Study of the influence of an external flow rate perturbation on the vortex structure and heat transfer in impinging jets

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Abstract. The study of physical processes dominating in submerged turbulent jets impinging on a wall is an important task because this configuration is utilized in various applications. The efficiency of heat transfer in this configuration has been a subject of a long-term study. Active flow control technique and the optimization of the control signal can be applied to exploit inherent flow properties to further improve the heat transfer from the wall in impinging jets. In this paper, IR-thermography and time-resolved PIV measurements are used for the diagnostics of wall temperature fields and large-scale vortex dynamics under external flow rate forcing control. It is found that the low-frequency forcing (for the Strouhal number $St = 0.6$) increases integral temperature on the wall as compared to the unforced case and the high-frequency forcing ($St = 0.9$).

1. Introduction

Impinging jets have been exploited widely in the industry due to their high heat exchange properties in the case of single-phase flows. The heat transfer coefficient for flows impinging into the surface is higher than in the case of tangential flow along the surface. There is a huge amount of previous studies referring the heat transfer in impingement flows, starting from early papers in which the measurements were taken with single-point heat flux gauges and liquid crystals thermography [1, 2], to relatively recent ones exploiting high-speed infrared (IR) thermography and 3D velocity measurements [3]. Different heat transfer augmentation techniques have been tested with passive control strategies by modifying a jet orifice geometry and impinged surface augmentation with vortex and turbulence enhancers [3, 4]. Another class of heat transfer enhancement methods is active flow control (AFC), which is mainly realized by external jet flow excitation modifying flow rate through a nozzle exit. A typical AFC realization that has been published includes an air jet with a loudspeaker or a volume with a moving piston in a plenum chamber, producing variation to a mean flow rate at non-dimensional frequencies of $St = 0.3–3$ [5, 6].

The described object of the study has a number of parameters that can influence heat transfer between the wall and fluid. For example: nozzle-to-wall distance $H/D$, Reynolds number $Re$, jet velocity profile, type of fluid, wall and jet temperatures, and many others. Configuration with the non-dimensional nozzle-to-wall distance lower than the length of the jet potential core $H/D < 6$ is more susceptible to the influence of the jet hydrodynamics on heat transfer than for the longer distances [7].
In the case of a developed turbulent flow (Re > 3000) this configuration produces one or two (depending on the nozzle-to-plate distance) annular peaks for the local heat transfer coefficient with a minimum at the stagnation point on the plate. The height of the annular peaks and their location strongly depend on the unsteady large-scale vortical structure of the flow moving along the wall.

Different explanations of the origin of the annular peak have been given so far. The majority of researchers tend to believe that its existence can be explained by an effect of the unsteady flow separation when the acceleration of the flow in the direction parallel to the wall (usually at a distance ~r/D = 1.8) changes its sign from positive to negative with a loss of wall jet stabilization, and adverse pressure appears triggering flow separation and promoting turbulence by secondary vortices [7]. Generation of secondary vortices locally increases turbulence level and, therefore, the local heat transfer coefficient. However, the additional augmentation of heat transfer quickly decays downstream due to separation of fluid with temperature substantially different from the temperature of the wall. Low frequency sinusoidal external flow rate excitation at half of the natural frequency can promote the stable vortex pairing with the strong large-scale vortex formation near the wall, which tends to separate regularly at a given distance from the stagnation point. On the contrary, high-frequency excitation leads to attenuation of the vortex pairing process with the formation of smaller vortices, which are less ordered in space. In this case, the probability of the unsteady flow separation decreases, and more medium-sized random vortices penetrate further downstream (behind the separation region) and modify local heat transfer coefficient in the area.

The motivation for this paper was to study how the amplitude and frequency of a sinusoidal signal for external flow rate perturbation influence the vortex structure and heat transfer rate in order to identify the key values of the parameters before advancing to more complex active flow control schemes for this type of flow. An additional goal of the work was to develop and test a technique for measuring the instantaneous 2D pattern of the intensity of convective heat transfer on the wall with an impinging liquid jet using infrared thermography, which is quite different from air impinging jet case described in most of the papers. The experiments are carried out in water, similarly to the previous study with a different experimental rig [8], in order to be able to compare results and to prepare the current experimental setup for the testing of closed-loop control, which is easier to perform in liquid media than in gas as it requires lower frequency of control actions. In future works, it is planned to use velocity data in the vicinity of the flow separation region for feedback.

Figure 1. (a) Experimental setup diagram: Q-ultrasonic liquid flow meter; P-pressure sensor; T-temperature sensor. (b) Flow measurement area for PIV with an offset 1.5D and H/D = 2.

2. Experimental setup and applied methods
The experimental setup is a closed hydrodynamic loop of continuous operation, consisting of a storage tank with a working fluid, a centrifugal pump, a thermostat, and a working section (Fig. 1). The working channel is made of acrylic glass with the following dimensions 425×300×300 mm. The flow
The rate of the liquid supplied to the working area is measured using the MULTICAL 402 ultrasonic flow meter with a relative measurement error of at least 2%. The water temperature in the test channel for isothermal experiments was kept within a range of ±0.1°C using a thermostat. Cooling and heating in the thermostat are carried out using the PID control system. The temperature of the water is measured by a thermocouple located in the storage tank. Additional information on heat transfer organization in the experimental rig can be found in [9]. Additionally, the viewing direction of the IR camera was located with an angle to the normal of the sapphire glass in order to get rid of the reflection of the camera itself in the recorded image. The image field of the IR camera was geometrically calibrated.

The system of external excitation of the jet flow rate consists of an electrodynamic vibrator ESE 201 (RFT 11075) with a frequency range of 5-2000 Hz and a maximum displacement of ±4.5 mm, and an amplifier RFT LV 103 with a power of 100 W. A bellows is attached to the rod of the vibrator to create a pulsating jet of liquid at the outlet of the nozzle. In the current experiments, a nozzle with a diameter of D = 20mm was used. The dependency of perturbation's amplitude on the frequency of harmonic oscillations was recorded by two methods: by measuring the flow rate fluctuations of the liquid and by the level of velocity fluctuations in the flow. In both methods, the maximum allowable excitation amplitude in the frequency range was determined. The amplitude of the perturbations was set by changing the gain K on the amplifier. The frequency of the sinusoidal perturbations was set programatically via a DAC controlled from the LabVIEW environment.

2.1. Characterization of the external excitation system

In the first case, the flow rate fluctuations were determined by the change in the height of the liquid column in a transparent cylinder connected to a bellows instead of a supply pipe with the nozzle. The measurements of the liquid column height were taken at atmospheric pressure at the measurement site, at the same elevation as in the test section (see Fig. 2-a). As can be seen, the minimum amplitude of the flow rate excitation was achieved at frequencies of 13-16 Hz with maximum signal amplification. In Fig. 2-a, the calculated values of the relative height of the liquid rise for constant values of the amplitude of the flow rate fluctuations (7% and 14% of the main flow rate), depending on the frequency of the superimposed disturbances, are shown.

![Figure 2](image-url)

**Figure 2.** Calibration of the forcing system: (a) the relative height of the liquid column h/Hmax for different amplitude of the flow rate fluctuations, normalized by the jet flow rate, Qjet (b) the intensity of the maximum achievable turbulent fluctuations at a distance of 1D from the nozzle exit depending on the excitation frequency f for the maximum amplitude of the vibrator and when the gain is set to K = 1.5.
In the second method, the level of jet core axial component velocity fluctuations \( Tu = \sigma_u / U_0 \), where \( U_0 \) is the mean flow rate, was measured directly in the test section at the jet axis at a distance of 1D from the nozzle edge using a laser Doppler anemometer LAD-05N (Fig. 2-b) with the size of the probing optical field of 0.05\times1 mm and the average accuracy of 0.5%. The statistical characteristics of the flow velocity were calculated using a sample of \( \sim 500 \) instantaneous realizations (registered flashes from polyamide particles of 20 microns in size added to the water).

The results in Fig. 2-b show that the maximum possible level of velocity fluctuations reaches 35% at a frequency of 2–4 Hz. For a fixed gain \( K = 1.5 \), the peak fluctuations in the jet core appear at the frequencies corresponding to \( St \approx 0.5 \), and their amplitudes reach 20% of the main flow rate. The pressure at the fixed end of the bellows was measured by the pressure sensor \( P \) (see Fig. 1-a). After passing the resonant frequency, a 180° change in the phase of the signal was observed relative to the control signal at the output of the amplifier.

2.2. Whole-field time-resolved velocity measurements

Whole-field measurements of the velocity fields were also carried out using the PIV method with resolution in time at the flow parameters \( Re = 4000, St = 0.6 \) and 0.9 and the baseline case without forcing, to obtain a detailed flow picture for these conditions. PIV results presented in this paper correspond to the optical configuration with the radial shift between the optical axis of the lens and the jet axis equal to \( \Delta = 1.5D \) in order to focus on the side region with the wall jet (see Fig. 1-b).

The gain factor \( K \) for the cases with forcing was selected so that the fluctuating flow rate was equal to 7% of the average liquid flow rate. The particles in the flow were illuminated by a single-channel Nd:YAG Photonics DM-532-50 laser with a pulse energy of 5 mJ at a frequency of 10 kHz (50 W). The Photron FASTCAM Nova S12 type 1000K-32GB camera with a sensor with a resolution of 1 Mp (12 bits, pixel size 20 um) and a maximum frame rate of 12.8 kHz was used for particle images recording. Sequences of 2000 images with duration of 2 seconds were recorded with a measurement frequency of 1 kHz. The focal length of the camera lens of 105 mm allowed registering a flow area of \( \sim 40\times40 \) mm (2Dx2D). The recorded images were processed with a final resolution of 16\times16 pixels, which corresponded to a spatial resolution of 0.625 mm per velocity vector.

3. Results

Figure 3 shows the distributions of the axial and radial components of the average velocity. It can be seen that for a excitation at \( St = 0.6 \) (4.75 Hz), the radial velocity at the wall decreases faster with the distance from the critical point, and a zone of negative axial velocity appears away from the wall (blue zone), which indicates that in this case the separation occurs earlier. For the case of \( St = 0.9 \) (7.13 Hz) forcing, in the vicinity of the wall, the flow in the direction away from the wall is more pronounced than without forcing, which may indicate a potentially better heat exchange with the wall.

Figure 4 shows the evolution of the velocity fields over time with a step of 50 ms with instantaneous vorticity as the background. It can be seen how imposed flow forcing leads to flow regularization, and at the same time, coherent vortex structures in the mixing layer and the near-wall jet region become more long-living and intense. In the case of \( St = 0.9 \), more intensive vortices accumulate near the wall in the zone after separation (x/D = -1.62), compared to \( St = 0.6 \), since their frequency is higher. Due to this fact, such flow configuration may potentially provide a broader area of effective heat transfer than the jet without forcing or with forcing at \( St = 0.6 \).

To analyze periodic behavior of the vortices near the wall, spectrograms of velocity fluctuations were plotted. Figure 5 shows spectral distribution for the three cases: \( St = 0, 0.6, \) and 0.9 along the wall at y/D = 1.95 (2 mm away from the wall). The spectrograms confirm a weak and broad spectrum of the events for the wall jet region without forcing where events with a frequency higher than 5 Hz occur almost randomly. Resonant external excitation makes the spectrum more periodic with a distinct position of the flow separation. Forcing at the higher frequency broadens the spectrum, increasing the filling of the spectrum area downstream of the separation.
Figure 3. Spatial distributions of the mean (a) axial and (b) radial velocity components for different excitation frequencies at \( \text{Re} = 4000 \), \( W = 0 \).

Figure 4. A sequence of instantaneous velocity fields with the vorticity field \( w_z \) as the background. The following cases are presented:
(a) \( \text{St} = 0 \), (b) \( \text{St} = 0.6 \), (c) \( \text{St} = 0.9 \) for \( \text{Re} = 4000 \), \( W = 0 \).
Figure 5. Spectrograms for the cases: (a) St = 0, (b) St = 0.6, (b) St = 0.9 in the horizontal section 2 mm away from the wall, Re = 4000, W = 0.

Finally, an example of the obtained mean Nusselt (Nu) distribution for the unforced non-isothermal case with the heating power of 243.8 W or 1.1 W/cm² at the impact wall is shown in Fig. 6-a. Nu field averaging was done by 500 images taken with 50Hz with further geometrical distortion correction due to the tilted viewing direction of the camera. In Fig. 6-b, temperature profiles at the jet axis plane are presented (see Fig. 6-a for the reference) for the baseline unforced case and two sinusoidal signals forcing at St=0.6 and 0.9 producing 10% of the velocity fluctuations and taken one minute one after another with the continues heating. Time averaged local Nusselt values are in agreement with those obtained for the circular air jet in [3] and other earlier papers. The results show that for the Re=4000 and the current electrical power switching to the low frequency case leads to the mean temperature rise about 0.2 K with the Noise Equivalent Temperature Difference (NETD) 0.018 K of the camera. Tests at Re=12500 showed a similar temperature gap between the cases with the clear indication of the lower integral heat transfer for the low frequency forcing and only local heat transfer improvement for the high frequency forcing.

Figure 6. Examples of (a) the mean Nu distribution at the heater surface for the unforced case, (b) the mean Nusselt radial profiles at the jet axis plane z/D = 0 for the unforced case and the ones with excitation at St = 0.6, 0.9; Re = 4000, W = 243.8 W, T_{water} = 26° C.

Conclusions
Results of the study of the vortex flow structure of the impinging jet are presented for Re = 4000 and a fixed distance to the wall H/D = 2. For time-resolved PIV measurements, the results correspond to isothermal flow.
The amplitude of the external excitation system of jet flow rate are monitored by the LDA system. The acceptable forcing amplitudes for different forcing frequencies are obtained to keep the constant flow rate fluctuation.

PIV results confirm pronounced unsteady flow separation for resonant frequencies of St = 0.6 at a distance of 2D from the critical point. An increase in the excitation frequency up to St = 0.9 leads to a broader spectrum of the velocity fluctuations near the wall and kept the strength of the large-scale vortices that can penetrate further along the wall compared to the unforced flow case.

Non-isothermal configuration with the constant heating power of the wall for the flow excited at St = 0.6 shows an increase of 0.2 K of the integral mean wall temperature compared to the unforced case. No substantial decreasing of the integral mean temperature for the forcing at St = 0.9 is observed.

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