A New Method for the Formation of Free Jets with Long Laminar Regions

J. Zayko, A. Chicherina, S. Teplovodskii, A. Reshmin and V. Vedeneev

Abstract A new method for the formation of free jets with long laminar regions using a small-size device is proposed. A free jet with a 0.12 m diameter at Reynolds numbers in the range of 2000–12560 is experimentally studied using thermoanemometer measurements of velocity and turbulent fluctuations profiles and laser visualisation of the flow. It is shown that the designed technology forms the free jet with a laminar region length of 5.5 jet diameters for an optimal regime with Re $\sim$ 10000. Numerical simulation of the flow in the forming unit and an inviscid hydrodynamic instability analysis of the jet with calculated profiles have been conducted to explain the existence of the optimal regime.

Keywords Laminar jet · Free jet · Turbulence transition delay

1 Introduction

Free jets and other shear flows occur often in nature and various technologies and are widely studied. Turbulent jets and their breakdown have been thoroughly studied over several decades in the context of many industrial applications, including mixing, combustion, noise generation, etc.: [1–3]. Laminar jets are much less studied due to their immediate breakdown at normal conditions.

Batchelor and Gill [4] first analysed the equation for an infinitesimal inviscid disturbance of a unidirectional round jet, using the instability condition [5], which is that the expression $Q(r) = ru'/(n^2 + \alpha^2 r^2)$ should have a numerical maximum at some point in the flow. Here n and α are the azimuthal and axial wavenumbers of the Fourier component of the disturbance, u is the mean axial velocity and r is the

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radial coordinate. Round jets of the "top-hat" profile, which represents the jet profile near the orifice, and the self-similar "far-downstream" profile, obtained in [6], were examined. For the cylindrical vortex sheet which is a limit form of the "top-hat" profile, the flow is unstable for all values of n and α. The disturbance, which grows most rapidly, corresponds to $\alpha \to \infty$, and does not depend on n. For the "far-jet" profile, it was shown [4] that only the sinuous modes ($n = 1$) are growing.

The critical Reynolds number Re_{cr} for an axisymmetric jet was found in [7], where this type of free shear layers with respect to linear azimuthally periodic disturbances with $n = 1$ was investigated. The "far-downstream" profile was examined, and the critical Reynolds number Re_{cr} was determined to be 37.9. Later [8] three types of jet profiles, which represented jet development from the profile near the orifice to the fully-developed jet profile were numerically studied. The first was the "top-hat" profile, the second represented the initial mixing region and the third described the developed annular mixing region. Disturbances with $n = 0$ and $n = 1$ were considered. For $n = 1$, the critical Reynolds number 37.64 was obtained ($\alpha = 0.44$, $\omega = 0.1$), which is close to the result of [7]. Such a low value of Re_{cr} explains the almost immediate break-up of free jets near the orifice at normal conditions.

Numerous more recent studies have been devoted to the control of submerged jets, and to the suppression of turbulence in free shear layers of such jets: [9, 10]. An extensive review of investigations of the subsonic jet flows instability, turbulent structures generation, propagation of disturbances and the influence of an acoustic field on jet structure is given in [11].

An experimental apparatus used by different authors to obtain round jets with long laminar region often consists of grids or honeycombs for turbulence reduction, and a long tube, where the parabolic Poiseuille profile is formed at the tube outlet end: [12, 13]. However, it is impossible to use such technology in practice for the formation of jets with diameters of ~0.1 m or larger because the tube would be several meters or more in length. That is why the crucial issue in the creation of laminar jets of large diameters is the jet forming device, whose size should be comparable with the jet diameter.

In this study, we investigate a new method for the formation of free gas jets with a diameter of 0.12 m, in which the transition to turbulence occurs at the distance of 5.5 jet diameters (for the optimal velocity regime) from the orifice. The forming device has a compact size; its length is only ~1.5 of the jet diameter.

2 Experimental Apparatus and Test Conditions

The experimental apparatus is shown in Fig. 1. The flow from (1) the pipe line enters the forming device, whose first part is a cylindrical channel of 0.04 m in diameter and 0.16 m in length, where the flow is laminarised when it passes through (2) a perforated plate and (3) a bushing with metal grids. The second section of the forming device, a short diffuser, is located at the distance of 0.06 m downstream of the

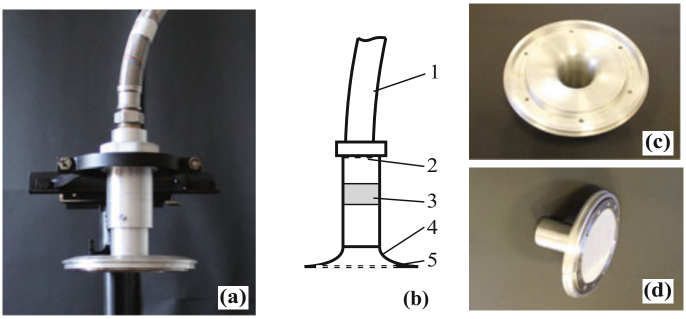

Fig. 1 **a** The photograph and **b** the sketch of the forming device, **c** the short round diffuser without and **d** with the metal grids package at the outlet

bushing. At the length of 0.04 m, the flow expands to the diameter of $D = 0.12$ m through (4) the short diffuser, from which the jet flows to the ambient medium. The diffuser wall profile and (5) a metal grids package at the diffuser outlet provide the velocity profile with almost constant velocity at the central jet core of ~0.05 m in diameter and low turbulence intensity.

Velocity profiles and turbulent fluctuations are measured by the thermoanemometer DISA 56C01 CTA with a hot-wire sensor Dantec Dynamics 55P11. The jet is visualised using glycerin mist and a laser KLM-532.

To analyse the flow inside of the diffuser at different velocities, and its impact on the jet velocity profile and the distance to breakdown, a numerical simulation of Navier-Stokes equations is conducted. Basing on the calculated jet velocity profiles, we analyse the inviscid hydrodynamic instability of the jet, which qualitatively predicts the distance to the jet breakdown.

3 Results

For various velocity regimes, we obtained various lengths L_{max} of the laminar region (Fig. 2a). The velocity and velocity fluctuations profiles for the optimal regime with $Re = 9200$ at the distances of 5.5 D and 6 D from the diffuser outlet are shown in Fig. 2b, c (the Reynolds number is based on the diffuser diameter and mean velocity averaged over a cross-section of the jet). Crosses with solid line corresponds to the measurements at the distance of 5.5 D. The intensity of turbulent fluctuations is less than 0.6% in the central part of the jet, which is not very different from the intensity near the orifice. So the jet stays laminar at this distance. Circles with dashed line correspond to the distance of 6 D, where the fluctuations grow and the transition to the turbulence occurs.

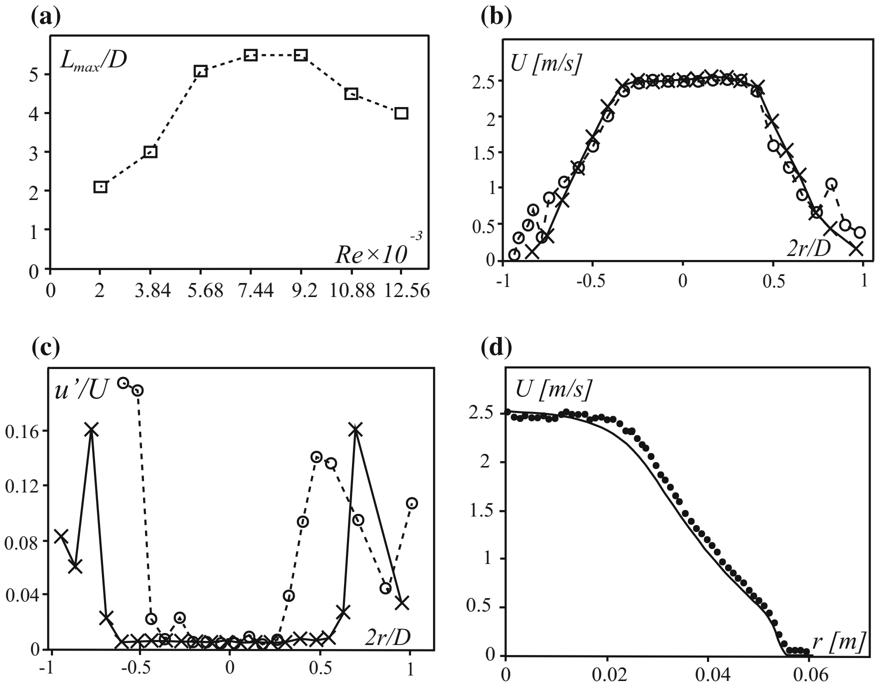

Fig. 2 **a** L_{max}/D versus *Re*, **b** velocity, **c** velocity fluctuations profiles at the distances of 5.5 *D* (crosses with solid line) and 6 *D* (circles with dashed line) from the orifice for $Re = 9200$; **d** comparison of experimental (circles) and calculated (solid line) velocity profiles at the distance of 5 mm from the diffuser outlet for the optimal regime

Numerical simulation of the flow in the diffuser explains the existence of the optimal regime with the longest laminar region. To validate the numerical model, calculated and measured velocity profiles at the distance of 5 mm downstream of the diffuser outlet are compared, and an excellent agreement is seen (Fig. 2d). The increase of the average flow velocity yields local laminar separation of the flow inside of the diffuser, which results in a change of the jet velocity profile that increases growth rates of the most unstable perturbations of the jet.

Figure 3 shows the results of visualisation by a laser sheet. Figure 3a shows the jet at the optimal regime with $Re = 9200$ and the length of laminar region $L_{max} = 5.5\ D$. Figure 3b corresponds to the jet breaking up near the orifice. Velocity time signals from the sensor at the distances of 5.5*D* and 6*D* near the jet axis are also compared (Fig. 3c). The amplitude of the signal at the distance of 5.5 *D*, where the jet is laminar, is ~23 times lower than at the distance of 6 *D*.

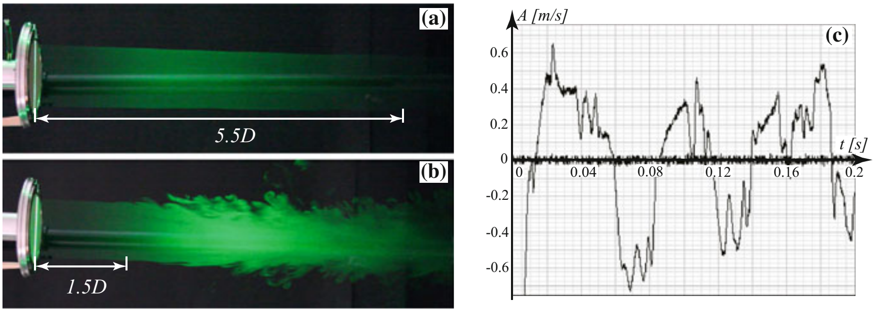

Fig. 3 **a** Jet with laminar region length $L_{max} = 5.5\ D$, **b** jet breaking up near the orifice, **c** comparison of the velocity time signals from the sensor near the jet axis for the optimal regime at the distances of 5.5 and 6 *D*

4 Conclusions

The main advantage of the proposed technology for laminar jet formation is a compact forming device of 1.5 jet diameters in size. We demonstrate a laminar jet with a diameter of ~0.1 m and $Re \sim 10\,000$, which is not achievable with other methods of creating of free jets. Laminar initial regions of free jets can be used to organise air curtains, which provide local clean zones with the desired properties in an ambient medium. Wall-free local clean zones can be used in medicine, the medical industry, microelectronics, plasma processing of monocrystal surfaces and other applications. Free jets with long laminar regions can also be used for detailed studies of perturbation growth and transition to turbulence in round jets.

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