Effect of coherent structures on convective heat transfer in a swirling impinging jet

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Abstract. The present paper reports on the detailed investigation of the flow dynamics and unsteady heat transfer in an impinging jet in regimes with high swirl and vortex breakdown. A combination of the time-resolved stereoscopic PIV, time-resolved PLIF and high-speed IR-thermometry methods is used. Two cases of distances between the jet nozzle and impingement surface are considered, H = d and H = 2d. The Reynolds number is fixed as Re = 5000. The temperature distribution in the flow has a maximum on the jet axis near the surface in the region of the central recirculation zone. The data are processed using the POD method to extract coherent flow structures and quantify temperature fluctuations on the impact surface. The helical vortex structure in the case of H = d influences heat transfer between the swirling jet and the surface, the temperature fluctuations on the surface reach 0.05 degrees.

1. Introduction
The problem of heat transfer in organization of jet cooling and surface heating is relevant for a number of technical applications (for example, cooling of microelectronics, turbine blades, paper drying, hardening glass). One of the major shortcomings in organization of impact isothermal and reacting flows is the heterogeneity of local heat transfer. For some applications, such as cooling electronics or chemical vapor deposition, high intensity of heat and mass transfer with the radial homogeneity is required. Using the swirl in the impact jet, characterized by the presence of the tangential velocity component that causes whirling motion and broadening of the jet, can significantly enhance processes of heat exchange and reach the radial uniformity of heat transfer near the impinging surface. On the other hand swirling flow promotes the formation of "stagnation" of the vortex zones which will adversely affect the uniformity of the heat sink. Moreover, swirling flows are characterized by the phenomenon of flow precession, the intensity of which increases significantly with intensive swirling flow and local collapse of the vortex core jet. These features of the swirling flows are still poorly understood, even for free jets and flames, and for movements of impingement upon obstacle, they are studied poorly.

Heat mass transfer in the impinging region is determined by the presence of three-dimensional structures in the flow. Large-scale flow structures play a role in the heat transfer at stagnation [1]. A large number of studies of a free impact jet is presented in the literature, for example [2-6]. The authors explored the role of flow coherence on the heat transfer performances of an acoustically excited impinging jet. Detailed studies investigating the dynamics of three-dimensional vortex structures and convective heat transfer in the round and chevron impinging jet have been carried out. The studies were carried out using a combination of particle image velocimetry (PIV) and planar laser-
induced fluorescence (PLIF) and IR-thermometry methods. The works include studies of the effect of the external flow swirling on heat exchange with the impinging surface, investigation of mass and heat transfer depending on the different distance between the nozzle and the obstacle [7-14]. Unfortunately, in the literature there are almost no works (in particular the study [15]) containing detailed information on the turbulent structure of the swirling impinging jet that is necessary for understanding the complex structure of these flows and the development of modern models of numerical calculation that can reliably predict the properties of the swirling impinging jet.

The aim of the present paper is to investigate in detail the dynamics of the flow and unsteady heat transfer in an impinging jet flow under the conditions of high swirl and vortex core breakdown.

2. Experimental setup and data post-processing

The experimental setup corresponded to a closed hydrodynamic circuit, including a plexiglass test section (1200×500×500 mm), pump, overflow tank, and piping system with flow meter and thermostat. During the experiments, the temperature of water was kept constant at 25°C. The turbulent jet flow was organized by a contraction nozzle (the outlet diameter of the nozzle exit was d = 15 mm) with a changeable vane swirler, installed inside. The jet Reynolds number and the swirl rates S are fixed as 5000 and 1.0, respectively. The distance H between the nozzle and the wall was set as d and 2d. The jet flow impinged normally on a flat heated surface made of a sapphire glass (4 mm thick, 150×150 mm² in size). From the water side the sapphire glass was coated with a thin conductive film (1.2 μm thick) of indium-tin oxide (ITO, solid phase (In₂O₃)₀.₉₋₀.₁(SnO₂)₀.₁) transparent in the visible range. An electric current of 16 A passed through the coating, providing a uniform heating of 3.3 W/cm². The Titanium HD 570M (FLIR Systems ATS) IR-camera with a spectral range of 3.7-4.8 μm recorded the temperature of the conductive film on the heating element, which varied from 27°C to 38°C.

![Figure 1](image_url)
The PIV/PLIF system (see Figure 1) consisted of a Photonics DM high-repetition pulsed Nd:YAG laser (150 μs pulses with energy of up to 8 mJ at a repetition rate of 10 kHz) and three Photon SA5 high-speed CMOS cameras (with 7.5 kHz rate of full frames with 1024×1024 pixel size and dynamic range of 12 bit). For the PLIF measurements, Rhodamine B fluorescent dye was solved in water. The PLIF camera was equipped with a long-pass optical filter, which blocked radiation with wavelength less than 560 nm. The acquisition rate was 3.5 kHz.

The PIV images were processed by in-house software: "ActualFlow". For the evaluation of the local displacement of the tracers, a multi-frame pyramid CWD algorithm (the size of each integration area was reduced from 32x32 to 16x16 pixels, the spatial overlap rate was 50%, 3x3 moving average for local validation and interpolation) [16] was used. The stereo reconstruction of three-component 2D velocity fields was conducted based on pairs of two-component 2D velocity fields and a pair of mapping functions [17]. The PLIF images were processed via several routines. The averaged background signal was subtracted from the PLIF images, the non-uniform spatial sensitivity of the detector was evaluated, and the non-uniform laser sheet intensity (on average) was considered. The PLIF system was calibrated by imaging local variation of the fluorescence yield with the temperature in the range of 24°C to 30°C. To reveal coherent structures in the flow, the fluctuating velocity fields were processed using a snapshot proper orthogonal decomposition (POD) method [18] based on singular value decomposition (SVD) [19]. The spatial distributions of the temperature fluctuations were conditionally sampled according to the temporal coefficients of the velocity POD modes [20, 21].

3. Results

Time-averaged results of measurements of the flow structure and temperature (ΔT is the difference between the measured temperature and the water temperature) of the jet and the impact surface by PIV, PLIF, and IR-thermometry methods for the distance between the nozzle and the impact surface H=d are shown in Figure 2.

![Figure 2](image-url)

**Figure 2.** Average field of velocity and temperature (a), comparison of the results of temperature measurements near the surface by PLIF and IR-thermometry (b), temperature distribution on the impact surface (c), in a swirling jet at H = d.
In the case of a distance between the nozzle and the impact surface equal to two nozzle diameters, one can see similar distributions. In the flow, a central recirculation zone is observed. The maximum temperature near the surface is observed on the jet axis in the region of the central recirculation zone. IR-thermometry shows similar temperature distribution on the impact surface. Good agreement is observed between the measured temperature near the impact surface using PLIF and IR-thermometry. The temperature distribution in the flow, based on the PLIF data, shows an increased liquid temperature near the nozzle. Additional heating of the flow near the nozzle is caused by nozzle heating by laser radiation. In this regard, the main emphasis was placed on the investigation of the effect of vortex structures on heat transfer near the impact surface. Figure 3 shows examples of instantaneous velocity fields (arrows show vortices) and spatial distribution of the first POD mode for two cases of the distance between the nozzle and the impact surface (H = d and H = 2d). PIV measurements show that, for distance H = d, vortices are observed in the mixing zones between the recirculation zone and the swirling jet and between the swirling jet and the external fluid, including the zone near the impact surface. An increase in the distance between the nozzle and the impact surface leads to destruction of vortices when moving downstream. Already at distance H = 2d, vortices are not observed near the impact surface. The presented spatial distribution of the first POD mode (corresponding to coherent structures) confirms the conclusions obtained in the analysis of instantaneous velocity fields.

Figure 3. Spatial distribution of the instantaneous velocity field (a, c) and the first POD mode of velocity fluctuations (b, d) measured in a swirling jet at H = d (a, b) and H = 2d (c, d).

To analyze the contribution of coherent structures to heat transfer on the impact surface, instantaneous images of the surface temperature obtained using IR-thermometry were used to estimate temperature fluctuations, conditionally sampled according to the temporal coefficients of the velocity POD modes. The spatial distribution of conditionally sampled temperature fluctuations ($t''$) on the surface is shown in Figure 4. For the case H = 1d, one can see the spiral structure on the impact surface, caused by the influence of the helical vortex structure in the heat transfer between the swirling jet and the surface. However, it should be noted that the contribution of the vortex structure to
temperature fluctuations on the surface is small and reaches 0.05 degrees. For the case \( H = 2d \), as expected, the effect of vortices on temperature fluctuations on the surface is not observed.

![Figure 4](image)

Figure 4. Spatial distribution of conditionally sampled temperature fluctuations on the impact surface at \( H = d \) (a) and \( H = 2d \) (b).

4. Conclusions
The dynamics of flow and unsteady heat transfer in an impinging jet flow under the conditions of high swirl and vortex core breakdown has been investigated by using a combination of the time-resolved stereoscopic PIV, time-resolved PLIF and high-speed IR-thermometry methods. The distance between the nozzle and the impact surface was \( H = d \) and \( H = 2d \). The swirling flow has a central recirculation zone and two mixing layers. The temperature distribution in the flow has a maximum on the jet axis near the surface in the region of the central recirculation zone. The contribution of the coherent structures to heat transfer on the impact surface has been evaluated via the SVD-based POD. It is found that for the case \( H = 1d \) temperature fluctuation related to a large-scale helical vortex structure reaches 0.05 degree. For the case \( H = 2d \), coherent structures have no noticeable effect on temperature fluctuations on the impact surface.

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