat canal with dimensions of 1000x200x20 mm. To create a sudden expansion, a flat 600 mm long and 12 mm high insert made of plexiglass was mounted into it. The step height \( H \) was 12 mm. In the experiments the liquid temperature in the loop was controlled in the range of 25.9–25.1°C by the automatic system of thermal stabilization. At the inlet of the test section, the honeycomb grid was installed.

To measure the velocity profile in the channel PIV and LDA were used. Polyamide particles with sizes of 20÷50 microns were added to the liquid. LDA system LAD-05 was used. The movement of the laser measurement volume was carried out automatically using the control-moving device at the given coordinates. The grids were built using appropriate software. The coordinate grid represented a set of points with a certain step spanning the channel from the near to the far wall. The pitch was 0.5 mm across the main channel width. Near the walls, the pitch was reduced to 0.1 mm due to the required increase in measurement accuracy. After obtaining the velocity profile at a certain distance from the step, the coordinate device moved to collect data on the next distance from the step, where the velocity measurement started again. After the measurements were completed, the obtained data was exported to the program for post-processing. High power green laser knife and CCD camera was utilized both for the flow visualization and organization of PIV measurements.

![Image](image.png)

Figure 1. Experimental setup: (a) the scheme of measurements; (b) the test section geometry; (c) the photograph of the test section.

3. Experimental results
As a result of PIV data processing it was found that in a vertical flow with a sudden expansion, smaller bubbles are drawn into the vortex motion behind the step, forming a profile of the local gas content with maxima near the channel walls. This is a significant difference from the case of a horizontal flow, in which bubbles of any size move near the upper wall of the channel. Bubbles of larger sizes move in the
high-speed region of the flow, as in the case of horizontal flow, however, the average distance from the wall to the centers of bubbles in the vertical flow is higher than in the horizontal one.

Behind the expansion of the channel, the images of bubbles have a complex shape, significantly different from spherical, and three different subspecies, depending on their position relative to the plane of the laser sheet. The processing of such images is an extremely difficult task and in our experiments was used only to determine the position and velocity of bubbles in a vertical flow. For the horizontal flow, the shadow shooting method was preferable. A new method was proposed to determine the velocity of the liquid phase [5]. For its implementation, fluorescent tracers were added to the stream, but no dye was added. As in the previous case, an optical filter was used. In this case, there were tracer distribution fields on the images, and the bubbles remained “invisible”. For such images, it was possible to use PIV algorithms without preliminary processing and subtraction of bubble images.

As a result, a database of experimental data has been obtained at various flow rates of liquid and gas. At relatively low flow rate gas contents ($\beta < 0.03$), the addition of a dispersed phase to the flow is shown to lead to a decrease in the length of the separation zone of the flow and an increase in the degree of turbulence of the carrier phase. It is clearly seen that the separated region is over for two-phase flow in this region of the flow in a contrast to single phase flow (see figure 2). The LDA measurements were carried out in single phase flow in order to verify the proposed PIV approach. A good agreement was found for two methods. It was found that, in comparison with the two-phase flow in a pipe with sudden expansion [3, 5], the gas in the centerline of a flat channel has a stronger effect on the flow structure, especially in separation region of the flow. The photo of such flow is shown in figure 3. It is possible that the observed effects are associated with an increase in the gas content in the central part of the channel.

At medium gas contents ($0.03 < \beta < 0.09$), the addition of bubbles leads to the formation of self-sustained vortex structures (see figure 4). The lifetime of such structures can be exceedingly long.

![Figure 2](image-url)  
**Figure 2.** Liquid velocity distribution at a distance $6H$ from the step $Re = 6600, \beta = 0.03$.  

This effect is not caused by the geometric position of the channel, which was carefully placed vertically using a laser level. It has been found that the movement of the vortex structure of the flow can occur when some capillaries supplying gas are temporarily blocked, after which a stable vortex structure is formed on the other side of the flow. At the beginning of the flow formation or in the event of a random event, a larger amount of gas begins to move at one of the channel walls, which further leads to a restructuring of the flow structure. The formation of such structures can be explained by the so-called “chimney effect”, where flow asymmetry occurs due to different densities in different areas. For bubble flows in pipes, this effect was found in the works of Lahey, Wang and Kashinsky, Gorelik et al. When such structures appear, the transverse velocity of movement of a large number of bubbles and an increase in the local gas content in the region of the transverse vortex are observed. At small $\beta$ and in a single-phase flow, the flow is symmetric, as was shown earlier in the framework of the project. In addition, during the formation of asymmetric flow regimes, a significant restructuring of the flow occurs in the central part of the channel.

A further increase in the gas flow rate leads to a decrease in the lifetime of such vortex structures and a rapid change in flow regimes occurs. At higher gas contents ($\beta > 0.1$), a flow is formed, with a maximum gas content in the central part of the channel, and return areas are formed near the channel walls. The presence of such structures complicates the comparison of the experimental and numerical data; the use of eddy-resolving means of computational fluid dynamics and complex computational domains is required. In general, a comprehensive experimental and theoretical study of such flow regimes is necessary.

**Conclusions**

A study of the hydrodynamic structure of a two-phase bubbly flow at constant flow rates of liquid and gas at $Re = 6600$ and $\beta = 0.03$ was carried out in a vertical rectangular channel with sudden expansion. It was found that the introduction of the gas into the flow reduces the length of the separation zone. It was shown that when a random event occurs (for example, the shutdown of some capillaries for gas injection), the unsymmetric vortex structure can occur due to different densities in the channel sectors. With an increase in the void fraction, the lifetime of such structures decreases.
Acknowledgments
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