Experimental study of the flow structure in cross flows

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Abstract. This study investigates the development of flow and mixing processes in the stationary and impulsive transverse jets with a small degree and frequency of blowing pulsation. Velocity field measurements were carried out using the TR PIV technique. The fields of statistical moments are obtained. It is shown that when a cross flow is injected, the main flow is turbulized, while the rise of the pulsating jet depends on the outflow mode. It is shown that with an increase in the frequency of pulsations of the transverse jet, it is more strongly "pressed" against the lower wall, maximum values of the intensity of pulsations of the transverse velocity component exceed by more than 1.5 times the values of pulsations of the transverse component.

Introduction

The transverse jet is used for dilution or injection of primary air jet into the combustion chambers of gas turbines to achieve the ratio of mixture components and NO\textsubscript{X} control, and also cooling the hot parts of the turbine; in film cooling of turbine blades; with primary fuel injection in high-speed air-breathing engines; and in thrust vector control for missiles and other high-speed vehicles. Cross jets are also used in environmental control systems such as wastewater control. Consequently, there are many variations in this, including jet fuel nozzle, injection into a transverse oxidant stream; round or rectangular jets with different injection of gas or liquid into high-speed transverse air currents with impacts or other wave structures that affect the behavior of the jet. The range of flow conditions and cross-flow applications requires a deep understanding of structural, mixing and, where appropriate, reactive flow.

Chimneys, vertical take-off and/or short take-off and landing aircraft, and fuel injectors are just a few of many engineering systems involving cross-flow jets, also called cross-flow jets, and have prompted numerous flow studies over the past 80 years. Among them, Fric et al. [1] and Bidan et al. [2] witnessed four main vortex structures involved in this type of flow configuration: shear layer vortices, counter-rotating vortex pair, horseshoe vortex, and wake vortices. Vortices of the shear layer are structures near field, typically taking the form of sequential vortex rings radiated in the incoming flow, and are generally considered to be the result of instability of Kelvin - Helmholtz cylindrical shear jet layer [1], although there have been other assumptions to explain this process, for example, Blanchard, Brunet & Merlen [3].

The CRVP (counter-rotating vortex pair) is generally considered to be the main mixing structure in transverse jets and is the topic of many studies related to improving or preventing mixing. The CRVP consists of a pair of quasi-longitudinal vortices, which are formed downstream of the jet outlet and dominate in the far zone. Several mechanisms for generating these vortices have been proposed,
including [4], who suggested that the CRVP vorticity was directly caused by the reorientation of the shear layer of the jet by cross flow. Another research group, Yuan et al. [5] identified a pair of dangling vortices at the base of the jet column as the source of the CRVP vorticity.

Studies of shear layer vortex structures by Kelso et al (1996) showed that upstream and downstream roll-ups compensated for each other, and vertical vorticity was created by CRVP due to the roll-up of transverse-layer vortices through their lateral branches. This mechanism was later confirmed by numerical simulations by Cortelezzi & Karagozian [6], which showed the formation of CRVPs through the folding of the original structures.

The third characteristic vortex structure is a horseshoe vortex. It is the result of the separation of the cross-flow boundary layer before the jet exits. Kelso & Smits [7] investigated the dynamic relationship with the shear layer structures of the jet leading to longitudinal oscillations of the horseshoe vortex ahead of the jet exit. Wake vortices were described as tornado-like quasi-vertical vortices located downstream of the jet outlet and below the jet core, resulting from the separation of the cross-flow boundary layer due to unfavorable pressure distribution.

Moreover, since improving mixing and short take-off and landing aircraft propulsion has been a major concern in past studies; most studies have focused on jet engines with a fairly high blow ratio, while only a few studies have looked at blow rates less than 1. Among them, Gopalan, Abraham & Katz [8] showed that vortex structures at low blowing rates can be fundamentally different from previously described jets. These systems exhibit jet reattachment associated with the formation of a recirculation region downstream of the jet outlet surrounded by a "semi-cylindrical vortex layer" arising from the jet shear layer. Other studies of the boundary layer transition have provided descriptions of the dynamics of individual structures also encountered in jets with a low degree of overflow blowing. Using a hemispherical protrusion or long longitudinal injection slots to create hairpin vortices, they established their overall dynamics in the near-wall region. Although some of these studies were conducted using transverse jet configurations, the significant influence of jet geometry, as evidenced by Haven & Kurosaka [4], resulted in many vortex structures and interactions completely different from those found in circular transverse jets.

Forced transverse jets were primarily investigated for their ability to mix and increase penetration. Gogineni, Goss & Roquemore [9] achieved an increase in penetration of up to 30% by simply energizing the shear layer of the jet with piezoelectric actuators, while Johari, Pacheco-Tougas & Hermanson [10] achieved a mixing rate increase of about 50% using fully modulated jets. In the latest study, two forced jet regimes were observed. The first for a long injection consisted of successive puffs, reminiscent of a steady stream during injection, and the second, for a shorter injection time, was associated with the formation of an initial vortex ring at the jet impulse, which led to a significant increase in penetration and mixing. Both studies agreed on the fact that duty cycle and pumping frequency can greatly influence jet behavior. More recently, Sau and Mahesh [11] investigated the formation and behavior of vortex rings in cross flow from a fully modulated forced jet using direct numerical simulations (DNS), including fairly low average blow rates below 2. They found that large hairpin vortices, rather than vortex rings, would be generated on impulse with a blow ratio below 2.0. They also provided a map of the initial vortex regimes depending on the degree of blowdown and stroke ratio with three different shapes: "discrete vortex ring", "vortex ring with back column" and "vortex structures like hairpins".

Using the TR PIV technique, a study was carried out to investigate the development of flow and mixing processes and impulse transverse jets with a low blowdown rate and pulsation frequency. The fields of statistical moments are obtained. It is shown that when a cross flow is injected, the main flow is turbulized, while the rise of the pulsating jet depends on the outflow mode. It is shown that with an increase in the frequency of pulsations of the transverse jet, it is more strongly "pressed" against the lower wall; maximum values of the intensity of pulsations of the transverse velocity component exceed by more than 1.5 times the values of pulsations of the transverse component.
Experimental details
A schematic of the experimental setup for studying pulsating turbulent flows is shown in figure 1. The installation consists of three main parts: I) aerodynamic channel; II) pulsating part; III) air supply system.

![Figure 1. The experimental setup.](image)

Aerodynamic channel I contains: axial fan 1; a chamber for the formation of a flat velocity profile, including a honeycomb and a confuser 2; working area 3; diffuser and exhaust system 4. The main elements of the pulsation part II are: ohmic heater 5; power controller 15; pulsation damper with a metal mesh inside 6; and disc pulsator 7. After the pulsator, pipe 8 with an inner diameter \((d = 19 \text{ mm})\) is installed, through which air is supplied to the working section. The inlet part III of the installation consists of a pipeline through which air from the pressure air line through the reducer 10 goes through the fine filter 11 (5 \(\mu\)m), the flow controller 12 and the flow meter 14 to the pulsation part.

The working section of the installation has a square cross section of \(0.125 \times 0.125 \text{ m}^2\) and a length of 1 m. The control unit 13 allows smooth changing in fan rotation, ensuring the maintenance of the average velocity of the flow core in the working section in the range \(u = 0.5–30 \text{ m/s}\).

One of the most important elements of the installation is the pulsator. Figure 2 shows a diagram of the pulsating unit. The pulsator is driven by a DC motor 6. The pulsation frequency changes in accordance with the number of revolutions of the electric motor and in width with smooth regulation and stabilization of the speed of rotation of the motor shaft 16.
Figure 2. Scheme pulsation block: (a) - a general view; (b) - sectional pulsator. 1 - outlet tube; 2 - pulsator; 3 - connecting sleeve; 4 - inlet tube; 5 - power frame; 6 - electric motor; 7 - fixed body; 8 - air path; 9 - axis; 10 - bearings; 11 - disc and hole pattern.

The pulsation organization unit is a plate valve - disc 11 with four holes, which is located on the axis 9 inside the stationary body 7. When the disk rotates relative to the body at a certain frequency, the air flow that passes through the pulsator is periodically blocked.

Results and discussions
To study the interaction of flows, we firstly visualized a perpendicular pulsating jet using particles of an aqueous solution of glycerin up to 5 μm in size, which were recorded by a Canon EOS1100D camera in the area of a light sheet. This sheet was created with a continuous laser LSR532H-2.5W-LN.

Visualization was carried out for a perpendicular pulsating jet with flow rates Q = 80 and 120 l/min (kept constant), which corresponded to average flow rates v ≈ 4.7 m/s and 7.0 m/s. Reynolds numbers in diameter were Re_d ≈ 5.9 • 10^3 and 8.8 • 10^3, respectively, where d = 19 mm is the inner diameter of puls tube. The frequencies of the flow rate pulsations of the jet were f = 6, 20 Hz. The velocities of the main blowing stream were u ≈ 3, 5, 7 m/s (Re_D = 2.5 • 10^4, 4.2 • 10^4, 5.8 • 10^4, where D = 125 mm is the channel characteristic size). The heights of the rise of the jet at the maximum impulse in the jet were determined. The heights of the rise of the jet (gray dot) were determined along its left edge (figure 3 (a)) relative to the vertical drawn through the right edge of the tube at the maximum momentum in the jet. Figure 3 (b) shows the data on the height of the jet rise (h_0) depending on the ratio of the velocities of the jet and the flow v/u, as well as the frequency of pulsations of the jet. The straight line on the graph is a linear approximation of the points. Also, measurement of the jet recovery were made for the case f = 0 Hz.
It is shown that with an increase in $v/u$, the height of the jet rise also increases. This means that the jet penetrates deeper into the main stream and has a stronger effect on its further development. Also, with an increase in the frequency of the transverse flow pulsations, the lifting height increases.

At this stand, an experimental study of the hydrodynamics of the interaction of the main and transverse pulsating flows was also carried out using the method of anemometry from particle images with high temporal resolution (Time resolved PIV, TR PIV). The measuring system consisted of a Photonics DM high-speed pulsed laser (pulse energy, duration of 150 μs, up to 8 mJ at a pulse repetition rate of 10 kHz) and a high-speed Photron SA5 camera (a frequency of capturing full frames of 1024x1024 pixels with a dynamic range of 12 bits up to 10 kHz.). For PIV measurements of flow seeded with particles, represented by drops water-glycerin solution ($d = 5 \mu m$), a series of experiments was carried out at the frequencies of the pulsating jet described above ($f = 6; 20$ Hz). The velocity of the pulsating flow was controlled using two flow meters with Bronkhorst mass flow controllers and was $v = 4.7 m/s$. The velocity of the main flow ($u = 3; 5 m/s$) was also varied in the experiment. The measurements were carried out in a plane along the main flow in the central section of the transverse pulsating flow. The number of realizations was 5000 snapshots.
Figure 4. Visualization of the flow (a); instantaneous velocity field (b); instantaneous vorticity field (c).

Figure 4 (a) shows a photograph of the measurement area with seeded particles. Experimental mode is $v = 4.7$ m/s, $u = 3$ m/s, $f = 6$ Hz. It can be seen how the vortex structures rise from the entrance of the pulsating jet and propagate down the main flow. Figure 4 (b) shows the instantaneous velocity field, where $\frac{V}{|v|}$ is the ratio of the amplitude of the instantaneous velocity to the average flow rate of the pulsating jet. It can be seen how vortex structures rise from the entrance of the pulsating jet and propagate along the main flow. It is observed that shear-layer vortices appearing as well-defined rollups on both the upper and lower jet cross-flow interfaces shed periodically while wake vortices located under the jet core are evidenced by seed particles, suggesting that these structures transport jet fluid. The vortices of the shear layer begin to break down approximately at $x/d \approx 2.5$. This is clearly observed by plotting the vorticity field (figure 4 (c)), where $w$ is the amplitude of the instantaneous vorticity. It is also shown that there is a reverse flow immediately after the exit of the pulsating jet. The maximum speed values for the period for the pulsating jet reach $2.5 \cdot \frac{V}{|v|}$.

Figure 5. Average velocity distributions for the main flow velocity $u = 3$ m/s, the transverse pulsating flow velocity $v = 4.7$ m/s and the frequency $f = 6$ Hz (left) and $f = 20$ Hz (right).
Figure 6. Distribution of pulsations of the longitudinal (top) and transverse (bottom) velocity components for the main flow velocity $u = 3$ m/s, the transverse pulsating flow velocity $v = 4.7$ m/s and the frequency $f = 6$ Hz (left) and $f = 20$ Hz (right).

From the analysis of the instantaneous velocity fields, it can be concluded that when a cross flow is injected, the main flow is turbulized, while the rise of the pulsating jet depends on the outflow mode. As an example, figure 5 shows the spatial distributions of the average velocity. It can be seen that with an increase in the frequency of pulsations of the transverse jet, it is more strongly "pressed" against the lower wall. The distribution of pulsations of the longitudinal and transverse velocity components has a characteristic form for all modes (figure 6.), and their intensity increases with an increase in the frequency of the pulsating transverse flow. The maximum values of the intensity of pulsations of the longitudinal velocity component exceed by more than 1.5 times the values of pulsations of the transverse component. The maximum intensity of pulsations of the longitudinal velocity component is located immediately behind the pipe cut, and the transverse velocity component is located in the center of the pulsating jet.

A similar behavior of the distribution of the average velocity and pulsations with increasing frequency also occurs at a high velocity of the main flow ($u = 5$ m/s, $v = 4.7$ m/s). In this case, in comparison with the mode $u = 3$ m/s, $v = 4.7$ m/s, all characteristics are "pressed" against the lower wall of the experimental stand.

Conclusion
Visualization and PIV-measurements were performed in pulsating transverse jets. It is shown that with an increase in $v/u$, the height of the jet rise also increases. This means that the jet penetrates deeper into the main stream and has a stronger effect on its further development. Also, with an increase in the frequency of the transverse flow pulsations, the lifting height increases. The distribution of pulsations of the longitudinal and transverse velocity components has a characteristic form for all modes, and
their intensity increases with an increase in the frequency of the pulsating transverse flow. The maximum values of the intensity of pulsations of the transverse velocity component exceed by more than 1.5 times the values of pulsations of the transverse component. The maximum intensity of pulsations of the longitudinal velocity component is located immediately behind the pipe cut, and the transverse velocity component is located in the center.

Acknowledgments
This work is funded under the State Contract with IT SB RAS.

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