Turbulent pulsations in the axisymmetrical submerged jet

V V Lemanov, V I Terekhov, K A Sharov and A A Shumeiko
S S Kutateladze Institute of Thermophysics of SB RAS, Novosibirsk, 630058, Russia
E-mail: lemanov@itp.nsc.ru

Abstract. Today, the turbulent characteristics of laminar jets remain almost unexplored, although all real flows have a pulsating component, which in technological processes can have a significant effect on the processes of mixing, heat and mass transfer. The turbulent characteristics of a submerged laminar air jet flowing out of a tube with a diameter of 3.2 mm and length of more than 100 diameters were experimentally investigated at Reynolds number of 436. The measurements were carried out using a hot-wire anemometer. The ranges of operating parameters at which the laminar, transitional and turbulent flows occur in the jet source have been determined. Based on the data obtained, the regime for the study was selected. For the selected regime, the profiles of average velocities and pulsations in cross-sections along the jet flow were measured and distributions of turbulent characteristics along the jet flow on the axis and in the mixing layers were constructed.

1. Introduction
The technological progress of recent decades towards miniaturization of technical devices has caused a significant increase in interest in laminar and transient flows in channels and jets. Microflows are widely used in MEMS (the Micro Electro-Mecanical Systems): flows around micro obstacles, microjets, and flows in microchannels [1-3]; the microchannel and microjet flows are used for the problems of heat transfer control [1, 4-6]. Laminar flows occur due to small geometric scales; however, the physical laws remain the same, with the exception of some cases [2] for macro- and microflows. Some types of jet burning are also characterized by laminar and transitional regimes [7].

Turbulent jets and jets with a laminar-turbulent transition have been studied quite well [8]. A number of theoretical and numerical works are dealt with the laminar jets. The fundamental and earliest work on the theoretical description of the laminar jet flow is the Schlichting model [9]. This theory does not work well near the jet source, where empirical relations are used [10, 11]. Attempts to improve the Schlichting theory do not stop today. For instance, a model for the potential jet core near the nozzle outlet was proposed in [12] to describe the flow in the near field of the jet taking into account the initial velocity profile; new relations for calculating the coordinates of a virtual source were also proposed in the Schlichting theory. The proposed theory is verified by experimental and numerical modeling. The effect of the coordinate of a virtual source on characteristics of velocity profiles in the far field of a jet was numerically studied in [13]. The work [14] is devoted to a numerical study of the features of formation of self-similarity of velocity profiles in a laminar jet.

Another direction is adaptation of the Schlichting theory to other types of jet flows, more complex than a submerged jet. In [15], the possibility of applying the Schlichting theory to co-current flows is investigated. The theory is verified by the LES method. The process of particle diffusion in laminar
jets is numerically simulated in [16]. Various aspects of application of the Schlichting theory for confined jets and jets with combustion are studied numerically and theoretically in [17-19].

All the above works are characterized by the fact that the influence of velocity pulsations on the flow of laminar submerged jets is not considered. The only exception is [15], which estimates the influence of initial turbulence on the integral characteristics of the jet, such as, for example, jet expansion along its length. The behavior of pulsations inside the jet flow is not studied.

The number of experimental studies on laminar jets is very limited. To date, the most famous experimental studies on laminar jets are the works of Andrade et al. The laminar round [20] and flat [21] liquid jets flowing into liquid are investigated there. Average velocity profiles measured by the tracks images of particles placed in a working fluid are compared with the Schlichting theory. For the first time, the idea that to compare the experimental data with this theory correctly, it is necessary to use a virtual point source, is formulated in these works, and the analytical formulas that determine the coordinates of this source for a flat and round jets are derived. There are no statistical characteristics of laminar jets in the works of Andrade et al.

A liquid laminar jet flowing from a long tube into liquid was studied in [22]. Measurements were performed using the LDA. Particular attention was paid to transformation of the average velocity profiles in the initial section and a change in the kinematic momentum of the jet along its axis. Despite the fact that the measurements were carried out using LDA, and the range of Reynolds numbers covered the values of the laminar-turbulent transition for the tubes (Re = 1000-4000), the authors did not give turbulent characteristics of the jet.

Investigation results on a laminar gas jet flowing out of a diffuser at high Reynolds numbers (Re = 2000–12000) are presented in [23]. Laminarization of the flow is achieved using a complex inlet device located in front of the diffuser. The authors present data on the distribution of longitudinal velocity pulsations along the axis obtained using a hot-wire anemometer and PIV, as well as pulsation profiles at the diffuser outlet and at the end of the laminar section of the jet. Unfortunately, the great complexity of initial conditions does not allow confident opinion about the degree of generalization of data obtained, and their extension to other laminar jets.

The dynamic characteristics of flat microjets in the range of Reynolds numbers Re = 30–140 were studied in [24]. The measurements were carried out using a hot-wire anemometer. Profiles of average velocities and velocity pulsations were obtained in cross-sections located along the jet flow up to 100 heights of a flat nozzle. The distributions of average velocities and longitudinal pulsations on the axis are given. A comparison with theoretical dependences for flat laminar jets is made.

Thus, it can be argued that the turbulent characteristics of laminar jets remain almost unexplored, although all real flows have a pulsating component, which can have a significant effect on the processes of mixing, heat and mass transfer in technological processes. In this paper, we study the pulsation characteristics of a submerged laminar jet without a laminar-turbulent transition zone.

2. Experimental setup

The experimental setup is shown in figure 1. Air was supplied from the compressor (4) to the supply line (5), then through the flow regulator it entered the tube (7) with diameter d = 3.2 mm and length of more than 100d. The tube formed a submerged jet, which flowed into the space bounded by a flow chamber made of Plexiglas with a size of 150x150x400 mm. A hot-wire anemometer sensor (8) was placed in the jet field; it could be moved by a coordinate device with a step of 100 μm along two axes in the range of 1400–1400 mm. The air flow rate was precisely controlled using a Bronkhorst digital flow controller (6) in the range of 0-2 g/s. In the experiments, the flow rate varied from 0.01 to 0.2 g/s, which corresponded to Reynolds numbers equal to 218 and 4360 (Re = Uavd/v, where Uav is the bulk velocity, v is the kinematic viscosity). No artificial disturbances were introduced into the gas path. The thermodynamic parameters at the beginning of the jet corresponded to atmospheric pressure and room temperature. The dynamic characteristics of the jets were measured using a DISA 55M (3) constant temperature hot-wire anemometer. A miniature DISA 55P11 probe (tungsten wire, thread diameter of 5 μm, thread length of 0.6 mm) was used as a sensor. To collect hot-wire anemometric data and save
them on the computer hard disk, a 24-bit E14-140 ADC/DAC (2) with a maximum sampling frequency of 4 kHz was used. The computer (1) was used to collect the hot-wire data and control the air flow regulator.

![Figure 1](image-url)

**Figure 1.** The experimental setup: 1 – computer; 2 – ADC/DAC; 3 – hot-wire anemometer; 4 – compressor; 5 – supply line; 6 – air flow regulator; 7 – tube; 8 – hot-wire anemometer probe.

3. **Results**

3.1. **Initial conditions**

At the first stage, measurements of the mean velocity profiles and turbulent pulsations at the outlet of the tube forming the flooded jet were carried out to determine the initial conditions of the jet flow and select operating regimes for studying the dynamic characteristics of the jet. The measurements were carried out at a distance of 0.5 mm from the tube outlet, the air flow took values of 0.01, 0.03, 0.12, and 0.2 g/s, which corresponded to the Reynolds numbers of 218, 654, 2616 and 4360. The profiles of average velocities and turbulent pulsations in dimensionless coordinates are shown in figure 2.

Distributions of average velocities corresponding to flows rates less than 0.2 g/s, as follows from figure 2a, are well described by the theoretical dependence for the Poiseuille profile. This means that at these flow rates the flow in the tube is laminar. As the flow rate increases to 0.2 g/s, the average velocity profile becomes less sharper, which corresponds to the developed turbulent flow in the tube.

The distributions of dimensionless velocity pulsations ($Tu = u'/U_0*100\%$, $U_0$ – velocity at the axis of the tube outlet) are shown in figure 2b. At air flow rates of less than 0.12 g/s, the distribution has a maximum on the jet axis. The value of turbulence degree at the maximum increases with increasing flow rate, but remains quite low, no higher than 2%. With an increase in the flow rate to 0.12 g/s, which corresponds to Re = 2616, there is a significant increase in pulsations in the tube and the type of distribution along the dimensionless coordinate $y / r$ (where $y$ is the transverse coordinate, $r$ is the radius of the tube) changes. Three maxima appear on the distribution, the largest is located on the axis.
Such a distribution of pulsations corresponds to a laminar-turbulent transition in the tube [25]. At this moment, turbulent regions (puffs, slugs) appear in the tube flow, and the flow becomes intermittent.

Figure 2. Average velocities (a) and turbulent pulsations (b) distributions at the distance 0.5 mm from tube outlet. Reynolds numbers corresponding to air flow rates are 218, 654, 2616 and 4360, theory – Poiseuille.

A further increase in the air flow to 0.2 g/s (Re = 4360) leads to transformation of the turbulence profile into a distribution with two maxima near the channel walls. Such a picture is characteristic of a developed turbulent flow in a tube.

Thus, for our conditions, the flow in the tube remains laminar to the air flow rate of 0.12 (Re = 2616), an increase in the flow rate above this limit leads to a laminar-turbulent transition. When choosing the operating regime, it is also necessary to take into account the presence of a laminar-turbulent transition in the jet itself. To obtain an extended laminar part, the degree of turbulence at the tube outlet should be minimal, but the jet momentum should be large enough to ensure a steady jet flow. After the analysis, the regime with an air flow rate of 0.02 g/s (Re = 436) was chosen.

3.2. Turbulent pulsations in the axisymmetric laminar jet
To study the turbulent characteristics of the laminar jet, the profiles of average velocities and velocity pulsations were measured in nine cross-sections along its flow. The cross-section closest to the tube outlet was at 10 mm from its outlet, and the farthest was at 100 mm. This corresponded to a range of values of dimensionless coordinates x/d = 3-31.

Figure 3. Average velocities (a) and turbulent pulsations (b) distributions at the cross-sections along the jet flowing. Reynolds number is 436, theory – Schlichting.
The profiles of average velocities and velocity pulsations in three cross-sections along the length of the jet are shown in figure 3 in dimensionless coordinates.

The average velocity profiles (figure 3a) are well described by the Schlichting theory in dimensionless coordinates for the laminar submerged jets (r_0.5 is coordinate where U = 1/2U_max for every cross-section). Small deviations from the Schlichting profile are observed in the cross-section farthest from the tube outlet at x/d = 31. This is because the jet lost momentum at these distances and began to perform low-frequency oscillations under the influence of, apparently, convective flows inside the flow chamber.

The profiles of the turbulence degree are presented in figure 3b. Pulsations are related to the maximum velocity in the cross section at a distance of 0.5 mm from the tube outlet. As it can be seen, in the cross-section closest to the tube outlet, the pulsation distribution remains the same as during the flow in the tube. With increasing distance, the maximum pulsation values shift to the jet periphery, which is explained by instability in the mixing layers. Moreover, as it can be seen from figure 3b, turbulence in the mixing layers, reached its maximum value, starts decreasing with increasing distance. This feature of behavior of turbulent pulsations in the mixing layer is well demonstrated by figure 4, which shows the distributions of turbulent pulsations on the axis and in the mixing layers, at the coordinates of pulsation maxima, and along the flow.

![Figure 4](image-url)

**Figure 4.** Turbulent pulsations distributions along the jet at the axis and in mixing layers at the turbulence degree maxima coordinate.

According to figure 4, turbulence on the jet axis decreases monotonically along the entire length of the flow, while in the mixing layers an increase in pulsation intensity occurs up to cross-section x/d = 12.5, and then it decreases sharply, followed by a slight increase. This pulsation behavior is unusual and requires further study.

**Conclusions**

The turbulent characteristics of a submerged axisymmetric laminar jet with Re = 436 flowing out of a tube longer than 100 of its diameters have been studied. The ranges of operating parameters when the laminar, transitional and turbulent flows occur in the jet source have been determined. Based on the data obtained, a regime for the study has been selected. For the selected regime, the profiles of average velocities and pulsations in cross-sections along the jet flow have been measured and distributions of turbulent characteristics along the jet flow on the axis and in the mixing layers have been constructed. Measurements have shown that turbulence on the jet axis tends to damp, while in the mixing layers
there is an intense increase in pulsations with a subsequent sharp decrease. This behavior is unusual and requires special research.

Acknowledgments
The study was partially supported by Government program (contract No. AAAA-A17-117030310010-9) and partially with assistance of a grant of the Russian Foundation for Basic Research (Project No. 17-08-00958).

References
[1] Ho C and Tai Y 1998 Ann Rev. Fluid Mech. 30 579
[2] Gau C, Shen C and Wang Z 2009 Phys. Fluids. 21 092001
[3] Kelemen K, Crowther F, Cierpka C, Hecht L, Kahler C and Schuchmann H 2015 Microfluidics and Nanofluidics 18 599
[4] Squires T and Quake S 2005 Rev. Mod. Phys. 77 977
[5] Kandlikar S, Colin S, Peles Y, Garimella S, Pease R, Brandner J and Tuckerman D J 2013 Heat Transfer 135 091001
[6] Rosa P, Karayiannis T, and Collins M 2009 Appl. Therm. Eng. 29 3447
[7] Fujiwara K and Nakamura Y 2013 Combust. Flame 160 1373
[8] Lemanov V, Terekhov V, Sharov K and Shumeiko A 2013 Tech. Phys. Letters. 39 421
[9] Schlichting H 1967 Boundary Layer Theory, 7th ed. (McGraw-Hill Book Company)
[10] Martin H 1977 Adv. Heat Transfer 13 1
[11] Kneer R, Haustein H, Ehrenpreis C and Rohlf W 2014 Proc. of the 15th Int. Heat Transfer Conf. IHTC-15 (Kyoto) (Begell House Publications) 497
[12] Kashi B, Weinberg E and Haustein H 2018 Phys. of Fluids 30 063604
[13] Revuelta A, Sánchez A and Liñán A 2002 Phys. of Fluids 14 1821
[14] Shin B and Tashiro S 2019 IOP Conf. Series: Materials Science and Engineering 491 012025
[15] Uddin M and Pollard A 2007 Phys. of Fluids 19 068103
[16] Schmidt-Bleker A, Reuter S and Weltmann K-D 2014 Phys. of Fluids 26 083603
[17] Revuelta A, Sánchez A and Liñán A 2002 J. Fluid Mech. 456 319
[18] Revuelta A, Sánchez A and Liñán A 2004 J. Fluid Mech. 508 89
[19] Revuelta A, Sánchez A and Liñán A 2002 Combust. Flame 128 199
[20] Andrade E and Tsein L 1937 Proc. Phys. Soc. 49 381
[21] Andrade E and Tsein L 1939 Proc. Phys. Soc. 51 784
[22] Rankin G, Sridhar K, Arulraja M and Kumar K 1983 J. Fluid Mech. 133 217
[23] Zayko J, Teplovodskii S, Chicherina A, Vedeneev V and Reshmin A 2018 Phys. of Fluids 30 043603
[24] Aniskin V, Maslov A and Mukhin K 2019 Microfluidics and Nanofluidics 23 57
[25] Lemanov V, Lukashov V, Sharov K and Abdrahmanov R J. Phys.: Conf. Ser. 1105 012015