Characterizing the dynamics of liquid boundary layers using infrared thermography

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Abstract
High-speed infrared thermography of liquid flows through infrared-transparent windows is a new approach to the investigation of fluid boundary layers. Here, we present two complementing methods that allow for visualization and quantitative analysis of near-wall non-isothermal fluid flows, in which a temperature difference serves as a passive contaminant. Both methods are based on the high absorption coefficient of liquid water in the working range of a mid-wave infrared camera. The first method extracts the spectral characteristics of turbulent pulsations within a flow. The second method allows obtaining flow velocity fields based on seedless velocimetry measurements. The methods are applied to infrared measurements of a submerged impinging water jet.
Keywords: impinging jets, infrared thermography, seedless velocimetry, turbulent pulsations, non-isothermal flows

1 Introduction

Infrared (IR) thermography has recommended itself as a versatile scientific tool in investigations requiring 2D temperature maps of solid surfaces. However, advances in IR technology in terms of spatial and, most importantly, temporal resolution open up possibilities for its effective application in fluid dynamics [1-3]. In non-isothermal liquid flows, in which temperature fluctuations are not large and do not govern the turbulent flow motion, heat can be regarded as a passive scalar [4]. Under this assumption, we propose two complementing methods to study the near-wall behavior of turbulent liquid flows: 1) Thermography of Liquid Boundary Dynamics (TLBD) based on extracting time-varying turbulent fluctuations; 2) Thermal Spot Velocimetry (TSV) technique based on applying the PIV algorithm to IR images with “thermal spots” serving as flow tracers.
In this work, the potential of the proposed methods is demonstrated on IR imaging of a submerged impinging water jet. For impinging jet flows, the investigation of a near-wall flow structure is of vital importance for many engineering applications associated with the jet-assisted heat/mass transfer enhancement. Submerged impinging jets often undergo intensive turbulent mixing with the ambient fluid. Numerous studies of impinging jets mostly focus on the measurement of shear stress or heat transfer between a jet and an impingement surface [2][5]. Local changes in heat transfer characteristics is still a disputed question, as they have been attributed to several fluid dynamic mechanisms: the laminar-turbulent transition within a boundary layer, the turbulence enhancement in a wall jet or the development of large-scale vortical structures. The IR-based methods have potential to provide additional insight into the near-wall flow dynamics of an impinging jet.

2 Experimental setup

The experiments were conducted using a glass tank filled with water at a temperature of T_0 = 5-60°C. Water of a temperature T_{jet} = 10-50 °C was exhausted from a separate beaker through a round nozzle of diameter D at a set flow rate. The nozzle was positioned at a distance H from a vertical impingement plate – a circular window made of calcium fluoride, which has a high transmittance in the mid-wave IR spectral range (over 90%). The experiments were conducted for a range of nozzle diameters, D = 1-4 mm, nozzle-to-plate spacings, H/D = 1-6, and jet Reynolds numbers, Re = 3000-35000.
An IR camera FLIR SC7000 working in the mid-wave spectral band (3.7-4.8 µm) was employed to capture near-wall thermal fluctuations in the impinging jet flow. Since water absorption in the studied IR range varies from 11 to 42 1/mm [6], the penetration depth of thermal radiation in water is no more than fractions of a millimeter. The images, 348x344 px in size, were acquired at 300 Hz for 1-2 s. To provide valuable

statistics, all results were averaged among 3-5 sequential experimental runs. Fig. 1 shows sample instantaneous and time-averaged images of an impinging jet with parameters: D = 3 mm, H/D = 2, Re_{jet} = 7700. The effects of non-isothermality were tested using different impingement conditions: a hot jet was submerged in cold water (Fig.1a) or a cold jet was submerged in warm water (Fig. 1b).

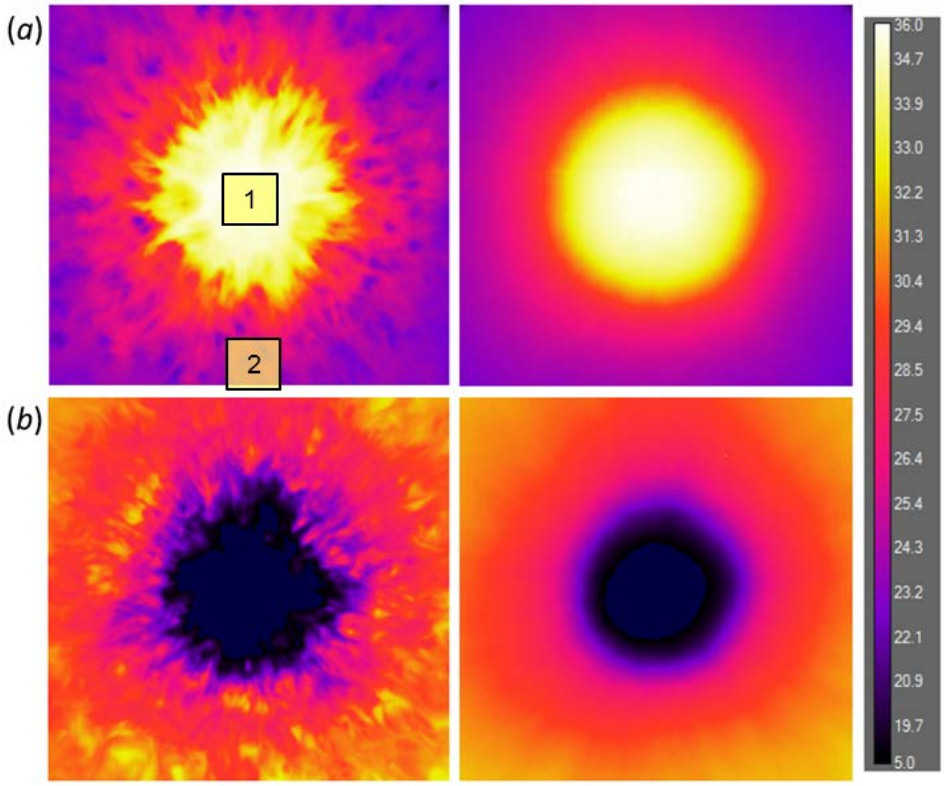

Fig. 1 Sample instantaneous (left) and time-averaged (right) IR images of jet impingement (a) T_{jet}-T_0 = 25 °C; (b) T_{jet}-T_0 = -15 °C. Images share the same color map.

3 Results and discussion

The proposed post-processing methodologies are based on following the dynamics of “thermal spots” on the IR images. The “thermal spot” is an element of a non-isothermal turbulent flow with the smallest possible size emitting IR radiation of specific intensity. In turbulent flows, with the characteristic time scales much smaller than those for heat transfer, the temperature of the “thermal spots” should remain constant. The spatial shift of each spot between two successive IR images defines the flow direction and velocity.

To study thermal fluctuations within the boundary layer of the wall jet flow, we extracted and post-processed time-varying thermal signal from each point of the obtained 2D thermograms. Of interest was the statistical and spectral behavior of thermal fluctuations. Fig. 2 (top) shows a root mean square (rms) map of thermal signal calculated for an impinging jet flow with parameters: D = 3 mm, H/D = 2, $Re_{jet} \sim 4000$. On each rms map, the largest rms values were found at a particular radial distance (about several jet diameters) from the stagnation point. The stagnation region could be clearly defined as an area around the symmetry point with the rms values close to zero.

By applying the Fast Fourier Transform algorithm to the IR data, we analyzed the energy spectra at each point in the near-wall flow. It was found that, at a certain radial distance (R) from the stagnation point, the power spectral density changes from frequency-independent to the one following a clear power law in the form of $E \sim f^{\alpha}$ within the frequency range of approx. 10-80 Hz. This is illustrated in Fig. 3a, that shows spectra with the corresponding power law scalings for two points in a thermogram (the approximate locations of points 1 and 2 are denoted in Fig. 1a). Fig. 3b shows the dependence of the slope scaling parameter, α, on the normalized distance from the stagnation point, R/D, for D = 2 mm, H/D = 3 and three values of the jet Reynolds number. These data show that the boundary layer of the wall-jet flow appears to stay laminar within 3-4 diameters from the stagnation point. Further downstream, the scaling exponent decreases and at some point approaches the Kolmogorov -5/3 inertial-range scaling [7]. The higher the jet exit velocity (jet Reynolds number), the further from the stagnation point this transition takes place.

By applying the PIV algorithm to the successive IR images, we obtained the velocity vector fields within the near-wall layer of the flow (the TSV method). The “thermal spots” in this case served as the flow tracers. We used the cross-correlation based on Fast Fourier Transform implemented in the LaVision DaVis software. Fig. 2 (bottom) shows the typical resulting velocity field averaged among 100 frames for an impinging jet flow with parameters: D = 3 mm, H/D = 2, Re_{jet} ~ 4000. This field is juxtaposed with the corresponding rms temperature map. It is worth noting, that the maximum velocity, which is possible to measure by the TSV method, is limited by the finite frame rate of the IR camera.

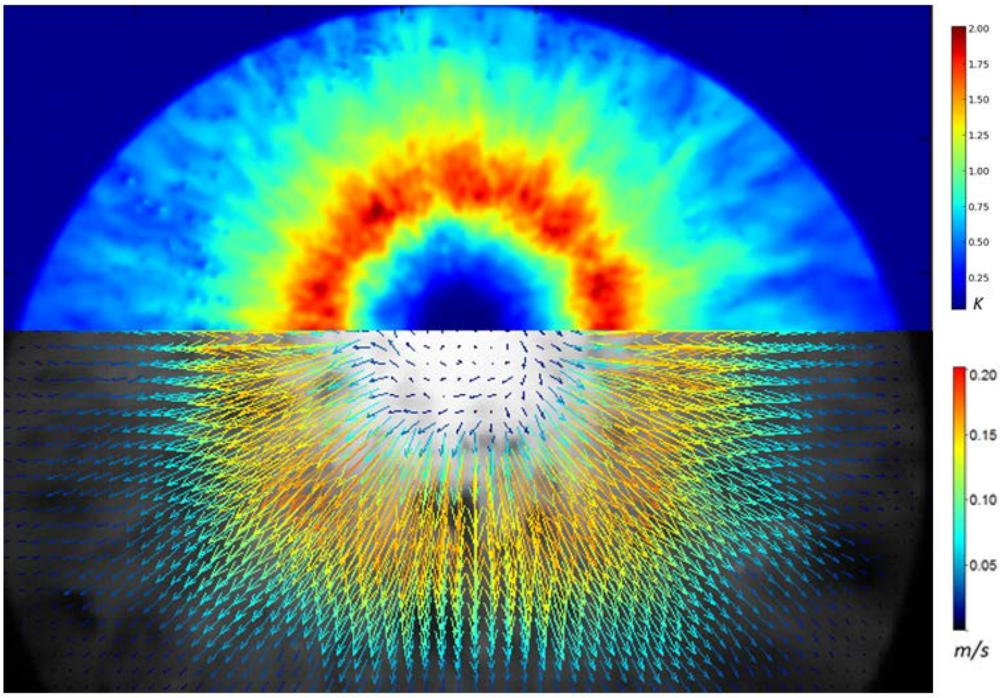

Fig. 2 2D maps of root mean square of thermal fluctuations (top) and velocity vector field (bottom) for an impinging jet flow with parameters: D = 3 mm, H/D = 2, Re_{jet} ~ 4000.

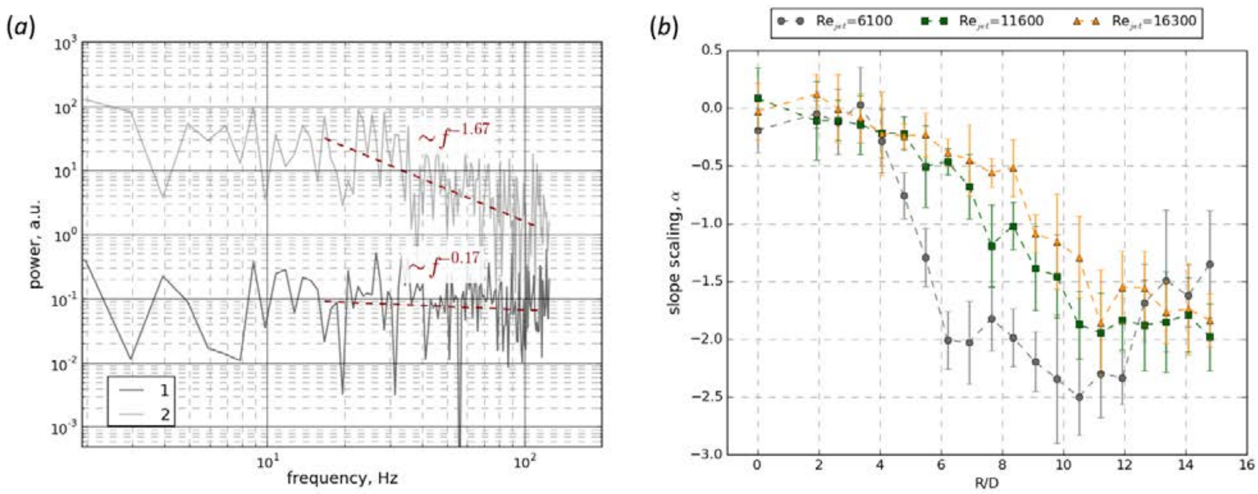

Fig. 3 (a) Power spectra for two points in the themogram (Fig. 1a) and (b) computed slope coefficient of the power spectrum depending on the normalized distance from the stagnation point (D = 2 mm, H/D = 3) for three jet Reynolds numbers.

5 Conclusions

Two infrared-based methods were applied to analyze the near-wall behavior of a non-isothermal flow induced by a submerged jet impinging on a vertical flat plate. The working fluid was liquid water that has high absorption in mid-wave infrared waveband. Statistical and spectral characteristics of thermal fluctuations within a thin boundary layer of the wall jet flow were calculated and analyzed. They were compared to the instantaneous and averaged velocity fields obtained by applying the PIV algorithm to the thermal data. The results provide information on: 1) the dependence of laminar-to-turbulent transition on a jet Reynolds number (in the range of 3000-35000) within the resolved boundary layer; 2) the spectral behavior of near-wall turbulent fluctuations at different distances from the stagnation point. Thus, the considered infrared-based methods provide a new scientific tool to resolve the flow behavior in infrared-opaque liquids within a thin near-wall turbulent layer.
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