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Velocity fluctuations in the Reynolds experiment at low degree of supercriticality

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The results of an experimental study of the distribution of velocity fluctuations in the Reynolds experiment at low degree of supercriticality $n = 0-0.3$ are presented. It is shown that for an intermittent flow in the range of intermittency coefficients of $\gamma = 0.5-0.85$, the distribution of fluctuations over the cross section has three maxima. The results obtained are in good agreement with the previously obtained theoretical estimates.

Keywords: laminar-turbulent transition, Reynolds experiment, low degree of supercriticality, intermittency, turbulent structures.

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In recent years, significant progress in the study of laminar-turbulent transition has been made [1] in the study of flow in pipes where the intermittency scenario is realized. An analogy with critical phenomena in physics is found [2]. In connection with that, the parameter of supercriticality, which characterizes the excess of the actual value of a physical parameter over its critical value, is widely used. This approach is used in Rayleigh–Benard convection, in Taylor–Quette cell, and in flow on a plate, where Rayleigh, Taylor, and Reynolds numbers are used as the physical parameter [3]. In modern studies in tubes, the internal structure of single turbulent regions (hereinafter referred to as „puff" type structures) and their interactions have been mainly studied [1]. At the same time, for calculation of heat and mass transfer coefficients in channels in the regime of transition to turbulence, statistical characteristics of the flow, for example, distribution of velocity pulsations along the pipe cross-section, are often in demand.

Such a problem was first considered in [4] using the intermittency parameter $\gamma = T_t/T$, where T_t — the total time taken by the turbulent part in the oscillogram, T — the total sampling time. The calculation was based on the assumption that in the intermittent flow of laminar and turbulent flow regions, the mean velocity profile is correspondingly evolved from a laminar profile to a developed turbulent profile and vice versa. This rearrangement sets the profile of the velocity pulsation distribution in the channel cross section. The pulsation distribution was calculated for $\gamma = 0.5$, with one half of the sampling time the mean velocity profile is developed turbulent and the other half (in between the turbulent parts) — laminar (Poiseuille). The calculation showed that the distribution of pulsation intensity along the radius has three local maxima (near the walls and on the pipe axis), i.e. a three-mode distribution was obtained. As it turned out, in the considered case, the turbulence level on the axis is much higher than in the laminar or turbulent flow regime.

It was further shown experimentally [5,6] and numerically [7] that the mean velocity profile within a single turbulent region rapidly evolves to the profile, which is specific for a developed turbulent flow. The maximum growth of turbulent pulsations is observed in the near-wall region of the pipe, and on the axis their growth is minimal. In these works, a three-mode distribution of velocity pulsations was not found. In the [8] experiments, three maxima in the distribution of velocity pulsations were observed, as well as its increased values at the pipe axis in the intermittent flow regime, but the obtained data were not analyzed. The present work is devoted to the study of velocity pulsations distribution along the channel cross-section at small values of the supercriticality parameter $n = (\mathrm{Re} - \mathrm{Re}_{cr})/\mathrm{Re}_{cr}$ in the intermittent flow regime. Here Re_{cr}, $\mathrm{Re} = U_m d/\nu$ — critical and current Reynolds number values (U_m — bulk velocity of gas through a tube of diameter d; ν — kinematic viscosity).

The experimental setup consisted of a test section, a working gas supply system, and a measurement system. The test section was a cylindrical tube over 100 diameters long to which the working gas was supplied. The gas flow rate was set by a Bronkhorst regulator. The dynamic flow parameters were measured at the outlet of the tube. A DISA constant temperature DISA 55M hot-wire anemometer with a DISA 55P11 single-strand miniature sensor and a PIV-system (PIV — particle image velocimetry) consisting of a Laser Photonics DM high-speed pulsed laser from Laser Photonics and a Photron SA5 camera (4 Mpix sensor) from Photron, Ltd for high-speed imaging were used. Video recording in the experiments was carried out at a frequency of 7 kHz. The flow from the tube was into the flow channel. In the case of hot-wire anemometer measurements,

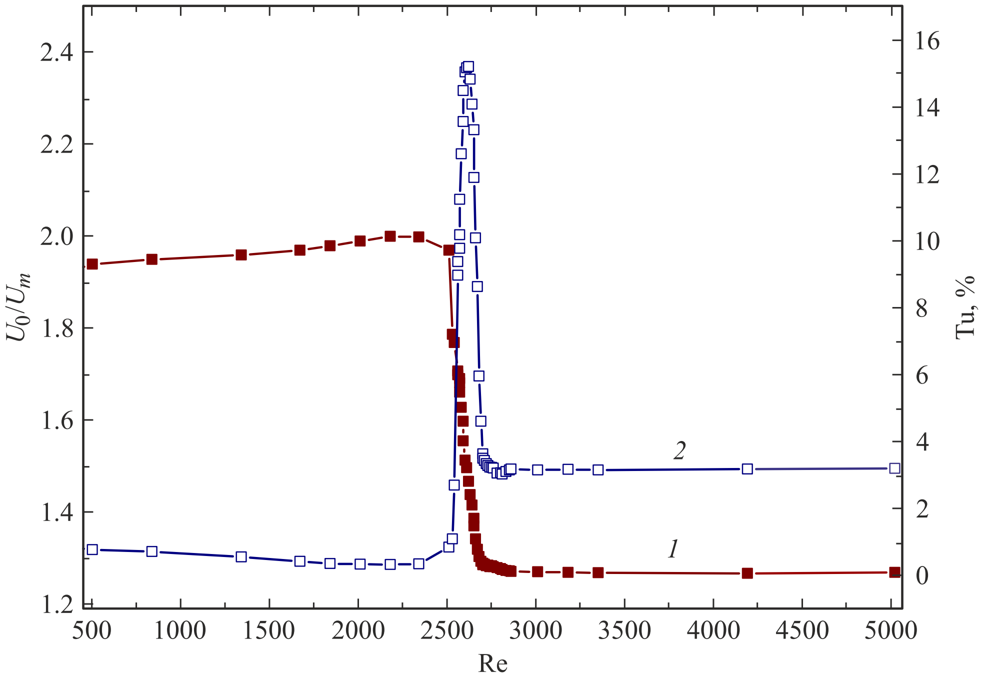

Figure 1. Dynamics of the variation of mean velocity U_0/U_m (*1*) and turbulence level Tu (*2*) as a function of Reynolds number (air, $d = 3.2$ mm).

a brass tube with a diameter of $d = 3.2$ mm was used; in the case of PIV measurements, the tube was made of aluminum and had a diameter of $d = 8$ mm. For hot-wire measurements measurements, air from the high-pressure line was used as a working gas. PIV measurements were performed in a stream of CO_2 fed from a cylinder. The CO_2 gas fed into the channel was first passed through an aerosol generator in which it was seeded with small glycerol droplets of 3–5 μm diameter used as tracers for PIV. hot-wire anemometer measurements were performed in the velocity range on axis 5–30 m/s (Re = 500–5000), while in PIV measurements the velocity varied in the range of 4–5 m/s (Re = 2400–3000). The Mach numbers in our experiments did not exceed $M = U/c = 0.073$ (where c — speed of sound), the turbulent Mach numbers [9] were $M_t = u/c = 0.011$ for air (u — RMS value of velocity pulsations) and $M_t = 0.0022$ for CO_2. Because of $M_t < 0.1$, the effects of compressibility were neglected [9]. Thermodynamic parameters at the beginning of the jet corresponded to atmospheric pressure and room temperature.

First, we investigated the dynamics of changes in mean velocity and pulsations at the tube axis when the Re number varies from that corresponding to laminar flow to that specific for fully developed turbulent flow. The measurements were carried out with a hot-wire anemometer, the sensor was placed at a distance $x = 0.3$ mm from the tube outlet. The measurement results are presented in Fig. 1.

In the figure, U_0 — the gas velocity at the outlet section of the tube on the axis, $\mathrm{Tu} = (u/U_0) \cdot 100\%$ — the turbulence level. A representation of the mean velocity dynamics on the axis in U_0/U_m–Re coordinates at the laminar-turbulent transition is given in [10]. As can be seen from the figure, the velocity ratio at Re = 2511 begins to decrease sharply and reaches a nearly constant value at Re = 2625. In this range, intermittent flow was observed in the tube. The turbulence level also increases, reaches a maximum at Re = 2620, and then decreases sharply. The maximum value of Tu = 15.2% is much larger than in the laminar flow regime in the pipe (Tu ∼ 1.2%) and turbulent regime (Tu ∼ 3.2%). This pulsation behavior at the laminar-turbulent transition in pipes is well known [11].

Next, the mean velocity and turbulent pulsation profiles were obtained in the same cross-section at the outlet of the tube. The measurements are shown in Fig. 2. Here $r = d/2$ — the tube radius, y — a coordinate with origin at the center of the channel. The mean velocity distributions (Fig. 2, *a*) at Re numbers less than 3488 are well described by the theoretical dependence for the Poiseuille profile. This means that laminar flow dominates in these regimes. As the number Re = 3488 is reached, the profile of the mean velocity changes and takes the form corresponding to the developed turbulent flow in the tube.

The distributions of the turbulence level at the outlet of the tube are shown in Fig. 2, *b*. For numbers Re = 218–654, the distribution has a maximum at the jet axis. The value of the turbulence level in the maximum slightly decreases with increasing Re number, which is specific for laminar flows in nozzles and channels. As the number Re = 2529 is reached, there is a significant increase of pulsations in the tube, and the distribution behavior

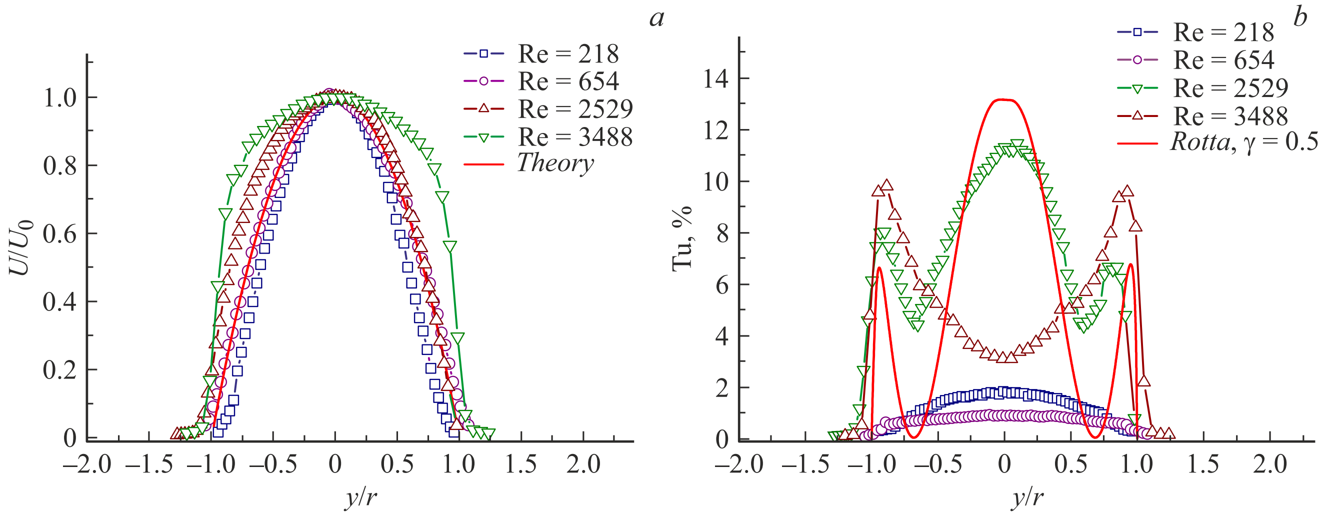

Figure 2. Distribution of mean velocity (*a*) and turbulence level Tu (*b*) as a function of Re number (air, $d = 3.2\,\mathrm{mm}$). Theory — Poiseuille profile, *Rotta* — calculation by the method [4].

changes. Three maxima appear on the distribution, with the largest one located on the axis. Further increase of Re leads to decrease of pulsation intensity at the channel axis and its increase in the near-wall regions. When $\mathrm{Re} = 3488$ is reached, the distribution of pulsations takes the form characteristic of a developed turbulent flow in the tube.

The figure also shows the calculation by using the method [4] for the velocity pulsation distribution assuming the mean velocity profile is changed in the intermittent flow. In the laminar part of the flow, a Poiseuille profile $U_L/U = 2[1 - (y/r)^2]$ was assumed, where y — is the transverse coordinate with beginning on the axis. In the turbulent part of the flow, the velocity profile was $U_T/U = 1 + (\lambda/8)^{0.5}[5.75\lg(1 - y/r) + 3.75]$, where λ — the pipe resistance coefficient. The velocity pulsations were determined using the formula $u = \gamma(1-\gamma)(U_L - U_T)^2$ [4]. As can be seen from the figure, the calculation for $\gamma = 0.5$ correlates with the distribution in the experiment for $\mathrm{Re} = 2529$.

As can be understood from Fig. 2, intermittency weakly affects the distribution of mean flow velocities in the tube, but seriously modifies the distribution of velocity pulsations in the tube cross-section. The pulsation distribution is determined by the number of turbulent regions (puff) in the pipe flow. This statement is illustrated by Fig. 3, which shows the velocity pulsation distributions along the tube cross-section and their corresponding time distributions of instantaneous velocities at the tube axis, measured with a high-speed PIV, which allow us to determine the presence of puff in the flow.

Puff type turbulent structures have a characteristic instantaneous velocity-time profile on the pipe axis with a smooth leading edge and a steep trailing edge [1]. The advantage of high speed PIV is that it allows us to obtain pulsation distributions over the cross-section and simultaneously an oscillogram on the axis corresponding to this distribution. The presence of puff type structures in the flow was determined from the oscillograms and the intermittency factor γ was found. In these experiments, the first turbulent jams appeared at a number $\mathrm{Re} = 2350$. We take this Reynolds number as Re_{cr} ($n = 0$, $\gamma = 0$). As can be seen from Fig. 3, the presence of single turbulent structures ($\gamma = 0.28$, $\mathrm{Re} = 2400$) in the laminar flow at the supercriticality parameter $n = 0.02$ (Fig. 3, *a*) does not lead to significant changes in the pulsation distribution ($\mathrm{Re} = 2400$) (Fig. 3, *b*). An increase in velocity leads to an increase in the number of turbulent structures, and when $\mathrm{Re} = 2462$ is reached, approximately half of the time in the oscillogram is occupied by the turbulent part ($\gamma = 0.55$, $n = 0.05$). The maximum of pulsations on the axis becomes noticeable, near the walls the turbulence also increases. As the Re number increases to the value $\mathrm{Re} = 2585$ ($\gamma = 0.85$, $n = 0.1$), the maximum on the axis is maintained. Further increasing the numbers $\mathrm{Re} = 2708{-}3077$ ($n = 0.15{-}0.3$) to the corresponding intermittency coefficients $\gamma = 0.92{-}0.98$ leads to a pulsation distribution specific for developed turbulent flow in tubes.

The results of the study in the Reynolds experiment at small supercriticality $n = 0{-}0.3$ showed the dynamics of the distribution of the longitudinal component of velocity fluctuations along the tube radius. In the range $n = 0{-}0.02$ it is characterized by a single maximum on the tube axis. It is shown for the first time that in the range of intermittency coefficients $\gamma = 0.5.{-}0.85$ the distribution of pulsations over the cross-section has three maxima (near the walls and at the tube axis, $n = 0.05{-}0.1$). At the supercriticality parameter $n > 0.1$, a flow with two extrema in the near-wall region specific for the developed turbulent flow in the channel is observed. The method of estimating turbulent velocity pulsations proposed by

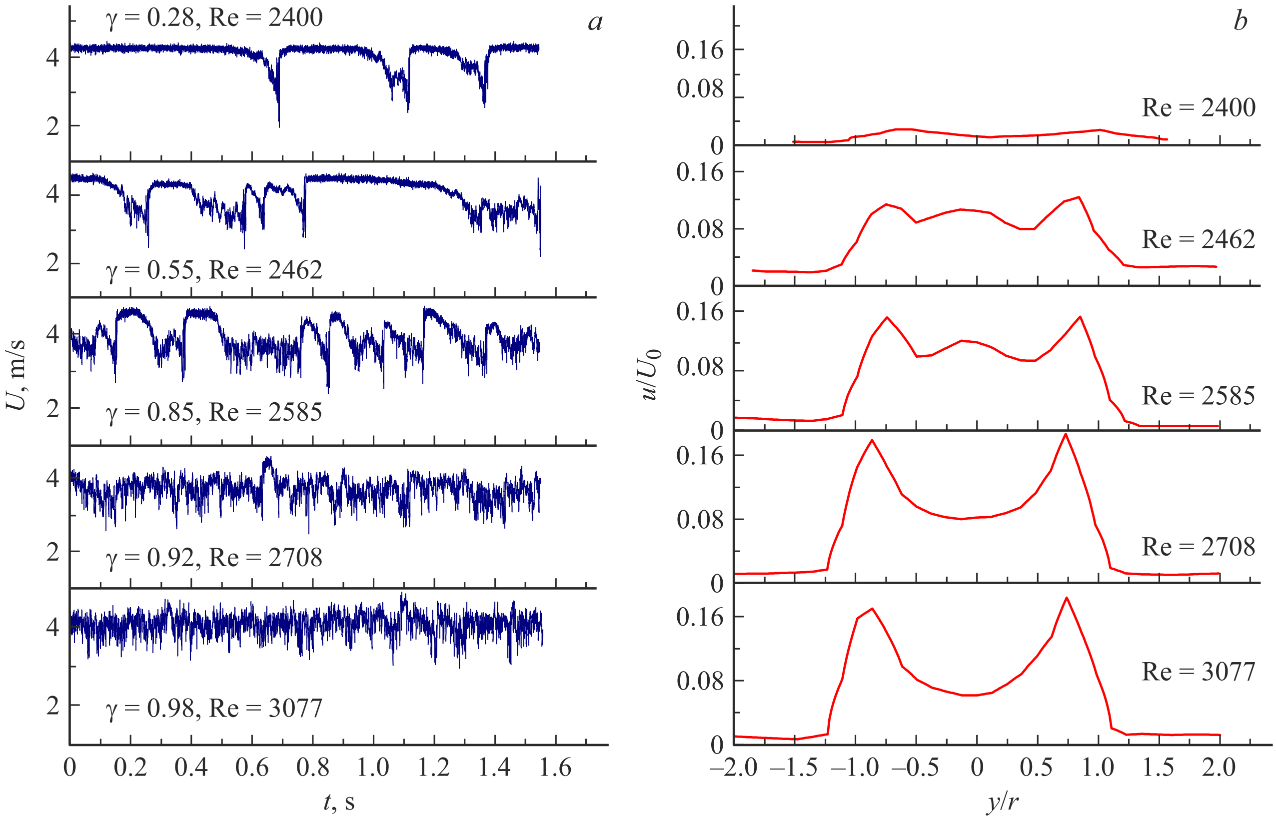

Figure 3. Oscillogram of instantaneous velocity (*a*) and velocity pulsations distribution (*b*) as a function of Re number (PIV, CO_2, $d = 8$ mm, $x = 6$ mm).

Rotta [4] for transient flow in pipes can be applied to technical calculations. Experimental data on the distribution of velocity fluctuations along the pipe cross-section are recommended for verification of methods for calculating heat and mass transfer in the regime of laminar-turbulent transition in pipes, for example, in models using the intermittency coefficient.

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Conflict of interest

The authors declare that they have no conflict of interest.

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