Penetration of vertical pulsed jets in crossflow at low velocity ratio

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Abstract. Using the visualization method, the initial rise and penetration of a circular turbulent pulsed jet into a transverse air flow are studied at the ratio of jet velocities to the transverse flow \( r = u_j/u_f = 0.67–2.33 \). A comparative assessment of the penetration of a pulsating jet into a transverse flow for frequencies from 0 to 20 Hz is carried out. The cases of both stationary and oscillating jet flows are analyzed. The penetration of a pulsating jet into a transverse flow is shown to be more significant than for a stationary one and depends on an increase in the ratio of velocities and frequency: it increases linearly at a fixed frequency and passes through a minimum at a fixed ratio of velocities.

1. Introduction
The jet exiting into the transverse flow is widely used in technical fields, such as film cooling of turbines, control of separated flows over the aerodynamic profile, industrial mixing and dispersion of pollutants from exhaust pipes [1–3]. The transverse jet is usually divided into two categories depending on the source: the jet may be ejected from an orifice in the wall or from a raised pipe. The jet coming out from the wall is characterized by three-dimensional flows that are subject to interactions between the jet, the wake-jet and the wall-boundary layer. The mixing and penetration of the jet into the transverse flow are often improved by pulsations, which are achieved by temporarily exciting the jet stream coming out of the orifice [4–6].

Experimental studies in a water channel [4] confirmed the formation of a series of initial vortex rings in the configuration of a pulsed jet, penetrating deeper into the transverse flow as compared to a stationary jet. In the studies of both stationary and fully modulated transverse jets with pulsation frequencies from 0 to 20 Hz, at low pulse frequencies, the vortex rings were found to penetrate much deeper. Experimental results of studying the dynamics and control of large-scale organized structures in an isolated circular jet exiting into a homogeneous transverse flow with a ratio of velocities (or blowout) of the jet to the transverse flow equal to 6 were presented in [5]. A rotating mechanical valve was used to modulate the jet flow. The Strouhal number of about 0.1 was found to be optimal for organizing instability and improving mixing.

A classification scheme for fully pulsed jets in a transverse flow, based on the repetition factor of jet pulses and the intermittency factor, was proposed in [7]. The criteria for the interaction of flow structures near the nozzle and in the far zone were presented. It was noted that both deep penetration into the transverse flow and the corresponding mixing can be achieved using pulsed jets, if the pulsation parameters are chosen specifically to create compact vortex rings for rapid penetration at the initial stage. In [8], controlled modeling of fully modulated, pulsed jets in a transverse flow with rectangular-shaped excitation was used. Optimal pulsation modes for maximum penetration and
propagation of the jet in the transverse flow were considered. It was found that at very high velocity ratios, vortices formed by successive pulses do not interact, and their behavior is similar to that of single vortex rings in a transverse flow. As the velocity ratio decreases, the vortex rings following each other begin to interact with each other, and the total penetration decreases.

The present work is devoted to experimental studies of the penetration of a vertical pulsed, fully modulated jet into a transverse flow at low relative velocity ratios using the visualization method.

2. Experimental method
An open-type wind tunnel is used to conduct experimental studies [9]. A scheme for organizing non-stationary interaction between the main stationary air flow and a jet of pulsating air is developed. The diagram of the working part for studying the penetration of the jet into the transverse flow is shown in Figure 1. The working section 1 of the unit has a square cross-section of $0.125 \times 0.125 \text{ m}^2$ and a length of 1.0 m.

![Figure 1. Diagram of the working part of the aerodynamic channel: 1 – working section; 2 – diffuser and exhaust system; 3 – tube; 4 – disc pulsator; 5 – pulsation damper; 6 – flow meter controller; 7 – laser; 8 – camera.](image)

The aerodynamic channel contains an axial fan (EL 315 D2 01), which supplies air to the channel. The control unit allows smoothly changing the rotation of the fan, ensuring the maintenance of a stationary flow in the working area.

One of the most important elements of the unit is the pulsator 4. The pulsation frequency is changed in accordance with the number of revolutions of DC electric motor using the Gwinstek SPS-3610 power supply, which allows smoothly adjusting and stabilizing the rotation rate of the motor shaft. The pulsation organization unit is a plate valve (a disk with four radially arranged slot orifices), which is located on an axis inside a fixed housing. When the disk rotates relative to the body with a certain frequency, the air jet stream that passes through the pulsator is periodically blocked [9].

To assess the characteristics of the main cross-flow in the working section of the aerodynamic channel, thermal anemometric measurements of velocity were carried out. The HWA point measurement technology was used. The thermoanemometric sensor is installed on the axis of the central part of the working area. The velocity profiles were determined by the unit height from 0 to 70 mm for some flow modes. For a certain time interval, an array of instantaneous velocities was determined at each fixed height with an interval of 0.5 mm.

The measurement of the velocity field in the vertical central section for various flow rates has shown that the profile has a constant velocity core $u_f$ (a boundary layer on the channel walls of 10–15 mm) with a turbulence level of about 0.5%. Figure 2 shows profiles of some velocities, in the range of which our studies were conducted.
The parameters of the pulsating jet flow were determined by the flow rate of the supplied air passing through the pulsator. The flow meter-controller 6 allowed setting and controlling the flow rate of up to 600 l/min. The supply channel of the pulse jet was implemented using a steel pipe 3 of circular cross-section with a length of 0.8 m and an internal diameter \(d = 19\) mm.

To study the jet in the transverse flow, visualization was performed using particles of an aqueous solution of glycerin with a size of up to 5 microns. The video recording of the flow pattern in the experiments was performed with Canon EOS1100D monochrome camera in a light sheet created by a continuous laser LSR532H-2.5 W-LN. The camera allowed shooting at a speed of 30 frames/s. The rise of the jet (the boundary from the windward side) was determined from photographs of the maximum penetration of the smoke jet into the transverse stream, which were obtained from video shooting. Figure 3 shows the diagram and the place of measuring the height of the jet rise at different distances from the center of the tube.

Figure 2. Profiles of the main flow velocity in the working area.

![Figure 2](image)

Figure 3. The jet in cross-flow: – measuring scheme (the vertical plane passes through the center of the jet).

![Figure 3](image)

A series of experiments was carried out at the jet pulsation frequencies: \(f = 0, 3, 6, 10,\) and \(20\) Hz. The volumetric flow rate of the jet stream \(Q\) was controlled and maintained using a flow meter. The average exit velocity was \(u_j = 4Q/\pi d^2 \approx 4.7\) and \(7.0\) m/s, which corresponded to the Reynolds numbers for the diameter \(Re_d = u_j d/\nu_j = 5.9 \cdot 10^3\) and \(8.8 \cdot 10^3\). The velocity of the main cross-flow was \(u_f = 3, 5\) and \(7\) m/s.

3. Results and discussion

The initial lifting heights (penetration depth) of the smoke jet along its left edge (Figure 3) were determined at the maximum pulse in the jet. Figure 4 shows data on the height of the jet rise depending on the ratio of the jet velocities to the flow \((u_j/u_f)\), and the Strouhal number \((St = fd/u_j)\). When the jet was blocked in the pulsator, the rise was equal to zero, which was recorded on all videos when the main parameters were changed.

With an increase in the superficial velocity of the jet, the rise of the jet (penetration depth) increased almost linearly for a constant frequency. However, with an increase in frequency, the rise of the jet had a minimum (with a constant velocity ratio), where the average straight lines almost coincided at \(f = 6, 10\) Hz and \(f = 3, 20\) Hz for \(x/d = 0.5\). It was shown that for \(x/d = 2\), the increase in lift depending on the frequency was not so pronounced (Figure 4 c) and the relative height difference at \(r = 2.33\) fell almost two times and for \(x/d = 3\), it was almost 3 times less than the initial one. It was found, that at \(r > 1.4\), the penetration (lifting height) of the jet into the stream had a minimum, after
which there was an increase with an increase in the Strouhal number, and at $r < 1.4$, the rise of the jet actually stopped already near the source of the jet.

![Figure 4](image)

**Figure 4.** The rise of the transverse jet depending on $r$ (a, c) and St (b, d) at a distance of $x/d = 0.5$ (a, b) and $x/d = 2.0$ (c, d) from the center of the source.

A similar ($r > 1.4$) picture of the behavior of dependence of the height (depth) of the jet penetration into the stream on the St number is shown in [4] at $x/d = 3, 10, 40$ for the Reynolds number $Re_d = 6200$ for full modulation and $r = 4.4$. In [8], different behaviors of the transverse jet are shown at $r < 2$ (low velocity ratio) and $r > 2$ (high ratio). At low speed ratios, penetration decreases.

4. Conclusions

A comparative estimate has been given for the penetration of a transverse pulsating jet into the cross-flow for a low ratio of velocities and frequencies from 0 to 20 Hz. The penetration of the pulsed jet into the transverse flow appears to be higher than in the case of a stationary jet in all cases. It has been found that the initial lift depends rather weakly on the Strouhal number, especially for very low relative velocities ($r < 1$). Controlling the pulsation frequency and the flow rate of the jet allows changing (regulating) the rise of the jet, and its penetration into the cross-flow, depending on practical tasks.
Analysis of the literature and our data suggest that the nature of the rise (penetration depth) of a fully modulated jet does not depend on the method of obtaining and the severity of the form of pulsations of the flow of liquid or gas. A significant response and rise of the jet in comparison with the stationary one are achieved even with sinusoidal forcing of the jet with a moderate range of velocity excitation.

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