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

P. Bühlmann[1,*], A. H. Meier[1], M. Ehrensperger[1], T. Rösgen[1]

1: ETH Zürich, Institute of Fluid Dynamics, Switzerland
* Correspondent author: buehlmann@ifd.mavt.ethz.ch

Keywords: Background Oriented Schlieren, Speckles, Wall-bounded flows, Fire backlayering

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.

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.

Such a scenario is experimentally simulated in a custom designed hot air tunnel. 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.

The fire is simulated by an electric heater delivering hot air at 400° C temperature to the test section. An extraction fan at the end of the tunnel controls the cross flow in the tunnel (speed: 0.52m/s).

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, l=532nm, P_{max}=5W). A monochrome digital camera (IDS uEye 2230SE, 1024x768 pixels) using a 8.5mm wide-angle lens records the speckle patterns.

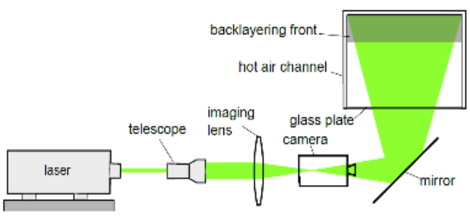

Fig. 1 BOS recording setup. The illumination creates speckle patterns on the tunnel ceiling in an area of approx. 1m².

The analysis of the recorded speckle images provides insights into several characteristics of the backlayering front:

- A simple image processing step (computing the absolute difference between consecutive images) is used to create a real-time flow visualization of the propagating hot gas layer.
- In order to visualize the frontal dynamics, the spatio-temporal signature along a horizontal line in the image center is displayed in a x-t diagram (see Fig. 2). 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).

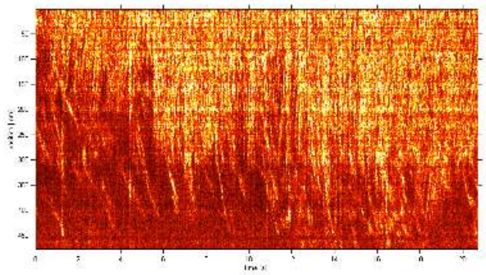

Fig. 2 Difference visualization of the backlayering front.

The speckle images can also be analyzed with a standard PIV algorithm in order to detect the apparent shifts in the local spackle 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. 3, where the displacement vectors are superimposed on the difference image for registration of the context.

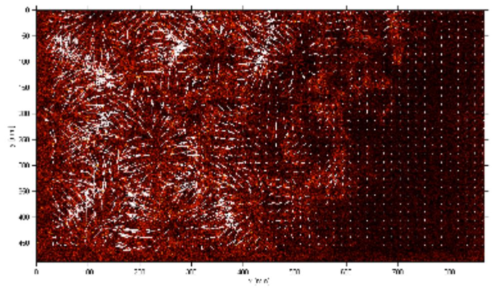

Fig. 3 PIV Analysis of the BOS speckle displacement field.

An analysis of this vector field reveals further information about the backlayering zone.

- The spatial autocorrelation of the vector field provides an estimate of the characteristic size of the structures visible in the image.
- The position of the (horizontal) correlation peak is tracked as the cross-correlation is computed between PIV maps with increasing delay. This provides an estimate of the advection velocity.
- 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.

The speckle BOS technique can thus be employed to study a variable density/temperature flow close to a wall, providing not only density / temperature but also velocity information.

References

[1] Meier A H, Roesgen T (2013) Improved background oriented schlieren imaging using laser speckle illumination. Experiments in Fluids, 54(6): 1-6.