Laminar-turbulent transition in the near field of the jet at the instability regime of the jet source

V V Lemanov\(^1,2\), V V Lukashov\(^1\), K A Sharov\(^3\) and R Kh Abdrakhmanov\(^1,3\)

\(^1\)Kutateladze Institute of Thermophysics, Siberian Branch, Russian Academy of Sciences, Novosibirsk, 630090 Russia
\(^2\)Novosibirsk State University of Architecture and Civil Engineering, Novosibirsk, 630008 Russia
\(^3\)Novosibirsk State Technical University, Novosibirsk, 630073 Russia

E-mail: sharov@itp.nsc.ru

Abstract. The paper presents the results of an experimental study of the hydrodynamics of jets flowing from long tubes at low Reynolds numbers. The main attention in the research is given to the mechanism of interaction between pipe and jet instability, which results in a vortical motion in several spatial regions. In the experiments we used Hilbert-visualization, high-speed visualization, and measurements with a hot-wire anemometer. The subsonic gas jet flows into the air space from a long tube with a diameter of 2, 3.2, and 5 mm within the Reynolds number range of 200-6700. Air and Freon-22 were used as the working gases. The critical pipe Reynolds numbers are characterized by the mechanism of a two-stage instability caused by the formation of turbulent spots (puff) inside the tube and generation of vortex structures in the jet mixing layer. These organized structures (puff) exert a strong influence on the free jet flow destroying the laminar flow part. The obtained data make it possible to consider in detail the evolution of turbulent spots along the distance downstream, while the spots are generated in a cylindrical tube due to the laminar-turbulent transition.

1. Introduction

The instability of gas jets appears at low Reynolds numbers (\(\text{Re} = 10-30\)) [1-3], but the transition to turbulence occurs at \(\text{Re} = 500-2000\) [4] that is currently poorly investigated. This may be explained by the relatively small application of laminar jets in technical devices in comparison with turbulent flows. Most often the nozzles, holes, and tubes are used as jet sources in industry.

It is known that the initial conditions play an important role in the development of jet flow. This includes the geometry of the nozzle, initial degree of turbulence, thickness of the boundary layer, degree of swirling of the flow, presence of co-current flow, etc. A huge number of research works are devoted to the study of the initial conditions for jets. However, most of them are devoted to turbulent jets. At present, jets flowing from the countered nozzles in turbulent flow regimes (the Reynolds number more than 4000), where the Kelvin-Helmholtz instability is the key mechanism for the formation of vortices in the initial section, have been studied in detail [1-3].

The velocity profile at the exit from the countered nozzle has uniform distribution and thin boundary layers. Unlike the nozzle, the gas flow at the outlet from the pipe has a developed non-uniform velocity profile with boundary layers that close to the axis of the jet, which introduces
significant changes in the development of the jet flow. Another feature of the jet flowing out of a long tube is the possibility of large velocity pulsations and vortex structures inside the pipe at the laminar-turbulent transition regimes. The resulting strong pulsations in the pipe can substantially modify the jet flow, which in turn exerts a strong influence on the mixing and combustion processes [2] in technical devices. In addition, the interaction phenomenon of two different types of instabilities acting in a jet and a pipe, and leading to a laminar-turbulent transition has a great scientific interest.

The known methods were applied to study the jet streams perturbed by vortex structures experimentally, such as the hot-wire anemometry and high-speed flow visualization. Also, the highly sensitive Hilbert-visualization method was used. It allowed us to record the optical density fields, and opened up new possibilities for obtaining information on the structure of the streams.

2. Experimental technique
The experimental setup consisted of gas vessels, gas reducers, and a flowmeter (figure 1). The experiments were carried out at atmospheric pressure and room temperature. The flow rate of gases was set by means of El-Flow Bronkhorst digital flowmeter. In the flows with density variation perturbed by the vortex structures, the Hilbert-visualization was used. For this purpose, the shadow device IAB-463M, additionally equipped with Hilbert optics, was applied.

Registration of the shift interferograms and video recording were made by Canon 650D digital camera with shooting frequency of 50 fps. High-speed visualization of light-scattering particles placed in the stream illuminated with a laser sheet was carried out using a Photron SA5 camera. The volume of a single sample consisted of 11000 frames made with 4000 fps. The circular quartz glass tubes with an internal diameter $d = 3.2$ mm and a length $l = 550$ mm, as well as $d = 2$ mm and a length $l = 1000$ mm were used as a jet source.

During measurements with a hot-wire anemometer, air was used as the working gas, the tube diameter was 5 mm, and the length was 1000 mm. The dynamic characteristics were measured by a constant temperature anemometer DISA 55M.
3. Results

Laminar-turbulent transition changes the flow dynamics. The flow becomes non-stationary, which is due to the presence of strong vortex structures. The dynamic characteristics of the flow in this regime were investigated by means of a hot-wire anemometer in air flowing from a tube with a diameter of 5 mm within the range of $Re = 900 - 6700$.

The appearance of turbulent spots at laminar-turbulent transition in a pipe changes significantly the distribution and magnitude of velocity pulsations along the channel section. This is illustrated in figure 2, which shows the degree of turbulence profiles, obtained by means of a hot-wire anemometer at the tube outlet. As can be seen, at $Re \sim 2500$, the degree of turbulence over the whole section of the channel increases strongly with a maximum observed in the central part.

This is explained by the presence of a large number of turbulent spots in the tube at this value of Reynolds number. The maximum values of the turbulence degree in this regime exceed the values of the turbulence degree for the turbulent flow.

It is known that free subsonic jets have sufficiently low Reynolds numbers, where the velocity pulsations begin growing (not higher than $10-30$) [1]. However, our experiments [4, 5] showed that the jet has a quite long laminar part (up to 200 tube diameters) even at $Re$ numbers of several hundred, and this applies not only to micro-jets, but also to macro-jets. Experiments with Freon-22 jet flowing into still air showed that the instability waves in the mixing layer (usually an asymmetric mode) were observed at $Re > 200$. The Reynolds numbers were chosen in such a way that a laminar-turbulent transition took place inside the tube.

Figure 3 shows the sequenced interferograms of the Freon-22 jet flowing into the still air: $Re = 4013$. Video recording - 50 fps.

![Figure 2. Distribution of turbulence degree in the initial cross-section of the jet: 1 - $Re = 900$, 2 - 2050, 3 - 2500, 4 - 6700; tube $d = 5$ mm, $l/d = 100$.](image)

![Figure 3. The jet of Freon-22 flowing from up to down into the still air. Tube $d = 3.2$ mm. $Re = 4013$. Video recording - 50 fps.](image)
Figure 4. The jet of Freon-22 flowing from down to up to the stable air. Tube $d = 3.2$ mm. $Re = 2230$. Video - 4000 fps.

This process can be observed in more detail during high-speed shooting (figure 4). The frames sequence shows that at the initial moment, perturbation waves develop in the mixing layer throughout the near field of the jet (figure 4b). Then, there almost instantaneous growth of perturbation amplitude during passage of puff was observed (figure 4d, e).

It is known [6] that a turbulent spot moving along a pipe generates weak pressure pulsations (sound waves). The pressure pulsations generated by the spot running through the pipe can modify the flow at the initial region of the jet, creating instability waves in the mixing layer and contributing to the reduction of its laminar part. In figure 4b, c the weak disturbances in the mixing layer of the laminar part of the jet are noticeable. We believe that they are caused by pressure pulsations, which are generated by the turbulent spot formed in the tube. Thereby, the high-speed visualization made it possible to establish the presence of an acoustic precursor of puff (figure 4b, c), which causes an increase in the perturbation amplitude in the jet mixing layer. We believe that there are two possible reasons for this: an acoustic precursor of the puff or the forward front beginning of the puff. The answer to this question requires further investigation.

The shift of the laminar-turbulent transition zone upstream is noted in figure 3 b; it also indicates the influence of acoustics. After the turbulent spot leaves the tube and moves downstream, the near field of the jet almost collapses. The velocity of the puff structure is consistent with the convective velocity of the jet on the axis. At small amplitude of the initial perturbations, the occurrence of local instability of small amplitude in the near field of the jet is recorded.

The turbulent spot coming into the jet is a three-dimensional structure. As a result, the disturbance of the mixing layer occurs both along the radius and along the circumference of the jet. However, visualization using a laser sheet parallel to the flow does not allow one to see the development of perturbations along the circumferential velocity component.
Visualization by means of two orthogonal laser sheets (figure 5) allows considering the structure of the jet mixing layer at the time of spot passage. As can be seen from the figure, the passing spot creates a lot of local instabilities along the circumference of the jet.

4. Conclusions
The results of experimental study of hydrodynamics of a jet flowing out of a tube within the Reynolds number range of 200-6700 are presented. It should be noted that Reynolds numbers characteristic of a laminar-turbulent transition in a pipe (both for air experiments and for Freon experiments) may differ due to the difference in the initial and boundary conditions in the pipe (pipe diameter, velocity profile, turbulence level, etc.), however, fundamental processes such as intermittency and formation of vortex structures are present in the initial section both in air and in gaseous jets of different density.

In the "laminar" regime, where there is no puff, the instability of the jet flow prevails [2, 3], which allows controlling the vortex structures, for example, by acoustic action. The use of a denser gas as a working fluid makes it possible, due to the density gradient, to weaken the effect of this instability [7] and increase the length of the laminar part of the jet. Thus, it becomes possible to observe the development of a turbulent spot in the jet stream.

As can be seen from the above data, the "transition" regime is characterized by two-cascade instability mechanism caused by the formation of turbulent spots inside the tube [6, 8] and generation of vortex structures in the jet [2, 3]. The velocity of the puff structure is consistent with the convective velocity of the jet on the axis.

Acknowledgments
This work was partially supported by the Russian Foundation for Basic Research (grant No. 17-08-00958). The measurements by the hot-wire anemometer were carried out at the expense of funds received from the FASO Russia.

References
[1] Abramovich G N 1963 Theory of Turbulent Jets (MIT Press Cambridge, MA) p. 671
[2] Ho C M, Huerre P 1984 Perturbed free shear layers. Annu. Rev. Fluid Mech. 16 365–424
[3] Michalke A 1984 Survey on jet instability theory *Prog. Aerosp. Sci.* 21 159–99
[4] Lemanov V V, Terekhov V I, Sharov K A and Shumeiko A A 2013 An experimental study of submerged jets at low Reynolds numbers *Tech. Phys. Lett.* 39 421–23
[5] Lemanov V V, Terekhov V I and Sharov K A 2016 Investigation of the Flow in Free and Impinging Air Micro- and Macrojets *Springer Proc. Phys.* 185 29–35
[6] Mullin T 2011 Experimental studies of transition to turbulence in a pipe *Annu. Rev. Fluid Mech.* 42 1–24
[7] Hallberg M and Strykowski P 2006 On the universality of global modes in low-density axisymmetric jets *J. Fluid Mech.* 569 493–507
[8] Lemanov V V, Lukashov V V, Abdakhmanov R, Arbuzov V A, Dubnishechev Yu N and Sharov K A 2018 Regimes of unsteady exhaustion and diffusion combustion of a hydrocarbon fuel jet *Combust., Explos. and Shock Waves* 54 255–63