

Loss of Pressure in a Smooth Pipe With a Pulsating Turbulent Course

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Abstract

This article presents the results of experimental studies of a fully developed turbulent air flow in a round pipe with superimposed flow pulsations. The time-averaged static pressure losses and instantaneous velocity values on the pipe axis were measured in a wide frequency range of superimposed harmonic pulsations of the air flow in three modes for the average flow rate. Data were obtained and analyzed on the dependence of the conditionally averaged values of the pulsation component of pressure and flow velocity in various sections of the pipe. It is revealed a complex spatio-temporal structure of the flow, which is influenced by both resonance phenomena and transfer of parameter fluctuations in the direction of average motion. It is revealed a complex spatio-temporal structure of the flow, which is influenced by both resonance phenomena and transfer of parameter fluctuations in the direction of average motion. It is also revealed a non-monotonic dependence of pressure losses on the frequency of flow pulsations. The nature of the change in pressure loss from the frequency of flow pulsations remains almost unchanged when the average flow rate is varied.

However, the analysis of the results of these studies left the relationship between the flow parameters in each cross section of the pipe under conditions of periodic flow pulsations. The goal of this article is to carry out this analysis.

Keywords

Unsteadiness, Flow Structure, Velocity Profile, Flow Pulsation.

Introduction

In various technical devices, the hydrodynamic processes in the channels are often unsteady.

Currently, the most studied is the kinematic structure of unsteady turbulent boundary layers. The experimental studies of Bukreev and Shakhin, Grigoriev and Fafurin, Ramapryan and Tu, Achary and Reynolds, Cousteau, Carlson, Paris, Simpson, Hartner, Mizushina, Shemer, Iguchi et al. are known. Given the complexity and diversity of effects of the unsteadiness impact on the kinematic flow structure, a number of attempts have been made to classify the unsteady flows. The most complete classifications are given by Ramporyan and Tu, Grigoryev and Fafurin. They distinguish five groups of unsteady flows in their works. The classification is based on the turbulence “transmission” mechanism, and the boundaries between groups are defined in the space with respect to the frequency and amplitude of superimposed pulsations.

Known literature data do not give a complete picture of the influence of the factors of unsteady flow through the channel on the hydrodynamic parameters in general and on the hydraulic resistance of the channels under unsteady conditions relative to aperiodic processes of transition from one flow to another. It was established that the hydraulic resistance is higher with increasing and lower with decreasing flow velocity compared with the steady flow [1, 2]. Systematic theoretical and experimental studies of the turbulent gas flow under conditions of hydrodynamic unsteadiness were carried out by G.A. Dreitser and V.M. Kraev [3, 4]. A significant impact of acceleration and deceleration of the flow on the averaged velocity profiles and the turbulent flow structure is established. A method for calculating the turbulent viscosity coefficient is proposed. The generalizing approximating dependences for unsteady flows are obtained, which can be used in practical calculations.

Study of the flows with periodic flow pulsations is complicated by the significant dependence of the profiles of hydrodynamic parameters on the frequency and amplitude of superimposed pulsations. In the work [5], the problems of studying the unsteady even negative values of turbulent viscosity were obtained. In the work [2], it is proposed to consider the problems of studying turbulent pulsating flows from the standpoint of the interaction of turbulence with an averaged flow in three areas: 1 – the frequency of superimposed pulsations is much lower than the characteristic frequency of turbulent pulsations; 2 – intermediate mode; 3 – the frequency of superimposed pulsations is much higher than the frequency of turbulent pulsations. Based on numerical simulations in the work [6], a significant and non-monotonic dependence of hydraulic resistance on the frequency of superimposed flow pulsations was revealed in a certain range of fluctuations in the pulsation amplitude and average Reynolds number.

The purpose of this research is to obtain experimental data on the relationship of pressure losses in a turbulent flow in a smooth pipe with factors of unsteady flow in regimes with flow rate (velocity) fluctuations of the flow.

Methods

The experiment was carried out on an experimental plant, the scheme of which is shown in Figure 1. The installation consisted of a working section 1, which was a round metal hydraulically smooth pipe with an inner diameter of 64 mm, a pulsator 2, a receiver 3 with a volume of more than 1 m³, a set of critical nozzles 4 and a turbocharger 5. The pipe was divided into an upstream section, the length of which was 5 m (about 80 gauges in inner diameter), a measuring section

2 m long and a post-included section. Fittings 6 were mounted for selecting static pressure, fittings 7 - for connecting a pressure pulsation sensor, and coordinate devices 8 with probes of a hot-wire anemometer were installed at the ends of the measuring section.

A receiver with a volume of more than 1 m³ in all modes effectively suppressed pressure pulsations in front of critical nozzles and thereby ensured a constant mass flow through them. In the course of experiments, the pressure drop across the nozzles was provided by a turbocompressor and was controlled by a manometer, sufficient to implement the critical flow regime in them. Rotary critical nozzles were used with a flow rate error of not more than 0.25%. Thus, in each series of measurements, a stable and highly accurate air flow rate known in time was maintained.

The pulsator 2 was a sealed compartment with a special device built into it to create superimposed flow (velocity) pulsations in the installation path over a wide range of pulsation amplitudes and frequencies. The flow pulsations were provided by periodically overlapping the hole 9 (in the form of a triangle with rounded corners) by an elliptical shutter 10 (Figure 1, b), driven into rotation by an electric drive with an adjustable and stabilized speed. It was possible to change the degree of hole overlap 9 (distance d) in the pulsator design to vary the flow pulsation amplitude.

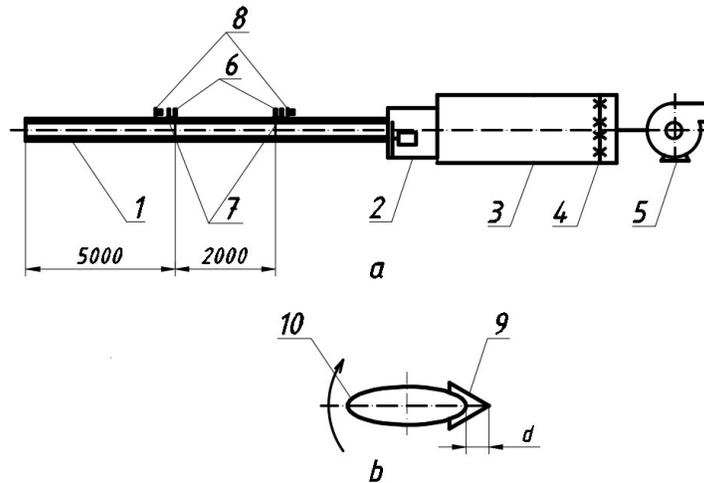


Fig. 1: Experimental Setup. The Main Operating Parameters of the Installation: – The Frequency of Superimposed Pulsations of Flow $f = 1 - 200$ Hz; – The Degree of Overlap of the Square of the Expenditure – Hole Pulsator $d = 0 - 100$ %; – The Average Air Flow Path $Q = 1 - 800$ m³/h.

The static pressure at the ends of the measuring section was taken through a hole with a diameter of 0.8 mm in the pipe wall. The pressure drop across the measuring section was measured using a U-shaped pressure gauge. Alcohol was used as a working fluid in the pressure gauge, the density of which was determined experimentally before the start of research. Each air duct connecting the pressure selection hole with the pressure gauge was equipped with a damping section made of a metal tube 350 mm long and an inner diameter of 0.8 mm. This pneumothorax design provided damping of pressure pulsations above the liquid column and virtually eliminated periodic mass transfer between the pneumatic duct and the installation path.

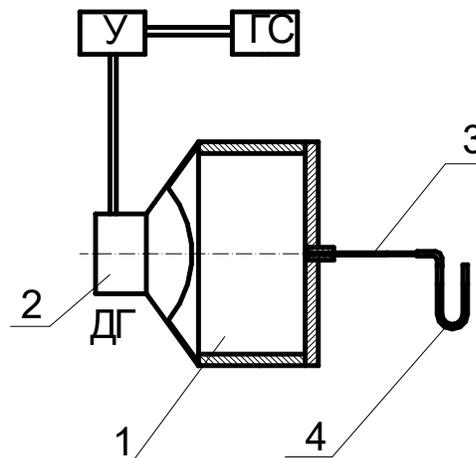


Fig. 2: Installation Diagram for the Study of the Characteristics of the Pneumotracer

As special studies have shown, the presence of such mass transfer can lead to significant distortions when measuring the average pressure in a pulsating flow. The installation diagram on which these studies were carried out is presented in Figure 2. Harmonic pressure pulsations of various frequencies and amplitudes were created in the sealed working chamber 1 of the plant using a dynamic head 2. An opening was made on the chamber wall for the selection of pressure with a diameter of 0.8 mm, which was connected using a pneumatic duct 3c with a U-shaped pressure gauge 4. The frequency and amplitude of pressure pulsations were controlled by supplying an amplified signal from the signal generator G6-27 to the dynamic head. Studies have shown that the average value of the pulsating pressure was measured without distortion in the entire studied range of frequencies and amplitudes of pressure pulsations in the presence of a tube-damper. If the damper was replaced by a tube with an inner diameter of 5 mm, the manometer recorded a noticeable excess of pressure in the working chamber at the actual average pressure. The excess magnitude depended on the frequency and amplitude of the pressure pulsations. The apparent increase in pressure in the chamber, recorded in the absence of a damper in the air duct, is apparently caused by the presence of mass transfer between the working chamber and the air duct and the difference in hydraulic resistance with forward and reverse air movement in the air duct.

Velocity measurements on the pipe axis were carried out using a single-line hot-wire anemometric flow rate sensor in the output section of the measuring section of the plant. The operation of the velocity sensor was supported by a hot-wire anemometric unit of the DISA 55M equipment. The collection and processing of experimental data was carried out using an automated system including PC and eight-channel analog-to-digital converter with parallel channel polling. When performing measurements, the frequency of the sensor polling was 5 kHz, the polling time was 2 s

Key plant parameters:

- frequency of superimposed flow pulsations $f = 1 \dots 200 \text{ Hz}$;
- degree of overlapping the area of the supply opening of the pulsator $d = 0 \dots 100\%$;
- average air flow in the tract $Q = 1 \dots 800 \text{ m}^3/\text{h}$.

Results and Discussion

Before conducting research, measurements of hydraulic resistance were performed in pulsating flows $\zeta = (d/L) \Delta P_c / (\rho \langle U \rangle^2 / 2)$ for a turbulent flow in a pipe in a stationary mode for the values of air volume flow through critical nozzles $Q_c = 543.7; 380.6$ and $307.5 \text{ m}^3/\text{h}$.

Where d - diameter of the pipe clear opening; L - length of the measuring section; ΔP_c - static pressure drop at the borders of the measuring section; $\langle U \rangle$ - average flow rate; ρ density. Moreover, the Reynolds number calculated by the average flow rate and the inner diameter of the pipe was $Re_Q = (1.2 \dots 2.0) 10^5$. The average flow rate was estimated by the flow rate through the nozzles taking into account the pressure drop between the measuring section and the receiver. The measurement results showed that the difference in value ζ from the experimental data of Nikuradze [7] for the developed turbulent pipe flow does not exceed 3 - 5%.

Experiments in a pulsating flow were carried out at the maximum degree of change in the area of expendable pulsator section - for one shutter revolution 10 (Figure 1, b), the area of the passage section of the hole 9 twice smoothly changed from 0 to 100% of the maximum area. The maximum area of the discharge port of the pulsator is close to the area of the pipe clear opening. The analysis of velocity oscillograms showed that the change in the frequencies of the flow velocity on the pipe axis changed according to a law close to harmonic in the entire range under study (Fig. 3). Given the presence of a certain change in the amplitude in time and the deviation of the oscillation form from the sinusoidal one, it is more convenient to characterize the intensity of oscillations not by the relative amplitude of pulsations $A_u / \langle U \rangle$, but by

the value of relative mean-square pulsations $\sigma_u / \langle U \rangle$, where $\sigma = \sqrt{\overline{(U')^2}}$ - the mean-square value of the velocity pulsation. The estimate $\sigma_u / \langle U \rangle$ is more stable in a statistical sense. The dependence $\sigma_u / \langle U \rangle$ on the frequency of flow pulsations is shown in Figure 4.

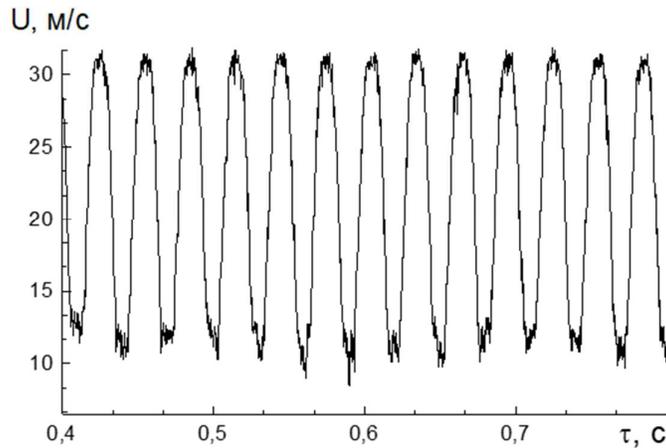


Fig. 3: Example of Flow Velocity Waveform on the Pipe Axis

As can be seen from Figure 4, the intensity of pulsations of the flow velocity on the pipe axis in the measuring section weakly depends on the average value of the flow rate, but, despite the same variation law in the area of the flow outlet of the pulsator, it varies greatly in the frequency of superimposed flow pulsations. Apparently, this is due to resonance effects in the tube, the presence of standing waves and a shift in the spatial position of their nodes depending on the pulsation frequency [8]. To unambiguously determine the flow nature in the pipe in a pulsating mode, it is necessary to have several points for measuring the pulsations of the flow velocity and pressure along the pipe length, which is stipulated in the next stage of the experiments.

In the experiments, the range of changes in the relative frequency $Sh = fd/\langle U \rangle$ was 0.01...0.5, and relative to the amplitude - $\beta = 0...0.95$. Following the classification [9], the studied flows depending on the frequency of flow pulsations and its average value can be attributed to the first, second and third groups, which corresponds to quasi-stationary and low-frequency flows.

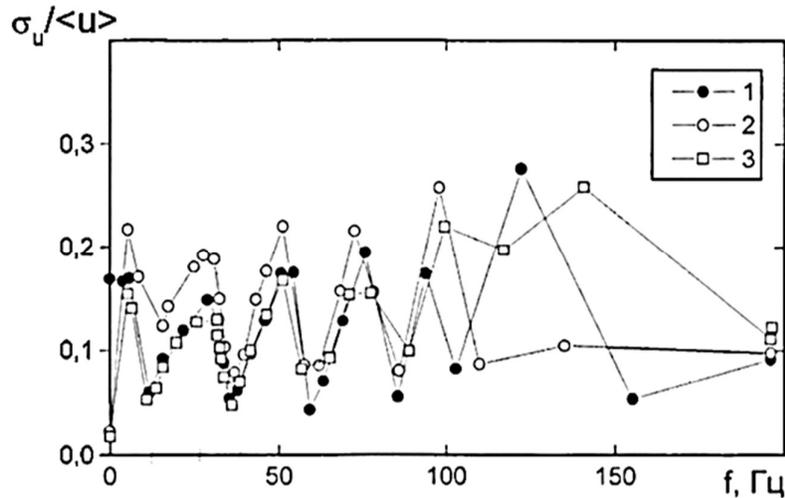


Fig. 4: Dependence of the Root-Mean-Square Intensity of Pulsations of the Flow Velocity on the Pipe Axis on the Frequency: 1 - $Q = 543.7 \text{ m}^3/\text{h}$; 2 - $Q = 380.6 \text{ m}^3/\text{h}$; 3 - $307.5 \text{ m}^3/\text{h}$

Figure 5 presents the dependences of the hydraulic resistance ζ of the measuring section of the pipe with a pulsating turbulent flow on the frequency of flow pulsations for three values of the average flow rate corresponding to the volumetric air flow through critical nozzles - $Q_c = 543 \text{ m}^3/\text{h}$; $380.6 \text{ m}^3/\text{h}$; $307.5 \text{ m}^3/\text{h}$. The figure shows that a non-monotonic dependence of pressure losses on frequency is observed over almost the entire range of changes in the frequency of flow pulsation measurements, including the region of negative values of pressure losses. In the frequency range $f = 0...100 \text{ Hz}$, the nature of this dependence remains almost unchanged for all studied flow rates. There are two pronounced minimum pressure losses - at a frequency $f = 8...11 \text{ Hz}$ and $f = 33...35 \text{ Hz}$. At $f = 33...35 \text{ Hz}$, the pressure loss at all Q_c takes a negative value, namely, the statistical pressure in the output section of the measuring section of the pipe becomes higher than in the inlet. It should be noted that the experimental data on the change in hydraulic resistance with

the frequency of superimposed flow pulsations are well reproduced during repeated measurements, including the region of negative values of pressure losses.

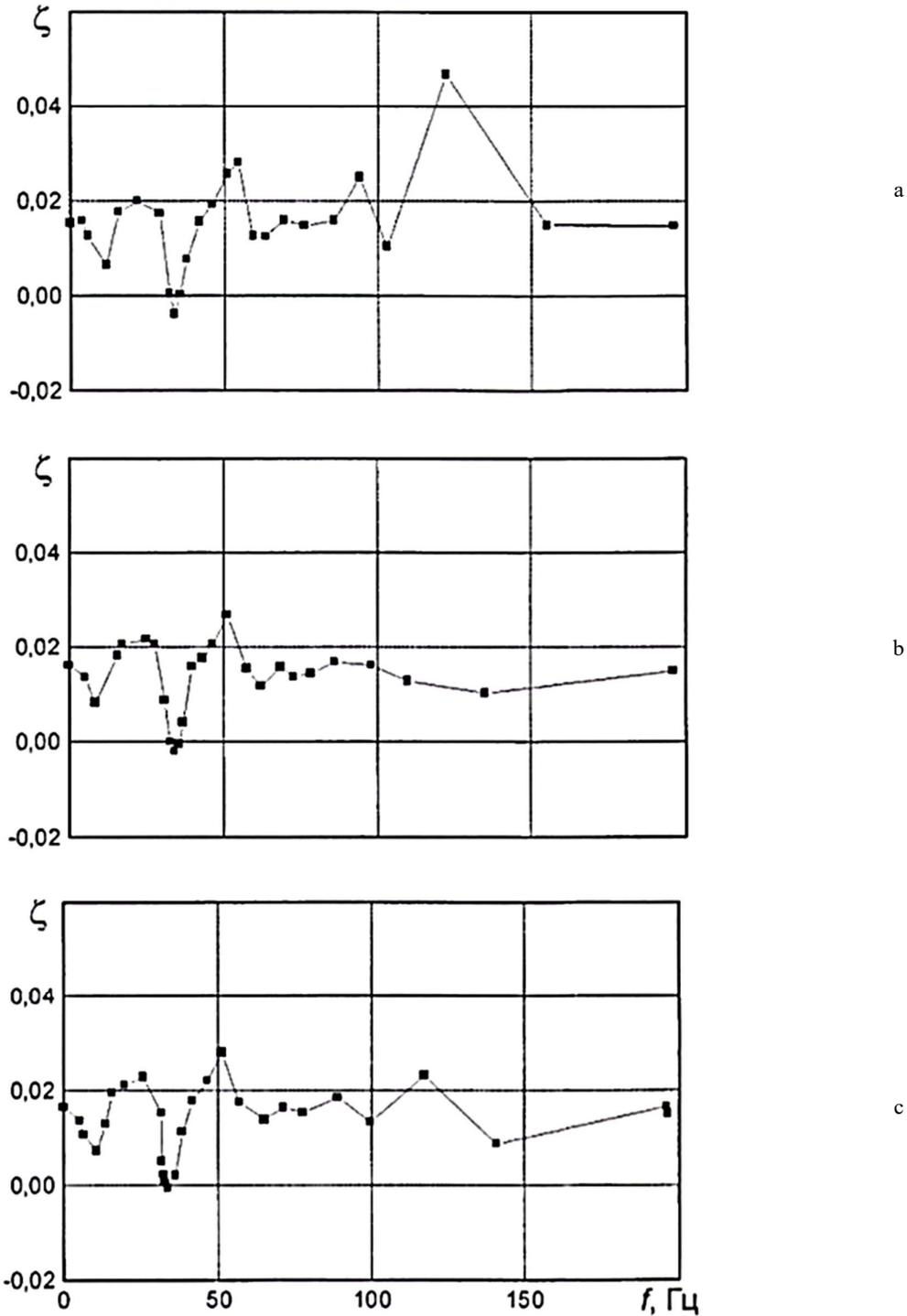


Fig.5: The Dependence of the Hydraulic Resistance of the Pipe on the Frequency of Superimposed Ripple Flow: a - $Q = 543.7 \text{ m}^3 / \text{h}$; b- $Q = 380.6 \text{ m}^3 / \text{h}$; c- $307.5 \text{ m}^3 / \text{h}$

The character of changes in hydraulic resistance obtained at experiments at a frequency of superimposed flow pulsations can be a consequence of the above-mentioned resonance phenomena, as well as the presence of periodically occurring flow separation regions unevenly distributed along the pipe length. As shown by previous studies of the authors [8, 10,

11], short-term flow separation near the pipe wall can occur for some values of the frequency and amplitude of the pulsations of the flow velocity in a pulsating flow.

Summary

Experimental studies of pressure losses in a smooth pipe in a turbulent flow with superimposed flow pulsations are performed. A non-monotonic dependence of pressure losses on the pulsation frequency is established.

Conclusions

To obtain more detailed information about the physical mechanisms of the impact of flow pulsations on the channel hydraulic resistance, additional studies are necessary, which shall include, in particular, simultaneous measurements of pressure pulsations, profiles of the averaged flow velocity and its pulsations at the boundaries of the measuring section.

Acknowledgements

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