***Представлені результати експериментальних досліджень розгінного руху рідини в циліндричній трубі зі стану спокою. За прискореного руху рідини спостерігається затягування ламінарного режиму із його подальшим переходом до турбулентного при миттєвих числах Re, які на кілька порядків перевищують критичне Re в стаціонарних умовах. Для визначення локальних характеристик нестаціонарного потоку використано термоанемометричну апаратуру. Як датчики для вимірювання локальної швидкості в трубі був застосований термоанемометричний конічний датчик, а для вимірювання дотичних напружень – датчик, що змонтований врівень з внутрішньою стінкою труби. Для обробки експериментальних даних крім усереднення за ансамблем було також проведено додаткове згладжування осередненням в часі за п'яти сусідніми точками. Виявилося, що для отримання більш гладких функцій для шуканої характеристики необхідно мати в ансамблі набагато більше дослідів, особливо в пристінній ділянці. Встановлено, що за прискореного руху рідини зі стану спокою до виникнення турбулентності зберігається рівномірний розподіл швидкостей в перерізі труби і лише в тонкому пристінному шарі спостерігаються градієнти швидкостей. Різкий перехід в характеристиці дотичного напруження на стінці труби $\tau_0$ за зміни ламінарного режиму турбулентним спостерігається також в характеристиках локальних швидкостей. У момент переходу до турбулентного режиму з'являється переломна точка на графіку зміни величини середньої швидкості, а розподіл швидкостей та інтенсивність турбулентності зазнають значних змін в порівнянні зі стаціонарними турбулентними потоками. Турбулентність генерується в пристінній ділянці та поширюється до центру перерізу трубопроводу практично з постійною швидкістю. Фронт переходу від ламінарного до турбулентного режиму за неусталеного руху рідини в трубі поширюється у напрямку центру перерізу майже з постійною швидкістю***

***Ключові слова: циліндрична труба, рух рідини, структура потоку, генерація турбулентності, термоанемометрична аппаратура***

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# DISTRIBUTION OF LOCAL VELOCITIES IN A CIRCULAR PIPE WITH ACCELERATING FLUID FLOW

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## 1. Introduction

Unsteady fluid flow is used in modern power devices and technological equipment. A wide range of applied problems of unsteady flow causes various approaches and statements of research of these problems.

There is a need to improve the design of special control devices for automated technological processes of various purposes and nature. In the existing hydraulic systems used in these processes, there are no effective calculation methods taking into account the structural features of the considered flows.

Experiments with unsteady fluid flows will clarify the physics of the phenomenon. Such experiments require the development of a special methodology, creation of measuring and data processing instruments.

Calculation of such systems usually begins with the development of a physical model and derivation of the corresponding mathematical relations describing the behavior of the working medium in the flow part of the device in the form of equations. When designing and operating modern branched pipelines, it is important to ensure the reliability and durability of pressure pipelines and control equipment.

Based on the experimental results, empirical dependencies are obtained, which allow closing the system of equations describing the pressure unsteady turbulent fluid flow.

An experimental study of the velocity distribution in the free cross-sectional area of the pipeline to improve the method for calculating the structures of unsteady fluid flows in circular pipelines causes the relevance of work in this direction.

## 2. Literature review and problem statement

With accelerated fluid flow, a delay of laminar-turbulent transition at instantaneous Re numbers, which are several orders of magnitude higher than critical Re in stationary conditions is observed. This is taken into account for the analytical solution of the problems of unsteady flow in pipes according to the one-dimensional model by the operation method. A modified version of the operation method – the method of contour integration in the frequency plane is given in [1]. Theoretical studies of the compressible fluid flow in the pressure pipeline are carried out in [2].

The study of the area of unsteady laminar flow is of practical importance. Since the laminar-turbulent transition with unsteady flows is more difficult than in steady flows, there is a need to study the mechanism of this transition. This is sufficiently substantiated and partly theoretically investigated in [3, 4].

The above works used simplified models and do not consider the fact that with unsteady flow there are volumetric local inertia forces acting on a fluid. Accordingly, one can expect the effect of these forces on the phenomenon of laminar-turbulent transition, as well as on the further development of flow turbulence.

There few published experimental studies on the unsteady fluid flow in pipes and they are devoted to measuring only integral characteristics – pressure or turbulence onset time. The study of local characteristics is made in [5–8], which present the results of the study of shear stresses at the pipe wall when fluid flow occurs in the pipe and some data on the velocity distribution before the onset of turbulence.

It should be noted that the above theoretical and experimental works relate to laminar flow, where the dissipative model of the incompressible fluid flow was further developed. However, of practical value for engineering practice is to study the phenomenon of laminar-turbulent transition and its subsequent development, which has not been investigated in previous works.

A detailed study of the velocity structure with the propagation of artificially generated disturbances in the transition from one stationary turbulent regime to another is given in [9, 10]. In these works, local velocities are determined electrochemically.

Measurements of the structure in stationary conditions showed a good agreement with the universal Karman profile. On the basis of conducted experiments to determine turbulence intensity, the authors raise the issue of turbulence distribution in time and space. It is concluded that the transition to a new level of turbulence intensity associated with the transition process depends on the distribution of coherent structures having the property of some inertia. Therefore, redistribution of turbulence intensity occurs over a time that greatly exceeds the time to establish a steady state.

The considered studies were conducted only for a 51 mm plastic pipe with electrolyte flow and insufficient accuracy of measurements.

Experimental studies in [6] show that fluid flow from rest remains laminar with larger instantaneous values of the Reynolds number, rather than with steady flow. An important issue is the dependence of turbulence onset on the characteristics of the nonstationary process.

In [12], time graphs of the ensemble-averaged local velocity for different points of the free cross-sectional area are obtained. The number of experiments in one ensemble ranged from 25 ($r/R=0$) to 47 ($r/R=0.92$). When processing experimental data, in addition to ensemble averaging, smoothing by time averaging over five adjacent points was made. It turned out that in order to obtain smoother functions for the desired characteristic, it is necessary to have much more experiments in the ensemble, especially in the wall area.

The dependences given in [12] relate to the initial pressure in the system $p_0=1.56\cdot 10^5$ N/m$^2$, with the opening time of the quick-acting valve $t=0.01$ s. As shown by the measurement data of pressure in the considered unsteady fluid flow process, wave phenomena caused by fluid compressibility attenuated at the onset of turbulence and the fluid can be regarded as incompressible. At the same time, both the velocities at the points and the average velocity change almost linearly with the acceleration $dV/dt=7.15$ m/s$^2$. It turns out that flow turbulence occurring in the wall area is distributed to the pipe section center at an almost constant velocity. As can be seen, turbulence onset at the change point of the flow regime causes a sharp deviation of the velocity functions from the linear law, which entails additional energy losses.

On the basis of the analysis, the conclusion is made on the necessity of conducting experimental studies to obtain local characteristics of the accelerating flow in the transition from one regime of unsteady flow to another and further development of turbulence.

## 3. The aim and objectives of the study

The aim of the work is to conduct experimental studies of the velocity distribution in the free cross-sectional area of the pipeline to improve the method for calculating the structures of unsteady fluid flows in circular pipelines. It is necessary to determine a connection between wall shear stresses and flow structure, to analyze fluid flow factors and features leading to unsteady turbulent flow, in order to take into account pulsation characteristics. This will provide an opportunity to get patterns of the vortex formation process.

To achieve the aim, the following objectives were set:

– to determine the velocity distribution in the pipe section from rest before the onset of turbulence with accelerated fluid flow;

– to determine the change in the average velocity at the moment of transition to the turbulent regime, velocity distribution and turbulence intensity in comparison with steady turbulent flows;

– to determine the direction of distribution of the laminar-turbulent transition front with unsteady fluid flow in the pipe.

## 4. Materials and methods of studying the velocity distribution in the free cross-sectional area of the pipeline

This work is a continuation of [5–8], which present experimental results of measuring the local flow velocities along the pipe radius with accelerating fluid flow from rest by the hot-wire method. Experiments were carried out on an experimental installation, the main units of which are described in [11]. The scheme used for conducting experiments has a closed circuit and is made of stainless steel, the working section of the installation with a smooth input has a length $L=12.6$ m and an internal diameter $d=0.0596$ m.

To determine the local characteristics of unsteady flow, hot-wire equipment of the DISA company (Denmark) was used. For measuring the local velocity in the pipe, a 55R42 hot-wire cone sensor (Denmark) was used, and for measuring shear stresses – a 55R46 sensor (Denmark), mounted flush with the inner pipe wall.

## 5. Results of studies of velocity distribution in the free cross-sectional area of the pipeline

### 5. 1. Velocity distribution in the pipe section with accelerating fluid flow

The physical nature of the accelerating flow from rest in stationary conditions is described by the intermittency factor $\gamma$ [13–15]. Below, in Fig. 1, the change in the factor $\gamma$ in the conditions of unsteady flow in the pipe is given. The factor $\gamma$ is determined as follows:

$$\gamma=\frac{S_T}{S}=1-\left(\frac{r}{R}\right)^2, \qquad (1)$$

where $S$ and $S_T$ are the cross-sectional area of the pipe and the cross-sectional area covered by turbulence at a given time; $R$ and $r$ are the pipe radius and the radius of the point in the flow regime transition location.

The factor $\gamma$ is expressed as a function of relative time:

$$\gamma=f\left(\frac{t-t_0}{\Delta t}\right), \qquad (2)$$

where $\Delta t$ is the time of turbulence distribution from the wall to the axis; $t$ is the moment of turbulence onset at a given point; $t_0$ is the instant of turbulence at the wall.

Velocity distributions along the pipe section are shown in Fig. 2, 3.

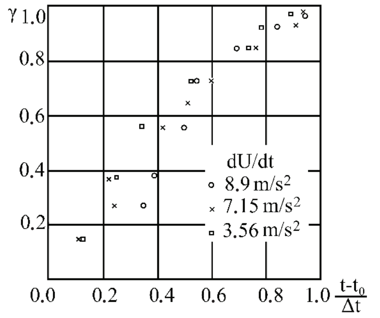

Fig. 1. Dependence of the interference factor $\gamma$ on relative time ($t-t_0/\Delta t$)

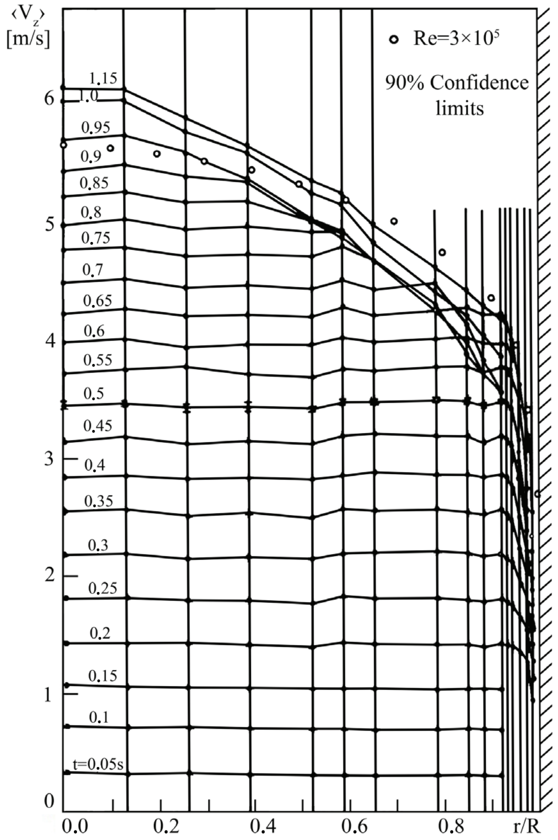

Fig. 2. Experimental data on the variation of longitudinal velocities $V_z$ in the process of fluid acceleration ($\xi=0.47$)

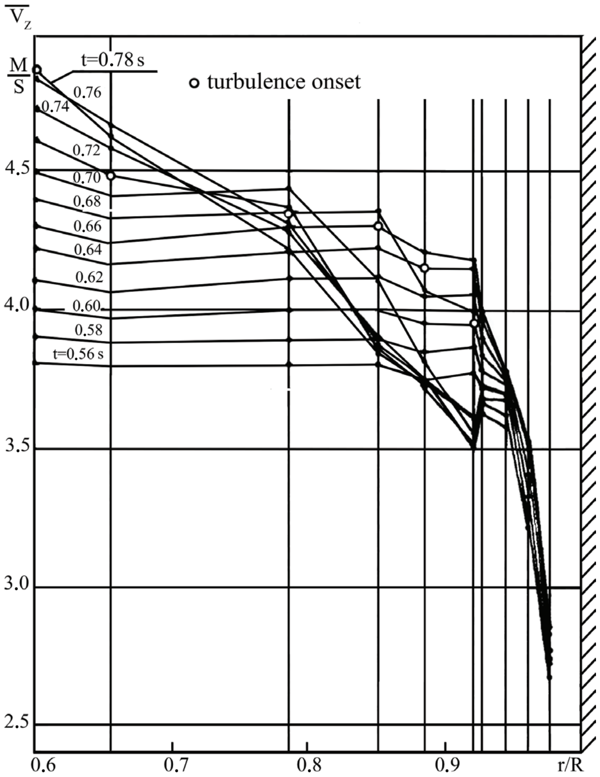

Fig. 3. Experimental data on the variation of longitudinal velocities $V_z$ ($r/R=0.6-0.99$)

It is evident that a uniform distribution takes place before the onset of turbulence, and velocity gradients are observed only in a relatively thin wall layer. Therefore, before the onset of turbulence, due to significant forces of inertia, the fluid behaves like an elastic body that performs an oscillatory motion and slides along solid walls. In this regard, shear stresses are concentrated in a thin wall layer and are characterized by the value of the wall shear stress $\tau_0$.

### 5. 2. Comparison of experimental data of shear stress $\tau_0$ with quasi-stationary values

As can be seen from Fig. 4, at the onset of turbulence, measured $\tau_0$ increases abruptly, which corresponds to an abrupt change in the velocity gradient at the wall.

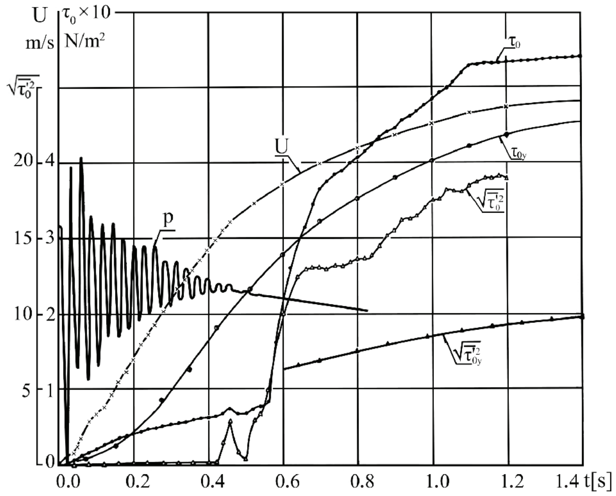

Fig. 4. Comparison of experimental data of shear stress $\tau_0$ and intensity of this value $\sqrt{\overline{\tau_0'^2}}$ with quasi-stationary values

As a result, fluid stagnation occurs in the wall area. Experimental data of this phenomenon are presented in Fig. 2, 3, where it is clearly seen that the closer to the wall, the greater the velocity reduction after the onset of turbulence $\sqrt{\overline{u}_x'^2}/u_*$.

### 5. 3. Change in the relative intensity of the longitudinal velocity component $\sqrt{\overline{V}_z^{12}}/u_*$ in the process of fluid acceleration

As shown in [6], the turbulent local characteristic $\sqrt{\overline{u}_x'^2}$ differs from the same characteristic of steady flow. Fig. 5 shows the experimental graphs of pulsation intensity of the longitudinal velocity $\sqrt{\overline{u}_x'^2}/u_*$.

It is shown that the maximum intensity is observed at the point $r/R=0.88$. From the research data it is seen that the maximum intensity gradually decreases over time, and also moves towards the pipe axis. Starting from $r/R=0.52$, the pulsation intensity practically does not exceed the intensity observed with steady flow. The dashed line on these diagrams shows the pulsation intensities corresponding to the final steady flow.

The change in the flow structure is also reflected in the change of the instantaneous average cross-section velocity $V$. Fig. 5 shows that flow acceleration to the time point $t=0.43$ s is almost constant, but $\tau_0$ begins to increase sharply at the time $t=0.55$ s. Such inconsistency can be explained by the fact that turbulence does not occur at the wall, and in the wall area at a certain distance from the solid boundaries and turbulence distribution to the wall takes time. This is confirmed by the behavior of the dependence of the standard deviation of the shear stress pulsation $\sqrt{\overline{\tau}_x'^2}$ in Fig. 4. At the time point $t=0.44$ s, overshoot appears, indicating that the turbulent pulse reached the sensor surface (pipe wall). This moment is in good agreement with the turning point of the average velocity characteristic $V$.

The change in the intensity at different points of the wall section depending on the time of the experiment is shown in Fig. 6. The data shown in Fig. 5, 6 confirm that turbulence is distributed from the wall to the flow axis. Moreover, it is observed that the intensity changes according to a different law in comparison with the distribution of turbulence itself. While in the central part of the flow there is a uniform increase in intensity, in the wall areas there are clear maxima in the beginning of fluid acceleration. At the same time, attention should be paid to the measurements made on the relative radius $r/R=0.88$–$0.96$. Here, the maximum intensity amplitude of the longitudinal velocity component occurs earlier than at other points of measurement. Such a change in the local intensity characteristic should be associated with the generation of turbulence in the wall areas.

Estimating the process of changes in the intensity $\sqrt{\overline{V}_z'^2}/u_*$ in the wall area, depending on time, we see that the maximum intensity is observed on the relative radius $r/R=0.96$. The intensity at this point at the time $t=0.52$ s reaches 2.5 times the magnitude of the final stationary regime. It should be emphasized that the average velocity at this time is approximately 60 % of the final regime velocity. Consequently, the turbulence intensity of the longitudinal component, corresponding to the instantaneous average velocity with respect to the stationary value of this characteristic, is even higher.

The above data are experimental confirmation of the predicted site of laminar flow stability loss and turbulence generation.

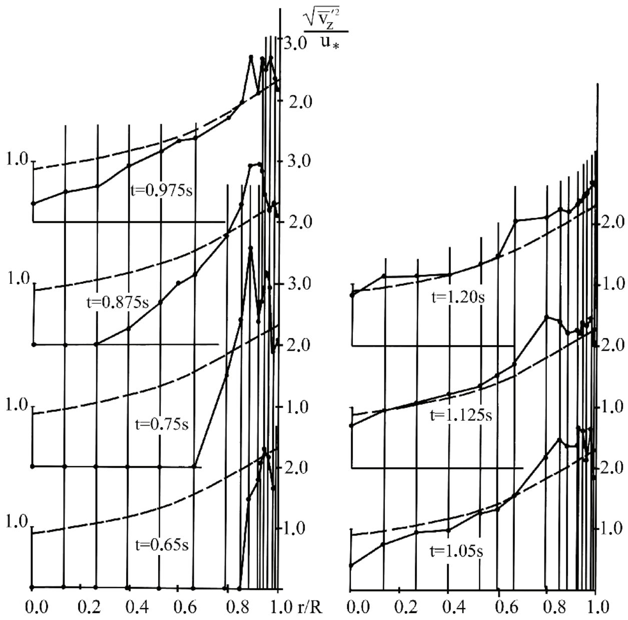

Fig. 5. Diagrams of the relative intensity of the longitudinal velocity component $\sqrt{\overline{V}_z'^2}/u_*$ in the process of acceleration

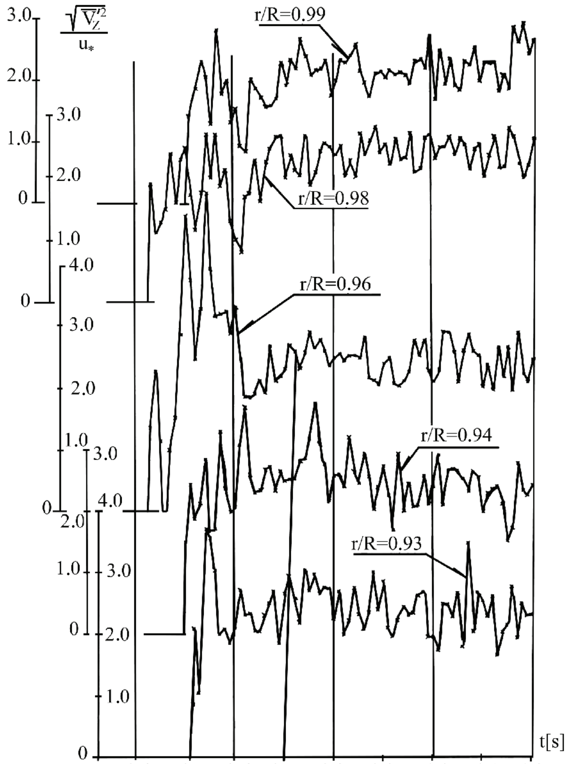

Fig. 6. Change in the relative intensity of the longitudinal velocity component $\sqrt{\overline{V}_z'^2}/u_*$ in the pipeline wall area

### 6. Discussion of the results and directions of further research

Determination of kinetic energy at any time is generally reduced to measurement of velocity fields during the unsteady process throughout the free cross-sectional area.

Measurements cause a number of technical difficulties due to the unsteadiness of the process.

The corresponding experimental data obtained in determining the structure of the accelerating flow are given. According to them, it is found that turbulence is distributed along the free cross-sectional area with the development of cross-dimensional coherent structures that arise in the process of flow regime change.

Before the onset of turbulence there is a uniform distribution, and velocity gradients are observed only in a relatively thin wall layer. Due to the considerable forces of inertia, the fluid behaves like an elastic body that performs an oscillatory motion and slides along solid walls. Shear stresses are concentrated in a thin wall layer and are characterized by the value of the wall shear stress $\tau_0$ (Fig. 2, 3).

At the onset of turbulence, measured $\tau_0$ increases abruptly (Fig. 4), which corresponds to an abrupt change in the velocity gradient on the wall. As a result, fluid stagnation occurs in the wall area.

Turbulence occurs not on the wall, but in the wall area at a certain distance from the solid boundaries and turbulence distribution to the wall takes time. This is confirmed by the behavior of the dependence of the standard deviation of the shear stress pulsation $\sqrt{\overline{\tau_x'^2}}$ in Fig. 4.

Results in Fig. 5, 6 confirm that turbulence is distributed from the wall to the flow axis. The intensity changes according to a different law in comparison with the distribution of turbulence itself. While in the central part of the flow there is a uniform increase in intensity, in the wall areas there are clear maxima in the beginning of fluid acceleration. Measurements made on the relative radius $r/R=0.88-0.96$ showed that here the maximum intensity amplitude of the longitudinal velocity component occurs earlier than at other points of measurement. Such a change in the local intensity characteristic can be associated with turbulence generation in the wall areas.

The analysis of experimental data shows that the layer where energy exchange between the main and disturbing motions occurs is quite close to the boundary layer edge. As long as flow velocity is insignificant, disturbance amplitudes are small and they are rapidly suppressed by the flow. With increasing flow velocity and energy exchange between the flow layers, disturbance increases, which affects the distribution of local velocity over the entire pipe section.

Due to the fact that it is technically impossible to carry out studies on turbulence onset and turbulent characteristics simultaneously on the entire flow radius, the ensemble method was used to determine the local characteristics of the flow. The number of experiments in it was not always sufficient for generalization, which is a lack of research.

An important moment in solving the problems of unsteady accelerating fluid flow is the moment of laminar flow stability loss and the associated accelerating laminar-turbulent transition. In applied calculations of accelerated flows, this transition corresponds to the change of the mathematical model for calculation.

The problems of velocity distribution in the free cross-sectional area with unsteady fluid flow are essential in determining the loss of mechanical energy. However, both theoretical and experimental difficulties do not allow considering the problem solved.

In existing hydraulic systems used in these processes, there are no efficient calculation methods that take into account structural peculiarities of the considered flows. Creation of reliable methods for calculating complex pipelines is possible only with the use of mathematical models of nonstationary processes that take place in such systems.

The direction of further research is an analysis of fluid flow factors and characteristics, which lead to unsteady turbulent flow, in order to take into account pulsation characteristics. This will provide an opportunity to obtain regularities of the process of vortex formation for predicting the hydraulic parameters of these flows in technological processes.

## 7. Conclusions

1. With accelerated fluid flow (with accelerations from 1 to 12 m/s$^2$) from rest to the onset of turbulence, a uniform velocity distribution remains in the pipe section and velocity gradients are observed only in the thin wall layer.

2. A sharp transition in the characteristic $\tau_0$ with the laminar-turbulent transition is also observed in the characteristics of local velocities. At the moment of transition to the turbulent regime, a turning point appears on the average velocity graph, and velocity distribution and turbulence intensity undergo significant changes in comparison with steady turbulent flows. Maximum intensities are observed on the relative radius $r/R=0.96$. The intensity at this point at the time $t=0.52$ s reaches 2.5 times the magnitude of the final stationary regime.

3. The front of laminar-turbulent transition with unsteady fluid flow in the pipe is distributed towards the section center at an almost constant velocity. The average velocity changes almost linearly with the acceleration $dV/dt=7.15$ m/s$^2$.

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