Technology for formation of axisymmetric free jets with long laminar region

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Abstract. A new technology for formation of axisymmetric free jets with a long laminar region is presented in the work. Such jets are created by a compact device and experimentally studied in the Reynolds number range from 2000 to 13000. The device is capable of creating a jet of 0.12 m diameter. Numerical simulations are conducted with the purpose to analyse the flow inside the device and its impact on the jet velocity profile. Also calculations are conducted in order to find a way for a jet laminar region prolongation. Based on the calculations, the device parameters are corrected and the jet laminar region length is magnified from the size of 5.5 to 6.5 jet diameters. Free jets with long initial laminar regions and the diameter more than 0.1 m are advantageous for detailed research of perturbation growth and transition to turbulence in round jets, and can also be used to organize air curtains in order to protect objects in medicine and high-accurate industries.

1. Introduction

Free jets and other shear flows often occur in nature and various technologies. The topic of turbulent submerged jets is thoroughly studied and it is the focus of various applications such as mixing, combustion, noise generation, and others [1–3]. Laminar jets are much less studied due to their immediate breakdown at normal conditions. Submerged laminar jets are unstable. The critical Reynolds number $Re_{cr}$ of transition to turbulence for the flat submerged jets is equal to 4 [4], for axisymmetric – 37.9 [5]. Many works are devoted to the research on transition to turbulence in laminar free jets at the Reynolds number considerably superior to critical [5–7] and also to the control of free jets and the turbulence suppression in free shear flows [8–10]. Flow characteristics, such as velocity profile and intensity of turbulence, have a dominant role in these problems. For example, flow with low turbulence level occurs in the case of the Poiseuille velocity profile formation at air flow in a smooth pipe [11, 12]. In this way the velocity profile is defined only by Reynolds number and the channel length. Experimental results show that the free jet maintains its laminar character at distances of 10 jet diameters in the Reynolds number range from 600 to 7000 due to formation in the initial section of the submerged jet with a low velocity pulsation level and a velocity profile closed to parabolic. It is worth to notice that a velocity profile, which differs from the Poiseuille profile by less than 1%, forms in the pipe of the diameter $d$ at its length $l = 0.065 \cdot d \cdot Re$ [13]. Therefore diameters of the studied jets do not exceed several centimeters.

Laminar initial regions of free jets of sufficient length could be used not only for fundamental research on transition to turbulence. Such regions could accept to organize air curtains, which
provide zones of clean air not mixing with the ambient medium. Local clean zones can be used in medicine, medical industry, microelectronics, and other technological processes.

In this study, we present a new method for the formation of free gas jets with the diameter of 0.12 m, in which the transition to turbulence occurs at the distance of 6.5 jet diameters (for optimal velocity regime) from the orifice. The forming device length is only of $\sim 1.5$ jet diameter. The device is designed on the basis of the works [14,15], where a similar design was used to study turbulent flows.

2. Experimental set-up

Figure 1 shows the experimental setup. The device is installed on a support (1). The equipment consists of two parts: a laminarization unit and a forming device. The flow enters the apparatus through the air line (2). A perforated plate (3) and a bushing with metal grids (4) are fixed inside the channel and serve for the flow laminarization. The perforated plate (3) has holes with diameter of 0.6 mm and its porosity is equal to 0.8. Wire diameter of the metal grids (4) is $30\,\mu m$ and the grid cell is $40\,\mu m$. The intensity of velocity pulsations becomes less than 1% as the flow passing through them. Further air comes to the forming device. At this stage it is necessary to create a desired velocity profile at once, otherwise turbulence begins to develop directly in the forming device. A short round diffuser (5) is used for formation of a flow with the set velocity profile and low intensity of turbulence. The short diffuser is represented by an axisymmetric track that expands three times in the diameter while the track length is about the inlet diameter. A metal grids package (6) is located at the diffuser outlet. It slows the flow down and directs air to the diffuser wall. The diffuser shape and the metal grids permeation coefficient are chosen in a special way in order to prevent flow separation inside the diffuser. The experimental setup provides the velocity profile with almost constant velocity at the central jet part about 0.05 m in diameter and low turbulent intensity.

![Figure 1](image)

**Figure 1.** The forming device and its components: support 1, air line 2, perforated plate 3, bushing with metal grids 4, short round diffuser 5 with metal grids package at the outlet 6.

The dimensions of the experimental setup are summarized in Table 1. The distance between the perforated plate and the bushing is 0.03 m and the interval between the bushing and the
diffuser inlet is 0.06 m. The jet flows to the atmosphere passing through the laminarization unit and the forming device.

Velocity profiles and turbulent fluctuations are measured by thermoanemometer DISA 56C01 CTA with small-size wire sensor Dantec Dynamics 55P11. The sensor of the thermoanemometer is located on the transfer equipment that allowed to measure flow parameters along the radial coordinate. The jet visualization is performed with an glycerin mist and laser KLM-532.

**Table 1.** Dimensions of the experimental set–up shown in Figure 1.

| Part            | Inlet diameter d, mm | Outlet diameter D, mm | Height h, mm |
|-----------------|-----------------------|-----------------------|--------------|
| cylindrical channel | 40                    | 40                    | 160          |
| perforated plate | 40                    | 40                    | 2            |
| bushing         | 40                    | 40                    | 50           |
| diffuser        | 40                    | 120                   | 40           |

3. Results

Three series of experiments were conducted. Velocity profiles measurements prove that the flow is axisymmetric with respect to the device axis and the jet parameters depend only on the radial coordinate \( r \).

![Figure 2](image_url). Experimental study of the jet: velocity \( U_c \) (a) and turbulent velocity fluctuations \( u'_c / U_c \) (b) at the jet axis.

The first series shows that velocity \( U_c \) and initial intensity of turbulence \( u'_c / U_c \) remain constant at the jet axis in a distance \( l \) of several jet diameters \( D \) downstream the flow at a fixed velocity regime. These characteristics start to change at the distance \( L \) increase: velocity decreases (Figure 2,a) and turbulent velocity fluctuations grow up (Figure 2,b). The flow characteristics are also noticed to remain unchanged in the jet core along diameter when they preserve at the jet axis.

The second experimental series is devoted to measurements of the jet laminar region length and detailed study of the flow characteristic behavior at different velocity regimes. The maximum
distance from the device outlet at which velocity remains constant and turbulent velocity fluctuations remain less 1% is claimed to be the jet laminar region length \( l_{max} \).

Numerical simulations are carried out with the purpose to analyse the flow inside the device and its impact on the jet velocity profile. The flow is assumed to be steady and laminar, hence, Navier–Stokes equations are solved. Calculated and measured velocity profiles at the distance of 5 mm downstream of the diffuser outlet are compared in order to check the numerical model. Figure 3 shows a good agreement of these profiles. Numerical simulations show that the flow inside the diffuser depends on the inlet velocity. The flow is attached to the wall at low velocities and small local separations appear when the velocity increases. This leads to the change of the jet velocity profile and jet unstable perturbations rising. As a result the diffuser geometry is modified for prevention of separations and the third series of experiments with the modified device takes place.

![Figure 3](image1)

**Figure 3.** Comparison of the calculated (1) and experimental (2) velocity profiles at the distance of 5 mm from the diffuser outlet.

![Figure 4](image2)

**Figure 4.** Free jet laminar region dimensionless length \( L_{max}/D \) versus velocity \( U_c \) and the Reynolds number for updated (1) and original (2) diffuser.

The third experimental series is analogous to the second one. Figure 4 shows the obtained jet laminar region length for the original diffuser and the length prolongation with the help of the updated unit versus the velocity \( U_c \) at the jet axis and the Reynolds number based on the jet diameter and average velocity. Relying on the experimental and numerical results the jet laminar region length is concluded to have the greatest value for the velocity regime \( U_c \approx 2 \) m/s, and it reaches 5.5 jet diameters in case of the initial diffuser and 6.5 jet diameters in case of the modified one. Figure 5 shows the jet visualization at the velocity \( U_c = 2.5 \) m/s.

![Figure 5](image3)

**Figure 5.** Free jets with laminar region length \( l_{max} = 5.5D \) (rotated).
4. Conclusion
The main achievement of the work is a compact laminar jet formation device and the short round diffuser is its major part. The device size is of order of the jet diameter. Laminar jet of 0.12 m diameter at the Reynolds number $Re_{10000}$ based on the jet diameter and average velocity is obtained. Experimental results confirm laminar character of a flow at distance of 6.5 jet diameters from the forming device at the optimal velocity regimes for the device. The calculations allowing to optimize geometry of the diffuser channel for prolongation of the jet laminar zone are conducted. Considerable length and diameter of the laminar site allows to conduct a detailed research of transition to turbulence in the submerged jets. Also results of the work are capable of assumption to form laminar free jets of a larger diameter with the aid of the proposed technology. Laminar sites of such jets can be used in medicine and high-precision industry for creation of local zones with the set characteristics.

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