Laser speckle based background oriented schlieren measurements in a fire backlayering front

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Abstract The recently introduced laser speckle based background oriented schlieren technique (speckle BOS) is used to study a variable density flow simulating the spread of hot gases in a tunnel fire. The specific advantage of the speckle BOS method is the possibility to measure in flow fields close to the schlieren reference pattern while maintaining a high sensitivity to refractive index variations. Visualizations are shown of the propagating hot gas layer under the tunnel ceiling, and the size of the coherent structures in the backlayering zone is determined using a correlation analysis of the refractive index gradient field. Since the flow structures preserve their coherence over a considerable time, a secondary PIV analysis is employed to compute the average advection velocity in the frontal zone.

1. Introduction

The background oriented schlieren technique is a by now well-established method for optical density imaging. Recently, this technique was extended by the introduction of speckle patterns as a virtual background image [1] leading to several improvements compared with the standard method:

- The camera can be focused at any position independent of the reference screen position.
- The overall sensitivity can be adjusted independent of the imaging geometry.
- The camera view can be aligned with the laser beam (double-pass BOS imaging), whereby a sensitivity increase is achieved.
- The reference screen can be placed close to the measurement object while maintaining sensitivity.

As an application of that technique, the backlayering zone of a simulated tunnel fire is investigated in the present paper. In a tunnel fire, a buoyant plume rises and spreads from the location of the fire towards the ceiling. As loss prevention, a ventilation cross flow should limit the spreading of the plume. Nevertheless, there are scenarios where the plume is able to creep along the ceiling against the cross flow, forming a so-called backlayering zone. The development and behavior of this zone can have a significant impact on the fire control strategy, which is often aimed at maintaining a smoke-free escape route.

Such a scenario is experimentally simulated in a custom designed hot air tunnel. An example of the establishment of a backlayering front is illustrated by a CFD simulation in Fig. 1. The backlayering phenomenon is restricted to a zone close to the ceiling where remote imaging of the optical density is difficult. Due to its specific properties, however, the speckle BOS technique is well suited for measurements in the thin backlayering zone. The analysis of the speckle images provides insights into density changes (using the Gladstone-Dale relation) and hence also into temperature distributions. Since heat transport is mainly governed by convection in this flow, the propagation of coherent structures in the temperature field enables an estimation of the velocity distributions within the backlayering zone as well.
2. Experimental configuration

The tunnel, depicted in Fig. 2, has a square cross section of 0.8x0.8m$^2$. The walls and the ceiling are made of fire-resistant material whereas the floor is formed by glass plates (6 mm thick) enabling optical access to the interior of the channel.

The fire is simulated by an electric heater delivering hot air at 400$^\circ$ C temperature to the test section. The outlet diameter of the heater is 0.2m and the injection speed is 1.43 m/s. An extraction fan at the end of the tunnel controls the cross flow in the tunnel (speed: 0.52m/s).

![Fig. 2 Geometry of the hot gas tunnel facility [2].](image)

The BOS diagnostic setup, sketched in Fig. 3, is positioned 1.4m upstream of the electric heater. The laser beam that creates the speckle patterns is generated by a diode-pumped solid state laser (Coherent Verdi, $\lambda=532$nm, $P_{\text{max}}=5$W). In order to expand the beam, a 10x-telescope followed by a biconvex lens ($f=25$mm) is used. A mirror redirects the beam through the glass floor into the channel, where the ceiling serves as the speckle generating surface.

![Fig. 3 BOS recording setup. The illumination creates speckle patterns on the tunnel ceiling in an area of approx. 1m$^2$.](image)
When the backlayering front with its temperature gradients passes the field of view the speckle patterns are distorted. A monochrome digital camera (IDS uEye 2230SE, 1024x768 pixels) using a 8.5mm wide-angle lens records the changing patterns. The image acquisition is continuous at 23Hz, and no shuttering is performed. Care has to be taken to create sufficiently large speckle patterns on the sensor so as to avoid peak-locking effects in the PIV analysis of the data. This can be achieved by adjusting the lens aperture and using a camera with sufficiently small pixel size.

3. Results
With the speckle BOS technique, refractive index measurements can be performed close to the reference surface which is the ceiling in the present fire tunnel scenario. A simple image processing step (computing the absolute difference between consecutive images) can be used to create a real-time flow visualization of the propagating hot gas layer. A typical result is shown in Fig. 4, where the fluctuating temperature in the backlayering zone creates refractive index variations visible to the BOS recording system. The cross flow in this image is from right to left, and the visible area is approx. 0.48x0.87 m².

![Fig. 4 Difference visualization of the backlayering front. The structures visible are regions of non-vanishing density gradients close to the tunnel ceiling.](image)

In order to visualize the frontal dynamics, the spatio-temporal signature along a horizontal line in the image center can be displayed in a x-t diagram (see Fig. 5). While the average position of the front is stable, local regions of flow reversal can be recognized by the different slopes of the visualized feature edges.

A close inspection reveals that at certain times, counter-propagating features are present in the flow at the same location and instance (crossing patterns in the x-t diagram). This is a consequence of the integrating behavior of the schlieren recording setup. The flow in the backlayering zone has the topology of a very long recirculation cell where both, upstream and downstream motions can occur.
Fig. 5 Difference visualization of the backlayering front. The frontal evolution is recorded along a single horizontal line in the image for 600 consecutive frames. Slanted features indicate spatial propagation.

The speckle images can also be analyzed with a standard PIV algorithm in order to detect the apparent shifts in the local speckle patterns. These shifts are proportional to the local refractive index gradients, integrated along the line of sight. A typical result of such an analysis is shown in Fig. 6, where the displacement vectors are superimposed on the difference image for registration of the context. The PIV correlation was performed with a 96x96 window size and an increment of 16x16 pixels. Note that the displacement magnitudes are usually well below 1 pixel so that sub-pixel interpolation in the PIV algorithm is mandatory.

Fig. 6 PIV Analysis of the BOS speckle displacement field. Two consecutive speckle images (Δt=45ms) are compared. (The corresponding absolute difference image is shown in the background.)
With a suitable calibration, this gradient vector field can be integrated to provide an estimate of the instantaneous refractive index distribution and thus also the temperature. This integration will not be performed here, however, because the inherent three-dimensionality of the backlayering zone makes a direct interpretation of the flow structures difficult (see also the discussion on counter flow patterns above). Nevertheless, useful information can be extracted already from the displacement gradient field.

First, one may look at the spatial autocorrelation of the vector field to obtain an estimate of the characteristic size of the structures visible in the image. The result is shown in Fig. 7, where the two-dimensional autocorrelation is computed for each of 1200 PIV individual PIV maps. The resulting correlation maps are averaged, and the plot depicts the shape of the averaged 2D autocorrelation function along the horizontal and vertical lines crossing the correlation peak.

![Fig. 7 Autocorrelation of the PIV displacement field demonstrating the presence of a characteristic length scale.](image)

In a further analysis step, the position of the (horizontal) correlation peak can be tracked as the cross-correlation is computed between PIV maps with increasing delay. This provides an estimate of the advection velocity. The result is shown in Fig. 8, indicating a velocity of 0.45 m/s which is close to the value of the outer cross flow velocity in the tunnel (0.52 m/s).

![Fig. 8 Cross-correlation of PIV displacement fields with increasing time delay, demonstrating the presence of a characteristic advection velocity.](image)

Finally, one may perform a complete second PIV analysis on the displacement vector fields themselves. Since the coherent structures extracted by the BOS-PIV analysis persist for some time in the flow, their displacement can be tracked with another PIV step to derive the local advection speed in a spatially resolved manner. This is shown in Fig. 9 for the same case as above.
Secondary PIV analysis of the displacement vector field

Note that in order to preserve a reasonable resolution / data density, the secondary PIV analysis shown uses a combination of spatial (“classical”) and temporal (“single pixel”) pattern matching. The feature vectors being tracked consist of a 5x5 neighborhood in the original displacement map and 23 time slices, making for 575 elements. The statistics of the derived flow field indicate a pattern convection speed which is again consistent with the external cross-flow velocity of 0.52 m/s (see also the 1D correlation shift analysis above). The central patch with reduced velocity is an artifact caused by a heat transfer sensor on the wall partially suppressing local speckle reflections.

4. Conclusion
The recently proposed speckle BOS technique is successfully employed to study a variable density/temperature flow close to a wall. Besides the extraction of refractive index gradient distributions, the calculation of coherent structure sizes via the autocorrelation of the displacement field is possible. Furthermore, a PIV analysis of the displacement field itself can be performed and does provide a spatially resolved estimate of the local advection velocities. Further development of the technique in the present application scenario will focus on the detailed analysis and interpretation of the coherent features which can be observed, taking into account the projective nature of the schlieren system when observing three-dimensional structures.

5. References