TEMPERATURE MEASUREMENTS INSIDE A THIN FLUID LAYER WITH BACKGROUND ORIENTED SCHLIEREN METHOD

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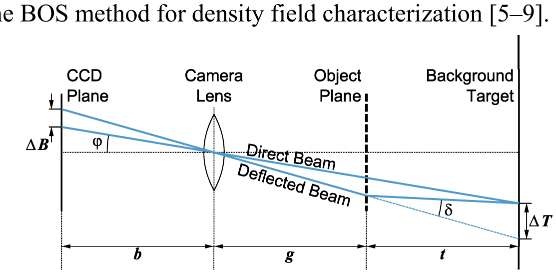
ABSTRACT: Quantitative background oriented schlieren (BOS) method is used to measure the 2D temperature distribution inside a thin fluid layer, where optical access is limited to one side. Instantaneous temperature gradient fields are obtained by implementing a highly reflective surface below the fluid layer. The temperature gradients are integrated to compute the temperature distribution. Temperatures can be estimated with an accuracy of the order of 10 mK. In this study the BOS method is applied to parallel jet flows with temperature offset.

1 INTRODUCTION

Changes of density, pressure, temperature and concentration in fluids result in local differences of the refractive index [1–3]. These variations are quite useful for investigating characteristics of flow using non-intrusive qualitative techniques such as schlieren and shadowgraphy [4]. Quantification of the measurements can be done using additional computational steps [2,5,6]. Recent introduction of background oriented schlieren (BOS) method enabled relatively simple quantitative measurements [7–10]. It is based on the principles of the schlieren technique with slight differences. A camera and a background target are placed on the opposite sides of the test section (Fig. 1; left). The background target (with random patterns) is used as the reference. Any changes of the refraction index along the optical path can be detected as the displacements on the recorded image of the background target [4,10]. These displacements can be integrated to estimate the measured quantity (density, temperature, pressure or concentration) distribution over the measurement plane [9]. Studies on wake of a cylinder, blade tip vortices of helicopters and even shockwaves utilized the BOS method for density field characterization [5–9].



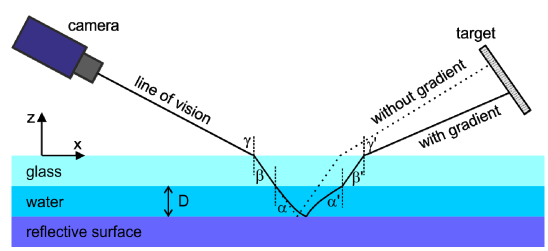


Fig. 1 Sketch of BOS principle (left), and of the theoretical optical path of current setup with and without refractive index gradient in water (right).

The conventional BOS arrangements require a test section that is optically fully accessible from two opposing sides [9,10]. However, this is not possible for all practices. Therefore we aim to extend the application of BOS measurements to systems where the optical access is limited to only one side. Adding a highly reflective surface to the non-transparent side of the test section, we aim to measure temperature gradients in a thin fluid layer with high precision. We integrate the gradients to calculate the 2D temperature distribution inside the fluid layer.

2 PRINCIPLE

In this study we observe the optical path through a plane-parallel stacked medium (Fig. 1; right panel). The light is deflected in the direction perpendicular to the refractive index (n) gradients passed [1]. Starting from air with refractive index n_a, a glass plate and a water layer of thickness D with the position-dependent refractive index n_w is passed. After reflection from a highly reflective surface, the light passes the layers in reverse order towards the CCD. Apart from the water, the media are assumed to have a constant index of refraction. The coordinate system is defined by the xy-plane parallel to the boundary layers ('horizontal') and the incident ray in the xz-plane.

The refractive index gradients inside the water cause an angular displacement as well as a parallel displacement of the ray, where the latter can be neglected. Due to the mirrored light path, gradients in z-direction have no contribution to the angular deflection. Since refractive index changes and thus deflections from the beam path are small, the Taylor approximation can be applied to the emergent angles in water α' and air γ'. For refractive index gradients in x-direction this leads to an angular deviation from the emergent angle γ' of

$$\delta_x = \frac{2D\cos\alpha}{n_a \cos\gamma}\partial_x n_w \tag{1}$$

where

$$\alpha = \arcsin\left(\frac{n_a}{n_{w0}}\sin\gamma\right) \tag{2}$$

is the initial beam angle inside the water and γ is the angle of incidence. Similarly, the gradients in y-direction deflect the line of vision from plane of incidence by an angle of

$$\delta_y = \frac{2D}{n_a \cos\alpha}\partial_y n_w\,. \tag{3}$$

A key to sensitivity of BOS setups is the fact that even very small deviation angles δ can be detected when amplified by long distances in the recording geometry. For high sensitivities, long object and target distances are advantageous with the schlieren object located in the center between camera and target (i.e. g = t in the panel of Fig. 1). The apparent displacement on the image sensor can be shown to be

$$\Delta B = \delta \frac{B}{G\cos^2\phi}\frac{gt}{g+t} \tag{4}$$

where B/G is the scale factor between the image (B), and schlieren object size (G). For small viewing angles $\cos^2\phi \approx 1$ can be assumed. In conclusion, the refractive index gradient inside the water can be determined from the apparent displacement by

$$\partial_x n_w = \frac{n_a\cos\gamma}{2D\cos\alpha}\frac{G}{B}\frac{g+t}{gt}\Delta B_x \quad \text{and} \quad \partial_y n_w = \frac{n_a\cos\alpha}{2D}\frac{G}{B}\frac{g+t}{gt}\Delta B_y\,. \tag{5}$$

The temperature gradients in this study are relatively small. Therefore the relation between the refractive index of water and temperature can be assumed linear ($dn_w/dT \approx -9\times10^{-5}\ K^{-1}$) for standard room temperature.

3 EXPERIMENTAL SETUP

Experiments are performed in a thin circular-shaped water layer with a thickness of D ≈ 3 mm (Fig. 2). Bottom of the fluid layer is covered with a highly reflective surface. Top of the fluid layer is covered with a glass plate

(≈ 36 mm thick), that is parallel to the bottom surface. The test section diameter is d = 44 mm. The flow is provided by two elliptical jets parallel to each other. The minor and major axes of the jets are 2 and 6 mm, respectively. The minor axes of the jets are in the direction normal to the reflective surface. The distance between the jet centers is 8 mm. The flow is provided by an elevated water tank to eliminate vibrations and flow speed fluctuations of using a pump. Flow speeds are measured and adjusted with rotameter type flow meters.

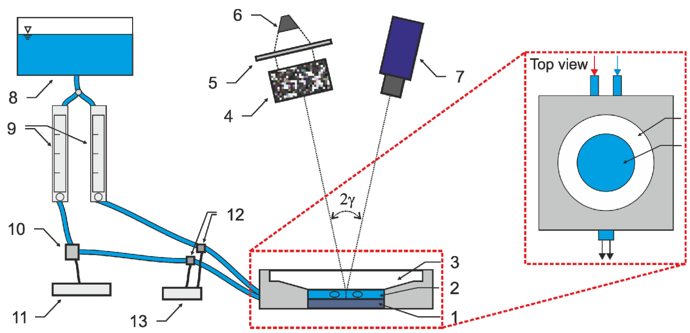


Fig. 2 Sketch of the experimental setup; 1: reflective surface, 2: fluid layer, 3: glass cover, 4: background target, 5: Fresnel lens, 6: metal halide lamp, 7: BOS camera, 8: reservoir, 9: flow meters, 10: heater, 11: heater controller, 12: thermistors, 13: temperature acquisition.

Temperatures of the jets are measured using negative temperature coefficient (NTC) thermistors that are placed in the supply line right before the jet exits to the test section (items 12 in Fig. 2). In order to impose a temperature difference between the jets ($\Delta T = T_H - T_C$), fluid of one of the jets can be heated prior to the thermistors. The amount of heat transferred to the fluid can be controlled by changing the applied electrical current.

Quantitative flow images are recorded using an Imager Pro SX camera with 2.5 × 2 k pixel resolution and 2 Hz frame rate. The acquisition and the analysis of BOS images are performed using commercial software (DAVIS 8 by LaVision GmbH). The camera is focused on the background target using the reflection from the bottom surface (Fig. 3).

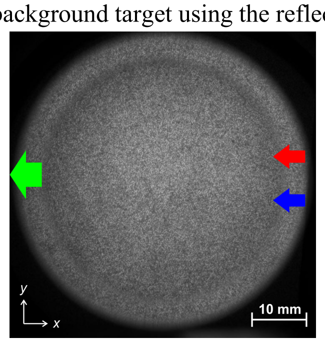


Fig. 3 An example of the recorded image. The warm and cold jet are indicated by the red and blue arrow, respectively. The drainage of the test section is indicated by the green arrow.

The background target is a thin ground glass plate with randomly placed dot pattern. Mean diameter of the dots are 0.4 mm. The illumination is done behind the target using a metal halide lamp (Prior Lumen 200). A Fresnel lens is placed between the light source and the target in order to achieve the necessary illumination diameter. The optical path between the camera and the reflective surface is equal to the distance between the reflective surface and the target (i.e. g=t). The angle between the CCD and the target is $2\gamma=7.4°$. In order to get rid of any thermal air flow schlieren, the optical path between the camera and the target is encapsulated.

The computations of the BOS measurements are relatively straightforward. The algorithm used in particle image velocimetry (PIV) technique is used for displacement estimations. Averages of first 50 instantaneous images, where both jets are at the equilibrium in means of temperature and the flow speed, are computed and used as the reference. The displacements of instantaneous images are calculated according to this reference image. The displacements were calculated with multiple pass approach [11] using an interrogation window size of 32×32 pixel and 50% window overlap. We fitted a first order polynomial over the displacements for the regions outside the jet expansion where the temperature gradients are small, and subtracted it from the whole image. This improves the results and corrects any inclination or offset of the setup that possibly have occurred during the experiments.

The 2D temperature distributions inside the test section are computed by numerically integrating the gradients. We use a second order central differencing scheme, solving it by conjugate gradient method [6]. We use the temperature of the heated jet measured by thermistor (T_H) as the boundary condition for the integration. The known temperatures of the heated and the cold jets are used to correct any offset error of the integrated temperature fields.

4 RESULTS

Although several temperature differences and flow speeds are used for investigations, results presented in this paper consider a constant flow speed of U=47 mm/s, at two different temperature differences of jets ΔT=60 and 1600 mK. The flow velocity corresponds to a Reynolds number of Re=185, based on the hydraulic diameters of the jets (D_H≡3.46 mm).

The measured displacements of instantaneous BOS measurements in x- and y-directions for a temperature difference of ΔT=60 mK are given in Fig. 4. Flow is in the negative x-direction (see Fig. 3). Therefore it is expected that the maximum gradients would appear in the y-direction in the region between the jets. The maximum temperature difference is expected close to the jet exits, and will gradually decrease downstream. Both displacements are consistent with these assumptions. However, the magnitudes of the displacements in the x-direction are relatively low and they are of the order of the noise level. This is expected for small ΔT, which results in low signal-to-noise ratio (SNR). The result of 2D integration (Fig. 4; right) reveals the temperature distribution. Zones of high temperature (shown as red), and relatively low temperature (shown as blue) are distinctive in the figure. The transition band between those regions is not straight but in slightly meandering pattern.

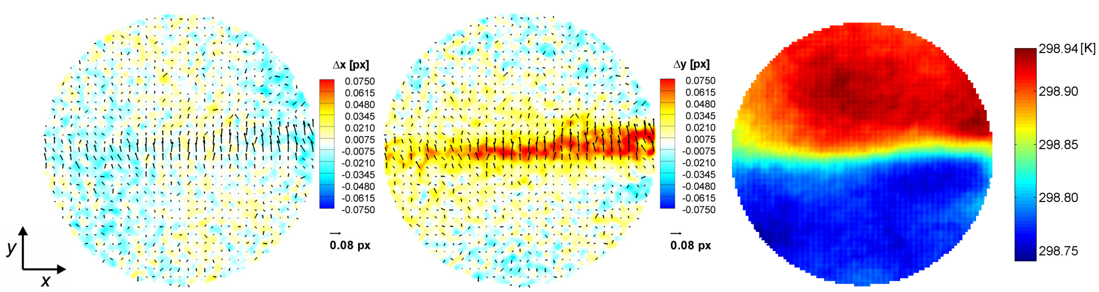


Fig. 4 Instantaneous measurements at ΔT=60 mK. Displacements are color coded in x-direction (left), in y-direction (centre) and corresponding temperature distribution (right).

The instantaneous measurements with higher temperature difference (ΔT = 1600 mK) are given in Fig. 5. The displacements in y-direction are one order of magnitude greater than those in x-direction. The displacements in x-direction are different compared to the previous case. Additionally, the SNR is higher due to the higher ΔT, which is clear for both displacement and temperature plots.

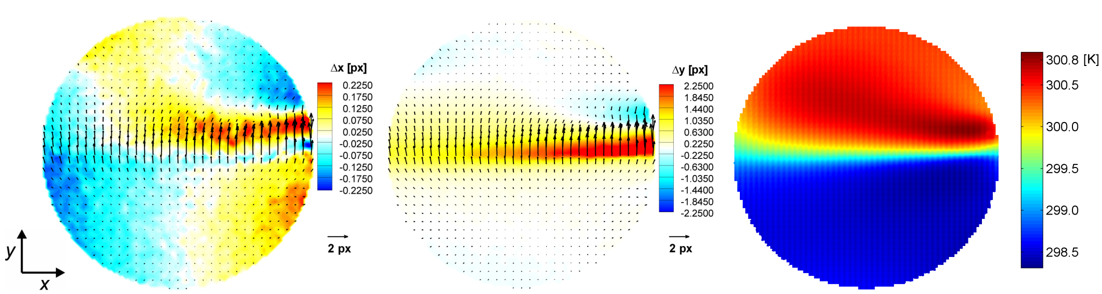


Fig. 5 Instantaneous measurements at ΔT=1600 mK. Displacements are color coded in x-direction (left), in y-direction (centre) and corresponding temperature distribution (right).

5 CONCLUSION

We applied the BOS method to investigate 2D temperature distributions in a thin water layer. Placing a reflective surface at the bottom of the layer made it possible to perform the measurements in an experimental setup where only one side is optically accessible. Measured gradients are integrated to estimate the 2D temperature distribution over the flow. We measured temperatures in the mK-range. Our measurements revealed that the BOS method is capable of measuring the instantaneous temperature distributions in a thin fluid layer.

6 ACKNOWLEDGEMENTS

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