Power VCSEL driven Schlieren visualization for cascaded injection in supersonic flow

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Extended abstract

Results are presented of a study on utilising Vertical-Cavity-Surface-Emitting-Laser (VCSEL) driven Schlieren visualization of cascaded injection in a supersonic flow. The background of the study is fuel injection within a supersonic combustion ramjet (scramjet). The scramjet is a ramjet airbreathing jet engine in which combustion takes place in a supersonic air flow. Scramjets promise significant economic advantages over rocket-based flight travel. However, at hypersonic flight speeds the compressibility effects delay shear layer mixing. In order to maintain for scramjets, the fuel-air mixture required for high combustion efficiency, the combustor becomes relatively long[1]. In the present case of cascaded injection, the downstream injector benefits from the shielding effect induced by the smaller upstream injector. This provides a reduction of the momentum in the flow, allowing better penetration of fuel in the air stream over a shorter length.

Validation of theoretical and computational results for the flow in scramjets requires a high spatial and temporal resolution of the flow field. In the present study Schlieren visualisation is employed to investigate the flow field. In our previous studies pulsed LED-driven Schlieren visualization was employed. However, for a Mach 1.6 free stream, the limited pulse width of 130 ns of LEDs creates a motion blur of roughly a pixel per second. Therefore, LED-based Schlieren visualisation is not adequate for Schlieren imaging of flows at higher Mach numbers. Furthermore, using an appropriate knife-edge filter, the power of 6 W/mm^2 of the LED employed, is only just sufficient to obtain acceptable Schlieren images.

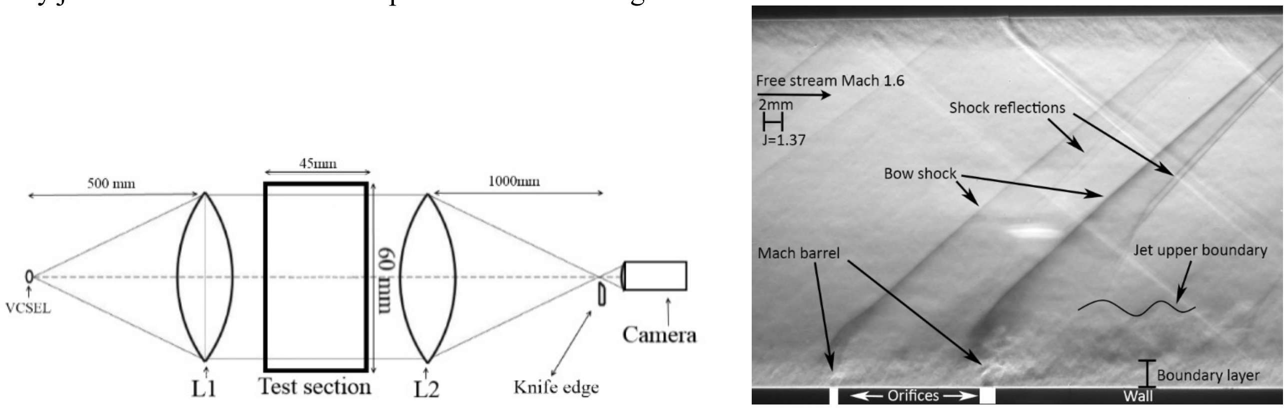

Fig. 1 Left: Schematic of Schlieren set-up. Right: Example of Schlieren image obtained for dual-jet injection in a Mach = 1.6 cross-flow. Diameter orifices 1 mm (upstream) and 2 mm (downstream). Visualised are the tandem jets, 20 mm apart, momentum ratio J = 1.37, each featuring a Mach barrel at their exit; the two bow shocks induced by the jets; the boundary layer along the walls and their interaction with the shocks. Also visible are Mach waves originating from small slope discontinuities of the walls of the wind tunnel

Power VCSELs provide the high-pulse modulation speeds necessary for high temporal resolution Schlieren imaging of high-speed flow fields. VCSELs consist of very small, densely packed, laser diodes, ordered on a chip in a 2D array, emitting light perpendicular to the chip's surface. Each VCSEL is around 25 micrometres in size and although its Continuous Wave (CW) power is limited, in our case to 10 mW, pulsing the laser increases the power up to a factor of 10. Furthermore, by integrating 600 lasers per square millimetre, the combined laser-light source is quite powerful. Thus, such an arrangement of the VCSELs creates a high power-to-area ratio, up to 30 W/mm^2. This device, with its relatively small emission angle of around 20 degrees and its small emission surface has the potential to increase the achievable contrast of Schlieren images. Also, the VCSELs used in the present study are driven by pulse electronics on a dedicated small printed circuit board (PCB). The price of such a VCSEL is less than 100 euros.

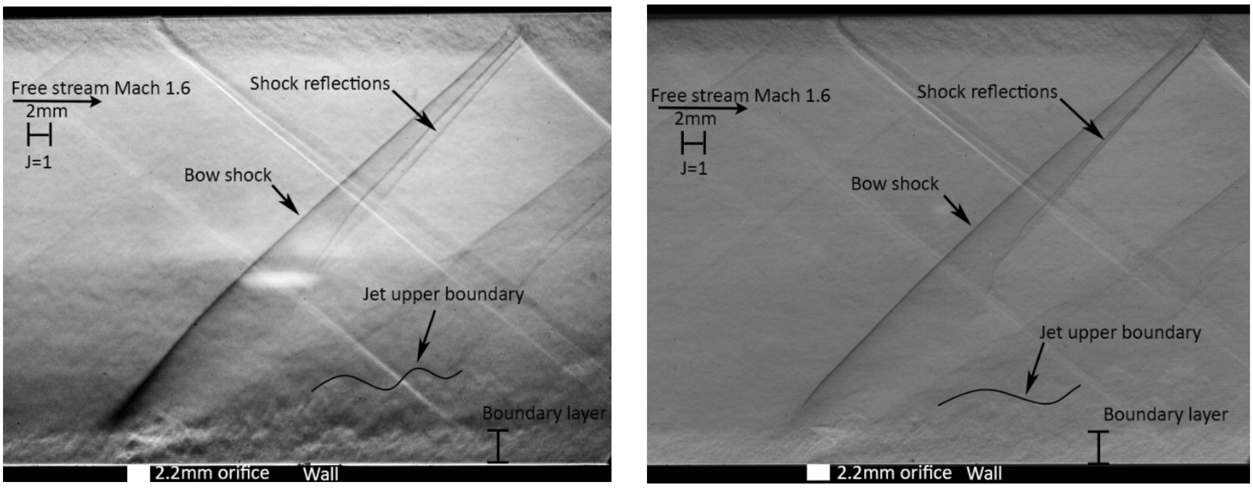

Fig. 2 Schlieren images obtained for single-jet injection in a Mach = 1.6 cross-flow. Diameter orifice is 2.2 mm. Left: VCSEL-based Schlieren. Right: LED-based Schlieren. Visualised are jets of momentum ratio $J = 1$. Both images feature: the bow shock induced by the jet; the boundary layer along the walls and their interaction with the shocks. Also visible are Mach waves originating from small slope discontinuities of the walls of the wind tunnel

Fig. 1 shows the flow observed in the supersonic wind tunnel of the University of Twente for a cascaded dual tandem injection of air, from orifices in the bottom wall, in a supersonic stream of Mach 1.6. The upstream (left) injection orifice is half the diameter of the downstream (right) orifice. The momentum ratios studied are $J = 1.0$, 1.37 and 2, with $J \equiv \frac{\rho_j U_j^2}{\rho_\infty U_\infty^2} = \frac{\gamma_j p_j \mathrm{M}_j^2}{\gamma_\infty p_\infty \mathrm{M}_\infty^2}$. By varying the distance between the two injectors, an optimal distance for maximizing fuel penetration is sought for, limiting the negative effects of total pressure loss and flow separation.

Results for dual-jet injection are compared with results for single-jet injection, at equal mass flow, i.e. for the case of an orifice of 2.2 mm. Example results for single-jet injection are presented in Fig. 2. This figure also shows a comparison of results obtained with the present Schlieren set-up employing VCSELs and results from a Schlieren set-up based on a LED light source. This illustrates the improvement of the quality of the Schlieren images obtained with VCSEL-based Schlieren.

Dual injection spacings of 4-24 mm showed increased air penetration and enhancement of the average fuel injection by 11-43% in comparison with single-jet injection. Best air penetration was found for a spacing of 12 mm. This spacing increased the average fuel penetration by 29-43%.

The Schlieren images obtained in the present study feature excellent temporal and spatial resolution. The VCSELs provide more than enough light needed for a clear bright image. Because of the abundance of light, the knife-edge cut-off can be increased, which enhances the contrast of the Schlieren images. As VCSELs can be pulsed easily down to 10 ns, visualizing high-Mach-number flows can be achieved with negligible motion blur. The optical power provided by VCSELs creates opportunities to alter the light path and visualize the flow field at angles different from 90 degrees with respect to the free stream, employing the same light source.

As a disadvantage it should be noted that anti-reflection coatings on lenses and glass surfaces are usually designed for visible wavelengths. These coatings will be less efficient in the near-infrared range of the light from the employed VCSELs.

In summary, the VCSEL-driven Schlieren system creates excellent spatial and temporal resolution with potential for multi-angled Schlieren images of high-Mach-number flows.

References

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