Effect of static pressure on friction reduction at gas saturation on turbulent boundary layer

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Abstract. The effect of static pressure on regularities of turbulent friction reduction by means of a bubble method at gas injection through a permeable wall has been experimentally studied in this work. The flat model (955 mm long) with gas saturation of the turbulent boundary layer was tested at the hydrodynamic setup of the Institute of Mechanics of Moscow State University within the ranges of flow velocity $U = (4 - 11)$ m/s and static pressure $P = (10 - 200)$ kPa. The Reynolds number along the plate varied within the range of $(3 - 8) \times 10^6$. Tangential stresses on the plate surface (plate on bottom) were measured directly by the “floating wall” sensor on tensoscales, located at the distance of 50 mm behind the porous coating. This paper presents data on local friction on the plate vs. gas flow rate, flow velocity and static pressure. It is shown that reduction of local friction at gas saturation of a turbulent boundary layer depends essentially on the static pressure, which should be taken into account by integral evaluation of method’s efficiency, considering energy losses for gas blowing through the permeable coating.

1. Introduction
One of the most promising methods for reducing turbulent friction on bodies moving in water is the gas saturation of the turbulent boundary layer (TPS), which has high efficiency (up to 80% or more), simplicity of design and environmental friendliness. In most cases, microbubbles are formed at gas injection into the boundary layer through a porous wall or special narrow slit. When assessing effectiveness of the method, it is necessary to take into account not only reduction of shear stresses in turbulent boundary layer (TBL), but also the energy costs for gas blowing through a porous wall to create a bubble layer, which strongly depend on the static pressure or model deepening.

The idea of hydrodynamic friction reduction by pushing the water flow from the wall by means of (an air layer) was first expressed by Froude in 1875. It was assumed that it would be possible to reduce friction of water substantially by blowing air into the near-wall part of the flow. At that, the multiple effect of reducing the tangential stresses on the wall will be obtained due to “gas lubrication”, i.e., very low air viscosity and density in a thin film separating water from the streamlined wall. Theoretical studies carried out within the framework of a homogeneous model of a gas-liquid mixture showed that in a turbulent boundary layer with variable density and viscosity, the effect of multiple reduction of friction can be obtained [1, 2].

In the first publication on this topic [3], it was reported that resistance of the towed model (body of revolution) with a length of 0.915 m, diameter of 0.127 m at motion velocity of 0.32 $\pm$ 2.6 m/s, can be decreased to 30%. A copper wire was laid around the model, and bubbles with the diameter of about 60 µm were generated by electrolysis.
In earlier works on gas saturation of TBL (in Russia), the shear stresses were reduced to (80-90)%, local distributions of friction, friction and pressure pulsations, and gas concentration profiles were investigated in a wide range of parameters [4–12]. Testing of these results and further studies of gas saturation of TBL was carried out in the USA [13–18]. Later, gas saturation of TBL on a plate (plate on top) at large Reynolds numbers of up to $2 \times 10^8$ was studied in [19, 20]. When gas was injected through a porous wall, the flow with almost continuous gas film was firstly obtained on a plate with the length gradient of 12.9 m and zero pressure gradient. Reduction of local friction, close to 100%, corresponded to this flow practically over the entire length of the plate. The video of the wall zone showed that this result was obtained at the flow velocity of 6 m/s due to coalescence of gas bubbles that floated to the wall under the action of buoyancy, merged and created an almost continuous gas film. When the flow velocity was increased to (12-18) m/s and gas was injected into the TBL, the bubble flow of the gas-liquid mixture was implemented, and the effect of local friction reduction downstream decreased from a maximum (80%) to (5-10)% at the distance of 3-4 m behind the gas generator. In subsequent experiments, it was possible to achieve the “gas” lubrication regime for the flow velocities of up to 15 m/s.

The works of Japanese researchers on this topic present the results of successful application of the bubble method of reducing turbulent friction on the plates with the length of up to 50 m and full-size ships [21-25]. When testing the tanker models with the plate length of 20, 40 m and width of 0.6 m, friction reduction of ~ 30 and 15% was obtained, and on the plate of 50-m length and 1-m width at the towing velocity of 7 m/s in a special basin, 10-15% reduction was obtained. In the full-scale experiment, using a training ship SEIUN-MARU (length of 105 m), reduction in the friction loss of 3% was obtained, and net energy saving was 2% for the ship velocity of 7 m/s. A review of studies on the topic can be found in [26-28].

The purpose of experiments performed at setup of the Institute of Mechanics of Moscow State University was to study the effect of static pressure on the value of decrease in hydrodynamic friction in the wall gas-liquid flows.

2. Experimental setup and research methods
The effect of static pressure on friction reduction at gas saturation of TBL was studied experimentally at the hydrodynamic setup of the Institute of Mechanics of Moscow State University. The flow velocity in the test section of setup can reach 25 m/s at static pressure variation from 0.02 to 8 atm. A flat model of 955 mm (length)×244 mm (width)×40 mm (thickness), whose longitudinal cross-section is shown in Fig. 1, was mounted along the axis of symmetry in the middle of a rectangular working part with cross-section of 120x1000 mm and length of 2000 mm.

![Figure 1. Scheme of experimental setup of the Institute of Mechanics of MSU (1, 2, 3 points of pressure measurements).](image)

The static pressure was measured at points 1-3 on the upper wall of the tube. The impenetrable front of the model was 80 mm long, the nose of the plate had the shape of an ellipsoid with semiaxis ratio of 1:4. A special permeable coating, assembled from 0.8-mm thick plates (D16T) with the risks on the side surface, was used on the plate for gas saturation of TBL. It consisted of three identical sections with the length of 180 mm, separated by 20-mm impermeable inserts. Gas permeability of the porous
coating was 0.35 (cm$^2$/atm×s), the average pore size was 1 μm, and surface porosity was about 1%. The shear stress on the plate surface (plate on the bottom) was measured directly by the “floating wall” sensor on tensoscales (with registering by the self-recorder EZ-2), located at the distance of 50 mm behind the porous coating. The area of the sensitive surface of the “floating wall” was 36×25 mm$^2$, and clearance was 0.18 mm. The measurement error was 5%. The model was tested within the ranges of flow velocity $U = (4 - 11)$ m/s and static pressure $P = (10 - 200)$ kPa. The Reynolds number along the length of the plate was $(3-8)×10^6$.

3. Results

Results of local friction measurements on the plate are shown in Fig. 2 for four flow velocities ($U$) at initial static pressure ($P_0$) equal to the atmospheric pressure. The difference between the measurement results and standard design values in a single-phase flow was not higher than 10% [29].

The effect of static pressure on reduction of friction at gas saturation of TBL was studied in the following manner. The gas flow through the permeable coating of the plate was set at a given initial static pressure. With a subsequent increase in the static pressure in experiments of up to 200 kPa, the gas flow was kept constant. Relative dependence of the local friction on the plate on gas flow rate coefficient ($C_q$) at the static pressure of 10 kPa is shown in Fig. 3. Here, gas flow rate coefficient

$$C_q = \frac{Q}{US}$$

is shown along the abscissa axis, where $Q$ (m$^3$/s) is the gas flow reduced to normal conditions, $S$ (m$^2$) is the area of the porous coating, and the ratio of local friction coefficients on the plate in the one- ($C_{f0}$) and two-phase ($C_f$) flow is shown along the ordinate axis. As we see, with an increase in the gas flow rate to the optimum value, the local friction on the plate decreases at all flow rates. The maximal effect of friction reduction is (80-90)% at $U = 10.9$ m/s and $C_q = 1.3×10^{-3}$. With excessive gas saturation of TBL (above optimal), this effect worsens. We should note that at flow velocity (4-6) m/s and $C_q < 0.5×10^{-3}$, the local friction on the plate increases by 2-4%. With the same gas flow rate coefficient ($C_q = \text{Const}$), the effect of shear stress decrease becomes stronger with increasing flow velocity, noted in [4]. However, if the surface is oriented in the opposite direction relative to the gravitational force vector (plate on top), it is shown in [13] that for gas saturation of TBL, a decrease in the flow velocity leads to a decrease in local friction because the bubbles move to the plate surface under the effect of buoyancy, creating large concentration. At flow velocity higher than 10 m/s, the buoyancy effect of the bubble cloud at gas saturation of TBL no longer has a significant effect on the reduction of local friction.
Figure 3. Local friction vs. coefficient of gas flow rate $C_q$ at initial pressure $P = 10$ kPa.

The results of measuring the local friction for three flow velocities at the static pressure of 80 kPa are shown in Fig. 4. The general laws governing the reduction of local friction at gas saturation of TBL are similar. The quantitative characteristics changed as follows: at $U = 10.9$ m/s and $C_q = 10^{-3}$, the effect of friction decrease was reduced to 60%; at $U = 4.55$ m/s, to reduce the friction by 30% it was required to increase the gas flow rate by the factor of 1.5.

Figure 4. Relative dependence of local friction on coefficient of gas flow rate $C_q$ at static pressure $P = 80$ kPa.

The effect of friction reduction at gas saturation of TBL on the plate vs. a change in the static pressure for flow velocity $U = 10.9$ m/s and four gas flow rates $Q = (0.5 - 1.85)$ l/s (solid lines) is shown in Fig. 5. A relative change in the static pressure is plotted along the abscissa axis ($P_0 = 100$ kPa), and relative variation of the local friction on the plate at gas saturation of TBL is plotted along the ordinate. As follows from the graph, the increase in static pressure leads to a decrease in the effect of reducing friction in the gas saturation of TBL by exponential law. Moreover, the greatest changes in shear stresses are observed with an increase in the static pressure within the...
range up to $P_0$. The reason for this effect is apparently a decrease in volumetric concentration of gas in the TBL (especially in the wall region of the plate) associated with an increase in the static pressure at a constant gas flow through the permeable coating. For comparison, the graph shows the measurement results at $U = 6.55$ m/s and $Q = 0.925, 1.39$ and $1.85$ l/s (dashed lines), which correspond to gas flow rates at $U = 10.9$ m/s. The dependence of the decrease in friction on static pressure also has an exponential form, but with less steepness. The data [30] (round light points) for $U = 11.1$ m/s and $Q = 1$ l/s confirm this regularity.

Figure 5. Effect of friction reduction at gas saturation of TBL vs. static pressure.

4. Conclusions
The influence of static pressure on the effect of friction reducing at gas saturation of TBL on a plate (plate on the bottom) was studied at the hydraulic setup of the Institute of Mechanics of Moscow State University. Local friction was measured by the “floating wall” sensor on the tensoscales. It is shown that an increase in the static pressure leads to a significant decrease in the effect of gas saturation of TBL. The reason for friction reduction is, apparently, a decrease in the volume concentration of gas associated with an increase in static pressure. Thus, the effect of friction reduction is a function of two variables (with other things being equal): gas flow rate and static pressure.

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5. References
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