# In Application

# Temperature Imaging in Thermal Gas Flows

## Comparison of imaging techniques

**Temperature imaging techniques for gaseous flows**
Four imaging techniques for temperature measurements in gas flows are discussed. Each technique is using another physical temperature effect featuring certain advantages as well as experimental limitations for a particular thermographic measurement. Three laser imaging techniques and one line-of-sight technique are compared and tested in a heated air jet.

| Imaging Technique | Measured Temperature Effect |
|---|---|
| Rayleigh Thermometry | Total gas density ~ 1/T |
| Laser Induced Phosphorescence, LIP | Thermographic phosphor particles |
| Laser Induced Fluorescence, LIF | Thermographic LIF gas tracers |
| Background Oriented Schlieren, BOS | Temperature induced density gradients |

Laser light sheet imaging techniques like Rayleigh, LIP and LIF are planar measurements stopping the flow motion with very short laser pulses. BOS is a line-of-sight technique recording a dot pattern in the background of the thermal flow. Temperature induced density gradients in the flow are detected as image distortions of the dot pattern (Schlieren). Due to the line-of-sight character of the BOS imaging technique these image distortions can only be converted to temperature for 2D or axisymmetrical flows. The tomographic version of BOS using multiple viewing directions overcomes this limitation and measures 3D temperature fields also in non-stationary and turbulent flows.

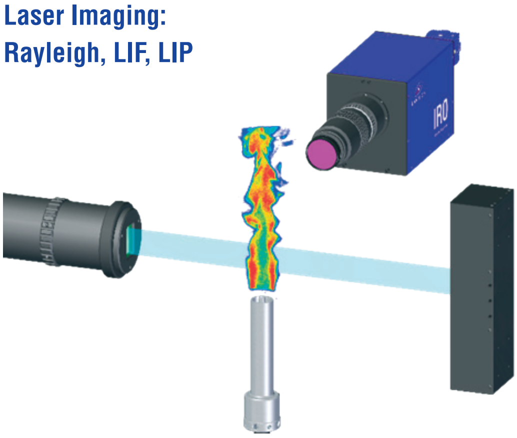
While BOS and Rayleigh are working in clean gas flows, LIF and LIP both need flow seeding with temperature sensitive LIF active gas tracers or thermographic phosphor particles, respectively. Particle seeding allows simultaneous temperature and flow field measurements with a combined LIP and PIV approach called "Thermographic PIV".

| | Rayleigh | 2-color LIP | 2-color LIF | BOS |
|---|---|---|---|---|
| Max. Temperature | > 1000 K | 800 K | 900 K | > 1000 k |
| Field of View | 50 mm | 200 mm | 200 mm | 1 m |
| Precision† | 3 % | 10 % | 6 % | 5 % |
| Seeding | no | phosphor particles | LIF gas tracer | no |
| Pros | accuracy | T + flow field | sensitivity | simplicity |
| Cons | stray light | complex setups | | simple flows |

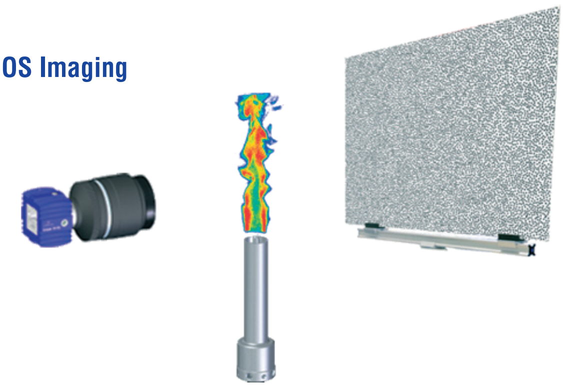
† these are only guidelines depending on experimental parameters

*Benchmarking chart comparing the four investigated temperature imaging techniques*

**Laser Imaging:**
**Rayleigh, LIF, LIP**




**BOS Imaging**



*Laser imaging on light sheets (top) and the line-of-sight imaging configuration of BOS (bottom)*

LIP and LIF are based on the change of the tracer's emission spectrum with temperature. Both use a 2-color ratiometric imaging approach to compensate for seeding density as well as laser intensity fluctuations.
Rayleigh is based on the elastic light scattering from gas molecules. Its signal strength is proportional to the local number density, which depends on temperature applying the ideal gas law. The gas mixture composition needs to be known.
Laser imaging can be prone to stray light especially when applied close to surfaces. This unwanted interference can be effectively suppressed applying the newly developed structured light sheet illumination technique called "SLIPI" (see LaVision Application Note "**Scalar Laser Imaging without Stray Light**").

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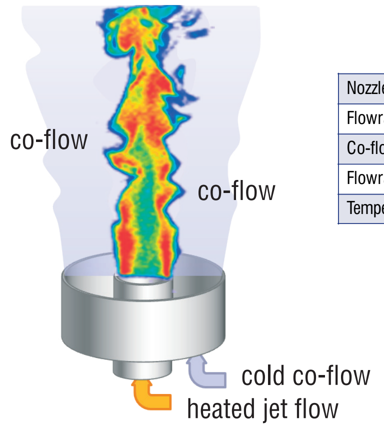
**Performance tests in a heated air flow**

All four imaging techniques were applied in the same heated air jet close to the nozzle in a nearly laminar and stable flow region of almost axisymmetric structure. The covered temperature was in the range of 300 K to 800 K. Some of the experimental parameters for each method are given in the table below. More detailed information can be found in the paper of Fuest et al. [1].

| | Light Source | Flow Tracer | Detection System |
|---|---|---|---|
| **2-color LIF** | Nd:YAG: 266 nm, 3 mJ/cm | Anisole | 2x (IRO+M-lite 2M) |
| **2-color LIP** | Nd:YAG: 355 nm, 5 mJ/cm | BAM:Eu | 2x M-lite 2M |
| **Rayleigh** | Nd:YAG: 355 nm, 60 mJ/cm | - | IRO+M-lite 2M |
| **BOS** | LED Flash: white, 200 $\mu$s | - | M-lite 5M |

**IRO: image intensifier M-lite 2M: 12-bit 2 Megapixel CMOS camera**




| | |
|---|---|
| Nozzle diameter | 9 mm |
| Flowrate jet | 10 lpm (unheated air) |
| Co-flow diameter | 35 mm |
| Flowrate co-flow | 200 lpm (cold air) |
| Temperature range | 300 K to 800 K |

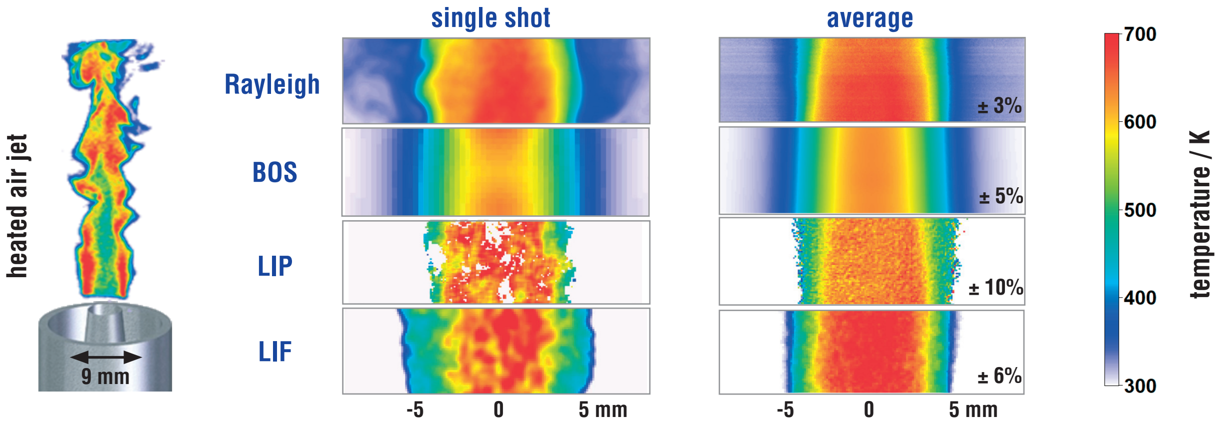
*Sketch of the heated air jet nozzle with operation conditions*

For the flow seeding techniques LIF and LIP anisole tracer gas and BAM:Eu phosphor particles were used, respectively. The applied laser pulse energies per cm light sheet height (mJ/cm) are quite different, reflecting the large differences in light scattering efficiency of the three applied laser imaging techniques: compared with LIF, Rayleigh imaging needs roughly 20x higher laser energy in the light sheet.

2D BOS measurements have to be averaged until an axisymmetric deformation pattern is achieved, only from which radial temperature profiles can be derived. Tomographic BOS based on multiple camera views overcomes this limitation.

Temperature fields of the air jet at 700 K measured with the four optical methods are shown in the figure below. The standard deviation of each averaged temperature field is also indicated.

Rayleigh thermometry shows the highest precision, while LIP temperatures are measured with a higher uncertainty mainly due to inhomogeneous particle seeding of the flow. Both seeding techniques LIF as well as LIP used much less pulse energies compared with Rayleigh allowing temperature measurements on much more extended light sheets. All laser imaging techniques can be performed with nearly the same hardware setup proving the versatility of LaVision's laser imaging systems for quantitative flow visualization.




*Single-shot (left) and averaged (right) temperature fields measured in the heated air jet at 700 K for each of the four indicated temperature imaging techniques*

**Reference**


[1] F. Fuest et al., "Gas thermometry using four different optical methods", 19th Intl. Symposium on the Application of Laser and Imaging Techniques to Fluid Mechanics, Lisbon 2018





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