On coherent structures and heat transfer in strongly swirling impinging jets

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Abstract. This work is devoted to the experimental study of coherent structures in swirling jets flowing onto a heated surface. To measure the velocity fields with a high acquisition rate of 3.5 kHz Stereo Particle Image Velocimetry (PIV) measurement system is used. Simultaneously with PIV measurements, the temperature of the heated surface is measured by high-speed thermometry. The experiments are carried out for three different cases of swirling and two distances from the nozzle to the impingement surface. It is shown that only in the case of strongly swirling jet breakdown of vortex core and bubble-type recirculation zone appear. In this flow regime, large-scale vortex structures of spiral shape are found. The contribution of coherent structures to the fluctuations of velocity and temperature is analyzed for a strongly swirling jet by using Spectral Proper Orthogonal Decomposition (SPOD) method and spatial Fourier transform. It is found that the strongly swirling jet for $H/d = 1$ provides most effective overall cooling of the surface for the considered flow configurations.

1. Introduction

Jets flowing onto flat surfaces are used in a number of technical applications, for example, where cooling and heating, coating on the surface, etc. are required. The velocity profiles near the impingement surface significantly affect the local heat transfer with the impingement surface [1]. In the near-wall region of a round jet the radial velocity is dominant. An increased level of turbulent pulsations in the near-wall region, as well as large-scale vortex structures in a mixing layer, lead to increased mixing [2] and an increase in the heat flux on the wall [3]. Studies show that for round jets at small distances to the impingement surface, the radial distribution of heat transfer may not monotonically decrease from the central axis of the jet and have several maxima and minima at different radial distances. The experiments show that the characteristics of heat transfer from the impingement surface depend on many parameters, such as the Reynolds number, the distance from the nozzle, the geometry of the nozzle and the level of turbulence. The use of flow swirl to organize impinging jets leads to an increase in the radial and tangential velocity components, causing the jet expansion [4]. Experimental studies of turbulent structure and dynamics of impinging jets using non-contact panoramic measurement methods were carried out in [5, 6]. The use of swirling leads to more intensive mixing due to the formation of large-scale vortex structures [2]. It has been found in the literature that swirling flow can adversely affect heat transfer [7]. This is explained by a thicker boundary layer arising on the impingement surface and the appearance of vortex breakdown with a strong flow swirl. On the other hand, other studies [8, 9] show an increase in heat exchange with a swirling flow in the reverse flow region, as compared to a non-swirling flow, which may be associated with more intensive mixing of the flow and formation of vortices near the impingement surface. The influence of the distance between the nozzle and the impingement...
surface on heat transfer is studied in a number of works, for example, [7, 10], and is also of considerable interest for further studies. There are a number of open questions, for example, regarding the dependence of the distribution of the Nusselt number and the heat transfer intensity depending on the distance to the impingement surface for different degrees of swirl and Reynolds number. It is worth noting that the above flow characteristics of impinging swirling jets are not well studied in the literature, especially with regard to their contribution to unsteady heat transfer.

The aim of this work is to study the turbulent structure and dynamics of strongly swirling impinging jets with the vortex breakdown and precession of the vortex core using the stereoscopic PIV method and the statistical analysis of coherent pulsations of the surface temperature using IR thermometry.

2. Experimental setup and measurement details
The experimental setup was a closed hydrodynamic circuit, including a plexiglass test section, a pump, an overflow tank, a piping system with a flow meter, and a thermostat (see photograph in Fig. 1). The temperature of the circulating water was monitored by thermal resistance sensors installed in the test section and the water tank. During the experiments, the temperature of the water was maintained constant. The jet flow, organized by a contraction nozzle (with the outlet diameter $d = 15$ mm), impinged normally on a flat heated surface made of a sapphire glass (4 mm thick, 150×150 mm in size). From the water side the sapphire glass was coated by a thin conductive film of indium-tin oxide transparent in the visible range. An electric current passed through the coating, providing a uniform heating of 3.6 W/cm$^2$. The Titanium HD 570M IR-camera recorded the temperature of the conductive film on the heating element.

A blade swirler was installed inside the nozzle to create a jet with angular momentum [5]. Using swirlers with different angles of inclination of the blades, jets with different swirl intensity (defined as the ratio of the jet angular momentum flux to the axial momentum flux, normalized by the nozzle exit radius) were produced. The swirl rates were estimated based on the geometrical parameters of the swirlers [5]. Swirlers provided swirl rates $S = 0.41$ and 1.0, respectively. The critical swirl rate for which
a vortex breakdown occurred in a free jet flow configuration with formation of a recirculation zone was approximately 0.6.

The PIV system consisted of a Photonics DM high-repetition pulsed Nd: YAG laser (150 ns pulses with energy of up to 8 mJ at a repetition rate of 10 kHz) and two Photon SA5 high-speed CMOS cameras (with 7.5 kHz rate of full frames with 1024×1024-pixel array). Polyamide tracer particles with minimal buoyancy were added to the water to provide PIV measurements. An in-house “ActualFlow” software developed in the Institute of Thermophysics was used to acquire and process the PIV data. The cameras and laser were synchronized by a BNC 575 device from Berkeley Nucleonics. The acquisition rate was 3.5 kHz. Two independent runs were performed for each swirl case. During each run 5500 images were recorded. Spatial calibration of the PIV cameras was performed by using a planar calibration target (100×100 mm) and a third-order polynomial transform. The particle displacement was evaluated by using a multi-frame pyramid correlation algorithm. The spatial overlap factor of the interrogation areas was set to 50%.

3. Data analysis methods

The standard Proper Orthogonal Decomposition (POD) method is based on the problem of finding an orthonormal spatial basis of dimension N, which best approximates the ensemble of velocity pulsation fields using the least squares method. The problem of finding the optimal orthonormal basis is reduced to solving the Fredholm integral equation, the kernel of which is a two-point spatial cross-correlation function.

To analyze the frequency characteristics of coherent pulsations, we used a modification of the POD method - Spectral POD [11]. Although the standard and spectral POD aim at identifying coherent structures, Spectral POD allows finding flow eigenmodes, which are periodic functions in space and time. This is achieved by replacing the spatial cross-correlation function in the integral equation by the space-time cross-correlation function. By the operation of the Fourier transform of the cross-correlation function, this problem is reduced to a spectral eigenvalue problem, which also takes the form of a Fredholm integral equation of the second kind.

Using the spectral POD decomposition, the ensemble of velocity fluctuation fields is represented as a finite series of basis functions that are orthogonal in space and time, with the corresponding spectral coefficients $a_n(f)$ [11]:

$$\tilde{u}(x, t) = \int_{-\infty}^{+\infty} \sum_{n=1}^{N} a_n(f) \phi_n(x, f) e^{2\pi i ft} df \quad (1)$$

In this case, the eigenfunctions and spectral coefficients must satisfy the following conditions:

$$\int_{\Omega} \phi_n(x, f') \phi_m^*(x, f') dx = \delta_{nm} \quad (2),$$

$$E\{a_n(f) a_m(f)\} = \lambda_n \delta_{nm} \quad (3).$$

To find the eigenvalues, modes, and spectral coefficients, the algorithm based on windowed fast Fourier transform and SVD decomposition was used [11]. Application of the method to an ensemble of instantaneous velocity fields enables obtaining a finite set of eigenvalues $\lambda_n(f)$ and basis functions $\phi_n(x, f)$ corresponding to the spectral representations of velocity pulsations that make the largest contribution to kinetic energy. Eigenvalues are a function of frequency. The eigenvalues are normalized to the total kinetic energy of the pulsations. For a fixed frequency $f$, the basis functions $\phi_n(x, f)$ with the largest eigenvalues $\lambda_n(f)$ show the spatial distribution of coherent velocity pulsations that make the largest contribution (commensurate with $\lambda_n$) to the kinetic energy of the velocity pulsations in the flow domain under consideration.

To reveal the coherent modes, present in the set of temperature fields, we performed the Fourier transform procedure of the three-dimensional instantaneous velocity fields using the azimuthal angle θ.
Thus, each 3D velocity field \( T(r, \theta, t_k) \) was represented as complex Fourier amplitudes \( \hat{T}^m(r, t_k) \), according to the formula:

\[
\hat{T}^m(r, t_k) = \frac{1}{2\pi} \int_0^{2\pi} T(r, \theta, t_k) e^{-im\theta} d\theta \approx \frac{1}{N_\theta} \sum_{i=1}^{N_\theta} T(r, \theta_i, t_k) e^{-im\theta_i} \quad (4).
\]

The Fourier transform procedure requires interpolating data from a Cartesian coordinate system onto a cylindrical grid. This was done with a constant grid spacing in each direction using the method of weighted nearest neighbors, where \( r \) is the radial coordinate, defined as \( r^2 = x^2 + z^2 \). 3D velocity fields were decomposed to maximum wave number \( |m| = M = 20 \).

For each azimuth mode \( m \), the obtained sequence of complex Fourier amplitudes \( \hat{T}^m(r, t_k) \) was analyzed by the POD method \([2, 14]\) to extract the most energetic coherent perturbations:

\[
T(r, \theta, t_k) = \sum_{m=-M}^{+M} \hat{T}^m(r, t_k) e^{im\theta} = \sum_{m=-M}^{+M} \sum_{q=1}^{N_r} a^m_q(t_k) \lambda^m_q \phi^m_q(r, \gamma) e^{im\theta} \quad (5),
\]

where \( \int_0^\pi \phi^m_i \phi^m_j r dr = \delta_{ij}, \quad \frac{1}{N} \sum_{k=1}^{N_t} a^m_i(t_k) a^m_j(t_k) = \delta_{ij} \quad (6). \)

The POD method is based on representing each \( k \)-th instantaneous complex Fourier \( \hat{T}^m(r, t_k) \) of the corresponding temperature field \( T(r, \theta, t_k) \) as a finite series (5) of the products of complex-valued orthonormal spatial basic functions \( \phi^m_q \) and time coefficients \( a^m_q \) satisfying equality (6), and real eigenvalues \( \lambda^m_q \) characterizing the amplitude of each POD mode in the data sequence. \( N_t \) corresponds to the number of measured temperature fields, i.e., \( N_t = 160 \). Eigenmodes and POD coefficients for wavenumbers \( m \) with the opposite sign are complex conjugate. To reduce the computational needs of the POD algorithm, we used the singular value decomposition (SVD) (see \([2, 12]\)) to calculate spatial orthonormal basis functions, eigenvalues, and temporal amplitudes. This procedure was previously tested and used in \([12-14]\).

![Figure 2. Distribution of the mean velocity fields (left) and the kinetic energy of the radial velocity pulsations (right) for strongly swirling impinging jets at different distances to the impingement surface \((H/d = 1 \text{ and } 2)\).](image-url)
4. Results

This part of the work is devoted to the analysis of an experimental study of submerged swirling impinging jets with intense swirling, accompanied by pronounced bubble-type vortex breakdown and precession of the vortex core. Two flow configurations with different distances from the nozzle to the impact surface $H/d = 1$ and 2 were considered. The swirl number $S$ was determined by the swirler geometry and equaled 1.0. The bulk velocity $U_0$ was 0.3 m/s. The Reynolds number calculated from the bulk velocity was $Re = 5000$. To measure the instantaneous velocity fields in the central plane of the jet with a frequency of 3500 Hz, the high-speed PIV system was used. In the process of analyzing the spatial structure and dynamics of large-scale coherent vortex structures, the statistical method Spectral POD was applied to an ensemble of 5500 instantaneous velocity fields. To analyze the contribution of vortex structures to temperature pulsations on impingement surface, azimuthal POD method was used.

![Figure 3](image-url)  
Figure 3. The eigenvalue spectra of Spectral POD decomposition of velocity fluctuations for strongly swirling impinging jets for $H/d = 1$ and 2. The values show the fraction of the kinetic energy of the velocity pulsations contained in this mode at a given frequency.

The spectra for different eigenmodes are shown in color.
The swirling of the flow leads to the appearance of radial pressure gradients due to centrifugal effects [4]. Their presence gives rise to a region with a pressure below atmospheric in the central part of the jet. With weak and moderate swirling, when the pressure gradients are not large enough, the fluid in the axial region begins to slow down, and a quasiperiodic occurrence of spiral-type vortex breakdown and the recirculation zone can be observed. Under critical conditions, the breakdown of vortex core leads to the forming of a central recirculation zone, around which an internal mixing layer appears, where an internal spiral vortex structure develops on a swirling vortex core.

In Fig. 2 for a strongly swirling impinging jet at different distances ($H/d = 1$ and 2) to the impingement surface, the mean velocity fields and distribution of the radial component of the kinetic energy in the central section of the flow are shown. The parts on the left show the distributions of the axial velocity component (color), and the kinetic energy of the radial velocity pulsations is shown on the right. For two flow configurations recirculation zone of “bubble” shape, visualized by a white area, is clearly visible (see Fig. 2).

**Figure 4.** Spatial distribution of real and imaginary parts of dominant Spectral POD modes for a strongly swirling impinging jet ($Re = 5000$, $S = 1.0$, $H/d = 2$)

**Figure 5.** Spatial distribution of real and imaginary parts of dominant Spectral POD modes for a strongly swirling impinging jet ($Re = 5000$, $S = 1.0$, $H/d = 1$)
In Fig. 3 the results of Spectral POD for a strongly swirling impinging jet and two positions of the impingement surface ($H/d = 1$ and 2) are shown. The spectra demonstrate that the most energetic first POD mode contains approximately 42% of the total kinetic energy for the case $H/d = 2$ and 50% for $H/d = 1$. For comparison, the second POD mode contains only 12% of the kinetic energy for $H/d = 2$ and 1.

The contribution of various harmonics to the kinetic energy is presented in the spectra. It can be seen that the spectral eigenvalue curve for the first POD mode has pronounced peaks at frequencies $f_1 = 14$ Hz, $f_2 = 28$ Hz and $f_3 = 42$ Hz. These harmonics for the case of $H/d = 2$ approximately contain 20%, 2% and 0.5% kinetic energy, respectively. For the case of $H/d = 1$, the energy content is 26%, 3%, and 0.5%.

It was found that the frequency of 14 Hz corresponded to the global frequency of the precession of the vortex core. The spatial form of the corresponding harmonics in the spectrum is shown on the eigenmode spatial distributions. The mode fluctuating at the frequency of $f_1 = 14$ Hz is associated with a double helical vortex structure consisting of a spiral vortex core and another spiral vortex in the outer mixing layer. Spectral POD modes are complex-valued functions. The real and imaginary parts of the eigenmodes have an insignificant phase shift associated with the dynamics of correlated vortex structures. Based on the visualization of the vortex structures, it is concluded that these spiral structures are connected by the global spiral mode $m = +1$, which has the direction of winding against the direction of the integral swirl of the flow. The global mode $m = +1$, associated with precession, is most pronounced near the nozzle exit at a distance $z/d = 0.2$. It is found that the dominant modes of velocity pulsations are superharmonics of global frequency: $f_2 = 2f_1$, $f_3 = f_1 + f_2$. Such a relationship between dominant flow harmonics can be explained by the concept of impinging jet as a hydrodynamic resonator [15].

Large-scale vortex structures that propagate further downstream and collide with the impingement surface create strong acoustic waves that can interact with the shear layer at the nozzle exit. Harmonics become more intense with decreasing distance to the impingement surface.

![Figure 6](image_url)

**Figure 6.** Radial distribution of azimuthal Fourier modes $m$ for strongly swirling impinging jets ($Re = 5000$, $S = 1.0$ and two distances to the impingement surface $H/d = 2$ and 1)

Fig. 4 and Fig. 5 show the vector fields and distributions of the components of the most significant Spectral POD modes of a strongly swirling impinging jet at the distance $H/d = 2$ and 1, respectively. As you can see, the real and imaginary parts of the Spectral POD mode demonstrate the spatial structure of global (in the entire flow domain) coherent pulsations in the inner and outer mixing layers of the strongly swirling impinging jet. The real and imaginary parts of the POD modes differ only in phase shift. These perturbations are associated with spiral vortex structures arising in the flow due to the global influence of intense precession of the vortex core in the flow with vortex breakdown.
Figure 7. Spatial distribution of azimuthal POD modes for strongly swirling impinging jets ($Re = 5000$, $S = 1.0$ and two distances to the impingement surface $H/d = 2$ and 1)

Fig. 6 shows spatial distributions of quadratic temperature pulsations obtained after spatial Fourier analysis for five azimuthal modes (azimuthal number $|m|$ is from 1 to 5) for a strongly swirling impinging jet and two distances from the impingement surface $H/d = 1$ and 2. The upper part of the Fig. 6 shows the radial profiles of mean temperature changes $\Delta T$. The basic part of Fig. 6 shows quadratic temperature fluctuations averaged over time and azimuthal angle for various azimuthal modes $m$. It can be seen that the temperature difference $\Delta T$ in the central region of the jet is smaller in the case of the distance $H/d = 1$. The axisymmetric mode $m = 0$, which has a two times higher value compared to the next mode $m = 1$, makes the largest contribution to the temperature fluctuations. The mode $m = 0$ is not shown in the figure for a visual representation of the rest of the azimuthal modes. As you can see, azimuthal modes $|m| = 1$ and 2 of a swirling impinging jet contain the largest amount of quadratic temperature fluctuations compared to other modes ($|m| > 2$). For the case $H/d = 2$, their amplitude is the largest in the jet core (maximum is near $r/d = 0.5$); for the case $H/d = 1$, the amplitude is lower, has several maxima, and the contribution of modes to temperature fluctuations is more uniformly distributed in the radial direction. The axisymmetric mode $m = 0$ is mainly created by velocity fluctuations around the axis of the jet. Fig. 7 shows the first POD modes ($q = 1$) for $|m| = 1, 2$. As can be seen, these POD modes of temperature fluctuations correlate well with spatial spectral POD modes calculated from velocity fluctuations. This confirms the hypothesis of a significant contribution of large-scale vortex structures to heat exchange with the impingement surface.

Conclusions
The study of the turbulent structure and dynamics of strongly swirling impinging jets with the bubble-type vortex breakdown and the precession of the vortex core has been conducted. Two flow configurations with different distances $H/d = 1$ and 2 from the nozzle to the impingement surface have been considered. The stereoscopic PIV method and temperature measurements using IR thermometry have been realized. A statistical analysis of coherent fluctuations of the velocity and impingement surface temperature has been performed using the Spectral POD method and the spatial Fourier transform over the azimuthal coordinate. From the statistical analysis, it may be concluded that heat transfer between the jet and impingement surface for the distance $H/d = 1$ is better due to the greater intensity of the vortex structures. A more intense mixing and influence on the boundary layer near the impingement wall occurs. This is evidenced by the average temperature drop, and temperature fluctuations are more uniformly distributed between different azimuthal modes in the radial direction. The first and second modes make the greatest contribution to quadratic temperature fluctuations. The first POD mode calculated from temperature fields strongly correlates with the Spectral POD eigenmode calculated from velocity fluctuations. The contribution of large-scale spiral vortex structures to the distribution of temperature pulsations of impingement surface has been revealed.

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