

Combined filtered Rayleigh and Mie scattering for simultaneous planar temperature and velocity measurements

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Abstract The combination of planar Doppler velocimetry (PDV) and FRS offers a promising way to obtain simultaneously 3 component velocity in a plane and corresponding scalar temperature maps. Implementation wise the two techniques are closely related since they both make use of a molecular absorption filter. This makes it possible to combine the necessary equipment using a single laser to illuminate a plane of interest that is observed simultaneously by multiple viewing directions. While PDV determines the frequency shift utilizing an absorption measurement with the laser light stabilized on the slope of an iodine line FRS measures the residual light passing through the molecular filter with the laser frequency tuned to the absorption minimum. The main challenge arises from the fact that PDV relies on the scattered light by micron-sized particles added to the flow. The intensity of this Mie scattered light is orders of magnitude higher than the light scattered by molecules of the gas flow itself known as Rayleigh scattering. In order to be able to record both signals both simultaneously but separately two iodine cells with different operation conditions were used for each camera system. The necessary criteria for successful measurements is the sufficient suppression of the Mie scattered light by the FRS camera while maintaining a proper dynamic range for the Doppler shifted light recorded by the PDV camera system. The combined PDV – FRS system was optimized by arranging the observation directions for the velocity and temperature measurements separately. An evaluation of the combined system was performed with an analysis of measurements taken on a hot free jet. Although the PDV velocity data agree reasonably with the calculated value the performance of FRS system suffered from technical problems.

1. Introduction

Driven by the demand of providing detailed experimental data in a cost-effective manner modern non-intrusive measurement methods currently focus on obtaining spatially resolved multipoint data using imaging methods while at the same time increasing recording frame rates to improve temporal resolution. In a similar manner the combination of different image based diagnostics promises the simultaneous measurement of a multitude of flow quantities. For example the combination of particle image velocimetry (PIV) and filtered Rayleigh scattering (FRS) is able to obtain combined planar velocity and temperature maps while the combination of the Raman-Rayleigh- planar laser induced fluorescence techniques simultaneously yield spatially resolved information on temperature and species concentration [1, 2]. The diversity and complexity of the respective measurement techniques requires an equally complex combination of a multitude of illumination (laser) and signal detection (camera) equipment to realize these combinatory methods. The spectrally resolved Rayleigh signal alone can be used in principle to obtain multiple flow properties on its own but is generally only suitable for point measurements. Furthermore it is difficult to obtain accurate velocity information from the shifted Rayleigh spectrum especially for low speed flows. Therefore a simultaneously recorded Mie signal can greatly improve a combined measurement approach as was being demonstrated by Mielke et al. for sparsely seeded flows [3]. The drawback of this technique is the tedious task to seed a flow with an appropriate level so that the Rayleigh and Mie signals have approximately the same intensities.

The combination of planar Doppler velocimetry (PDV) and FRS using a filter technique for both scatter signals offers a promising way to obtain simultaneously the all three component of the velocity field and corresponding scalar temperature maps independent from the seeding level. Implementation wise the two techniques are closely related since they both make use of a molecular absorption filter and a frequency stabilized laser. This makes it possible to combine the necessary equipment using a single laser to illuminate a plane of interest that is observed simultaneously by multiple viewing directions.

2. Combination principle

Both measurement techniques PDV and FRS exploit a frequency stabilized laser system and detect the scattered light filtered through a molecular absorption cell containing iodine in our case. However the sources of the scattered light are vastly different. PDV relies on the scattered light by micron-sized particles added to the flow (e.g. seeding) which falls into the category of Mie scattering. In contrast FRS uses the scattered light by molecules of the gas flow itself known as Rayleigh scattering. Therefore both light signals have different properties regarding intensity and spectral distribution.

Due to the large differences in the diameters between seeding particles and gas molecules the intensity of this Mie scattered light is orders of magnitude higher than the Rayleigh light and thus must be suppressed sufficiently by the FRS detection system. Another major distinction results from the mass discrepancy between molecules and micron-sized particles. The Rayleigh signal is thermally broadened to a few GHz due to the lower mass of the flow molecules whereas the Mie signal follows the spectral width of the used laser system - typically a few MHz.

While PDV determines the frequency shift utilizing an absorption measurement with the laser light stabilized on the slope of an iodine line (fig.1a, b) FRS measures the residual light passing through the molecular filter with the laser frequency tuned to the absorption minimum (fig. 2a,b). This filter technique offers two advantages in contrast of recording the pure Rayleigh light. First it allows an effective discrimination of the Rayleigh signal against unwanted background light such as laser reflections or scattered light from dust and fuel droplets. Additionally the spectral information containing the physical quantities density, temperature, pressure and velocity are not completely lost when the FRS signal is integrated over the spectral range. Hence it may be difficult to obtain single-valued results for multi-property measurements but together with further assumptions or knowledge about the investigated flow this multi-value problem can be overcome [4,5].

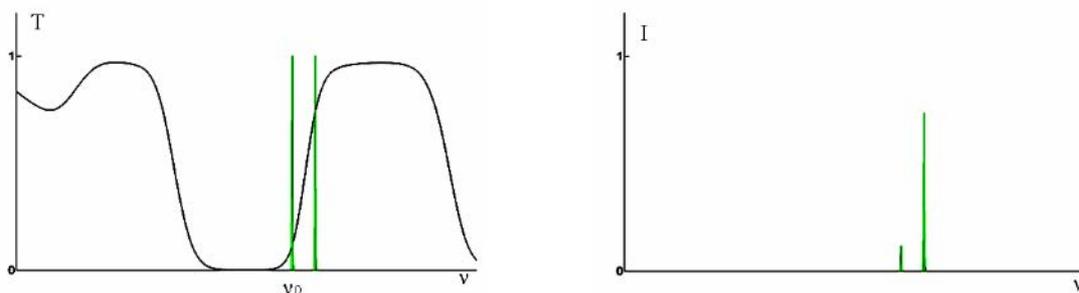


Fig.1a,b (PDV principle) The Doppler frequency shift can be obtained with an absorption measurement using the varying transmission profile (black) from the slope of an iodine absorption line (left). The measured change of transmission determines one component of the flow velocity (right).

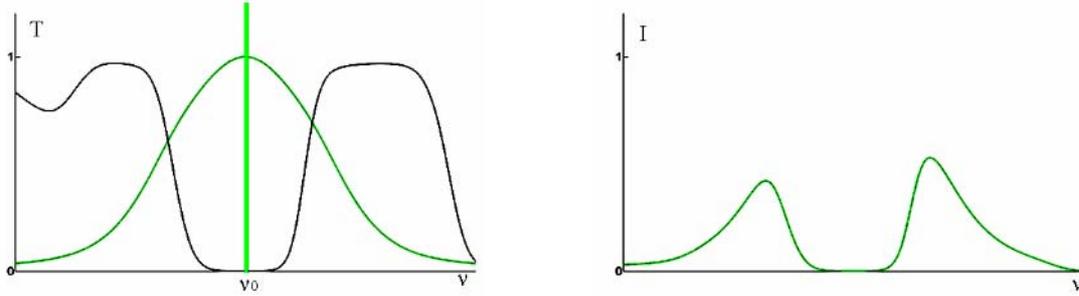


Fig.2a,b (FRS principle) The central part of the Rayleigh scattered spectrum (green) containing also the much stronger Mie part for seeded flows is filtered by the transmission profile of an iodine line (left). An on-chip spectral integration of the residual light (right) results in an intensity signal which determines the temperature of the flow.

Since both frequency stabilization points are different this represents the fundamental problem to be overcome for developing a combined system. For typical iodine absorption lines the transmission minimum allowing the highest degree of extinction and the central part of the slope corresponding to the point of highest sensitivity for PDV measurement are approximately separated by 500-800MHz.

A common feature of both methods is the Doppler shift in frequency of the Mie signal as well as the Rayleigh spectrum with respect to the laser frequency ν_0 , flow velocity \mathbf{V} , illumination and observation directions \mathbf{l} and \mathbf{o} according to the equation:

$$\Delta\nu = \frac{\nu_0}{c} (\vec{o} - \vec{l}) \cdot \vec{V} \quad (1)$$

Depending on the exact arrangement of the observation directions for both techniques the Doppler shift for each signal can be different in magnitude and sign. This fact offers a design opportunity for the optimization of a combined system as will be shown in the next chapter.

If the intensity of the Mie scattered light is orders of magnitude higher than the Rayleigh signal for seeded flows the contribution of the Rayleigh signal can be neglected and the intensity signal recorded by the PDV camera system can be written as:

$$I_{PDV} = C_{PDV} I_0 N_{seed} \sigma_{Mie} t(\nu_0 + \Delta\nu_{PDV}) \quad (2)$$

By recording simultaneously a reference image without filter a normalization of the signal is provided. This process eliminates the dependence of the PDV signal on the laser power I_0 , the seed particle density N_{seed} , the Mie scatter cross section σ_{Mie} and a geometrical calibration factor C_{PDV} for the PDV setup. As a result the change in the absorption strength of the transmission profile $t(\nu)$ due to the Doppler frequency shift can be measured and determines one component of the flow velocity. To obtain all three velocity components simultaneously three observation views are required. This is realized by using a fiber image bundle.

The contribution of the Mie signal to the recorded FRS signal is strongly dependent on the transmission of the iodine absorption line at the Doppler shifted frequency as seen by the FRS camera system:

$$I_{FRS} = C_{FRS} I_0 \left[N_{gas} \int_{-\infty}^{+\infty} \sigma_{Ray}(\nu - (\nu_0 + \Delta\nu_{FRS}), p, T) t(\nu) d\nu + N_{seed} \sigma_{Mie} t(\nu_0 + \Delta\nu_{FRS}) \right] \quad (3)$$

This intensity signal is also normalized by recording the corresponding FRS signal at known reference conditions. Analogous to the normalization procedure for the PDV technique the ratio of both FRS signals eliminates the geometrical factor C_{FRS} of the FRS setup. The remaining convolution integral of the iodine transmission profile t and the Rayleigh cross section σ_{Ray} maintains information about thermodynamic flow properties pressure p , temperature T and the projection of the flow velocity onto the difference vector $\mathbf{o-l}$ according to equation (1). The latter is causing the frequency shift $\Delta\nu_{FRS}$ of the Rayleigh spectrum [6].

If for example the pressure is known the ideal gas law can be used to correlate temperature and the gas number density N_{gas} . Together with the velocity information from the PDV measurement the complicated dependency of the measured FRS intensity on multi parameters reduces to a single-valued function of the gas temperature. Therefore the combined system benefits from reducing the parameter space for the evaluation of the FRS signal. By contrast the unfiltered spectrally integrated Rayleigh signal is only dependent on the gas number density.

Preliminary extinction experiments indicated that a transmission value of lesser than 10^{-6} is necessary to suppress this Mie light completely for a flow seeded with a sufficient high density for PDV measurements. Under such conditions the second term on the right hand side of equation (3) can be neglected.

In order to be able to record both signals simultaneously but separately two iodine cells with different operation conditions were used for each camera system. The necessary criteria for successful measurements is the sufficient suppression of the Mie scattered light by the FRS camera while maintaining a proper dynamic range for the Doppler shifted light recorded by the PDV camera system.

3. Optimization of Extinction and Sensitivity

In order to investigate the properties of both systems a simple free jet operating with heated air was used. A laser light was formed and illuminated a plane of 40mm height above the nozzle exit.

The laser system used for the illumination of the flow field consists of an injection seeded, pulsed Nd:YAG laser system delivering 250mJ SHG pulses of 1 to 10 microsecond duration at a 40 Hz repetition rate. Because of the long temporal pulse duration the spectral width of the laser system isn't Fourier limited and is specified to be lesser than 5MHz. Since the laser system consists of a seed laser and multiple amplifier stages the frequency becomes tuneable and can be stabilized in the region of 18787.80 1/cm which coincidences with the P(83)33-0 transition of the iodine molecule

While the PDV system uses two thermo-electrically cooled CCD cameras the FRS recording system utilizes an EM-CCD to account for the weak Rayleigh signal. Another focus is to maintain the applicability of the combined system within environments which have limited optical access. Therefore image fiber bundles were used for each PDV observation direction which can be used with minimal access to the test rigs [7]. The FRS system also employed a separate image fiber and thus the desired combined viewing directions could be easily and flexible arranged as indicated in fig. 4.

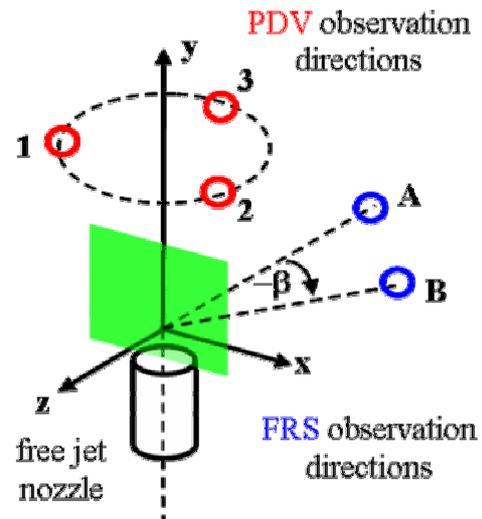
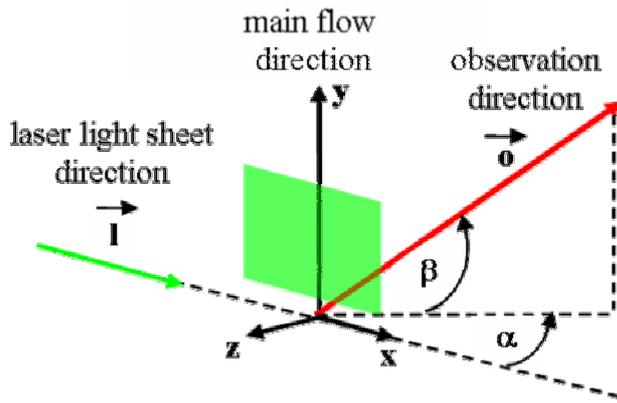


Fig.3 Definition of light sheet and observation directions **Fig.4** Configuration of the combined setup

Our main idea for a combined technique is to use an iodine absorption cell with a high gas pressure for the FRS system to suppress the Mie scattered light and another cell with a comparatively low pressure for the PDV system. Since the cell's transmission profile strongly depends on the temperature and vapour pressure a cell temperature is chosen 5°K above the point where all of the iodine is evaporated – the saturation temperature [8]. An extensive computer simulation was performed to estimate the optimized temperatures of the iodine cells and the frequency stabilization point of the laser light sheet. As a result for the FRS detection system an iodine cell with a saturation temperature of 80°C was chosen while exploiting a saturation temperature of 36°C for the PDV measurements. Both cells are 50mm long and have an inner diameter of 48mm

Preliminary extinction measurements using an iodine absorption cell with a saturation temperature of 60°C corresponding to a minimum transmission value of lesser than $3 \cdot 10^{-7}$ indicated that under such absorption conditions the Mie signal from a seeded flow is completely suppressed and a pure Rayleigh signal can be detected. But since the corresponding transmission value of the PDV cell is only 0.05 together with a weak increasing slope due to the transmission minimum this frequency is insufficient as a working point for the combined system in the case of a low speed flow field (fig.5). Nevertheless this configuration of iodine cells together with a laser stabilized in the transmission minimum at 18787.80 1/cm can be used for measuring combined temperatures and velocities in the order of a few 100m/s. For the jet velocity of 40m/s used in our experiment the sensitivity of the PDV system had to be increased which is equivalent to the use of a higher laser frequency in order to increase the PDV start transmission.

The latter requirement was realized by detuning the stabilized laser frequency away from the absorption minimum to the expected limit of complete suppression of scattered Mie light in order to facilitate the PDV measurements. With a suitable frequency shift away from the transmission minimum it should be possible to reach nearly the middle part of the slope for the PDV system while maintaining the extinction properties of the FRS cell. (fig.5, 6)

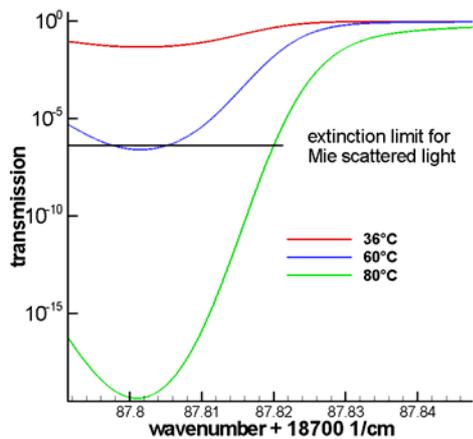


Fig.5 Indicated is the extinction limit for the complete suppression of the Mie scattered light with respect to the transmission profiles of three vapour pressures and thus saturation temperatures. Note the logarithmic scale.

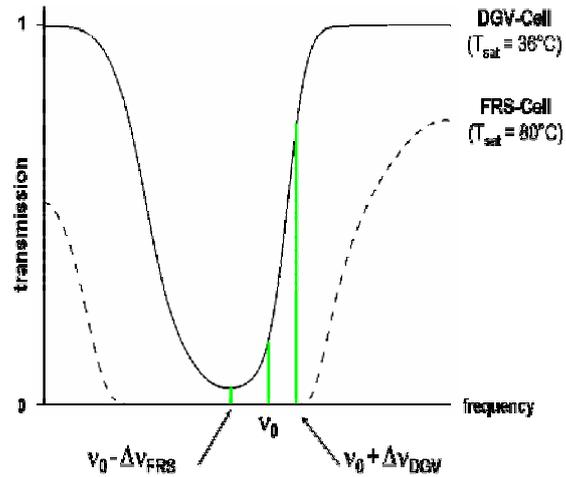


Fig.6 Iodine cell transmission lines for two different vapour pressures. Note that the Doppler shift as seen by the PDV system is positive and thus the PDV signal is shifted towards the slope of the 36°C cell while the Doppler shift as seen by the FRS camera is negative and thus the Rayleigh spectrum is shifted towards the minimum of the 80°C cell.

The combined PDV – FRS system was optimized by choosing the observation directions for the velocity measurements in such a way that the resulting Doppler shifts were nearly equal in magnitude and sign – i.e. $\alpha_1=90^\circ$, $\alpha_2=225^\circ$, $\alpha_3=315^\circ$ and $\beta_1=\beta_2=\beta_3=45^\circ$ (see fig.3 for the definitions of α and β). This arrangement ensures that all three transmission measurements were performed on the e of the corresponding iodine line (fig.6) due to the resulting frequency shifts as seen by the PDV optics.

It is helpful to arrange the view of the FRS system so that the Doppler frequency shift pushes the Rayleigh spectra back to the transmission minimum. This further reduces the additional Mie signal and ultimately leads to a sufficient suppression. Therefore two viewing directions for the FRS measurements were chosen and compared: $\beta(A)=0^\circ$, $\beta(B)=-50^\circ$ and $\alpha(A)=\alpha(B)=90^\circ$.

The optimization of the viewing direction for both methods is relying on the fact that the flow velocity has a dominant component which in our case coincides with the axial direction of the investigated preheated free jet flow. This results in a designed positive frequency shift for all three PDV viewing directions and thus increases the slope of the used portion of the iodine absorption line for measuring the flow velocity.

In order to quantify the suppression capability of the iodine filter cell we carried out FRS measurements on the free jet. A Laskin-type seeding generator provided the necessary Mie particles in form of oil droplets and can be operated with pressures up to 6bar which determines the amount of seeding produced. FRS intensity signals with different particle concentration levels were recorded and normalized. Three different seeding conditions were chosen: no seeding, a mean level corresponding to a pressure of 3bar and the maximum available seeding at 6bar. Both levels are sufficient high to allow PDV measurements exploiting the Mie signal.

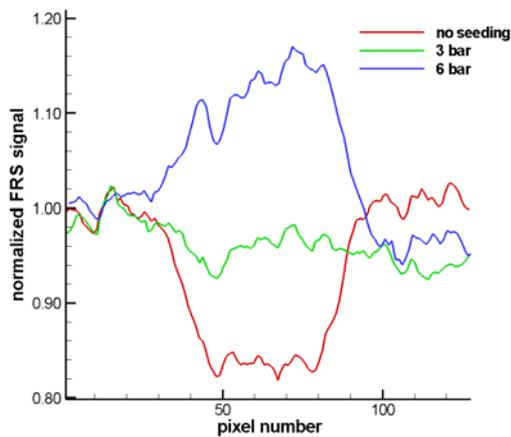


Fig.7a Profiles of the normalized FRS signal under different seeding conditions for a viewing direction A: $\alpha=90^\circ$, $\beta=0^\circ$.

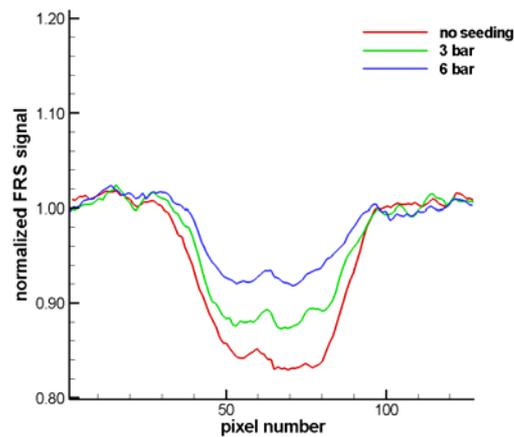


Fig.7b Profiles of the normalized FRS signal under different seeding conditions for a viewing direction B: $\alpha=90^\circ$, $\beta=-50^\circ$.

The horizontal profiles for a FRS viewing angle of $\beta=0^\circ$ show the influence of the Mie scattered light on the ratio of the FRS intensities. Even at modest seeding rates a decreasing in the normalized FRS signal corresponding to an increased temperature of the jet core compared to the environment can't be detected. A change in the observation direction for the FRS system to $\beta=-50^\circ$ reduces the influence of the detected Mie signal considerably. The observed effect confirms the underlying design idea for the combined system.

But of course it was expected that a detuning of the laser frequency away from the transmission minimum up to 18787.82 1/cm would allow a complete suppression of the Mie signal for the FRS absorption cell having a saturation temperature of 80°C (fig. 5). The reason for this failure regarding the complete extinction of the Mie signal by the FRS cell was an erroneous filling of the iodine corresponding to a saturation temperature of only 70°C . Thus the required absorption of the Mie signal wasn't efficient enough to allow the undisturbed detection of the FRS signals.

4. Combined Measurements

A first evaluation of the combined system was performed with an analysis of measurements taken on a hot free jet even though it was clear that the measured temperatures would be systematically lower than the real values due to the insufficient suppression of the Mie light by the FRS absorption cell.

The exit plane of the jet was located at $y=-20\text{mm}$ and the laser light sheet illuminated a plane of 40mm height crossing the symmetry axis of the jet. Velocity and temperature values of 40m/s and 380K were calculated for the free jet core and compared to single-shot and averaged data (fig. 6).

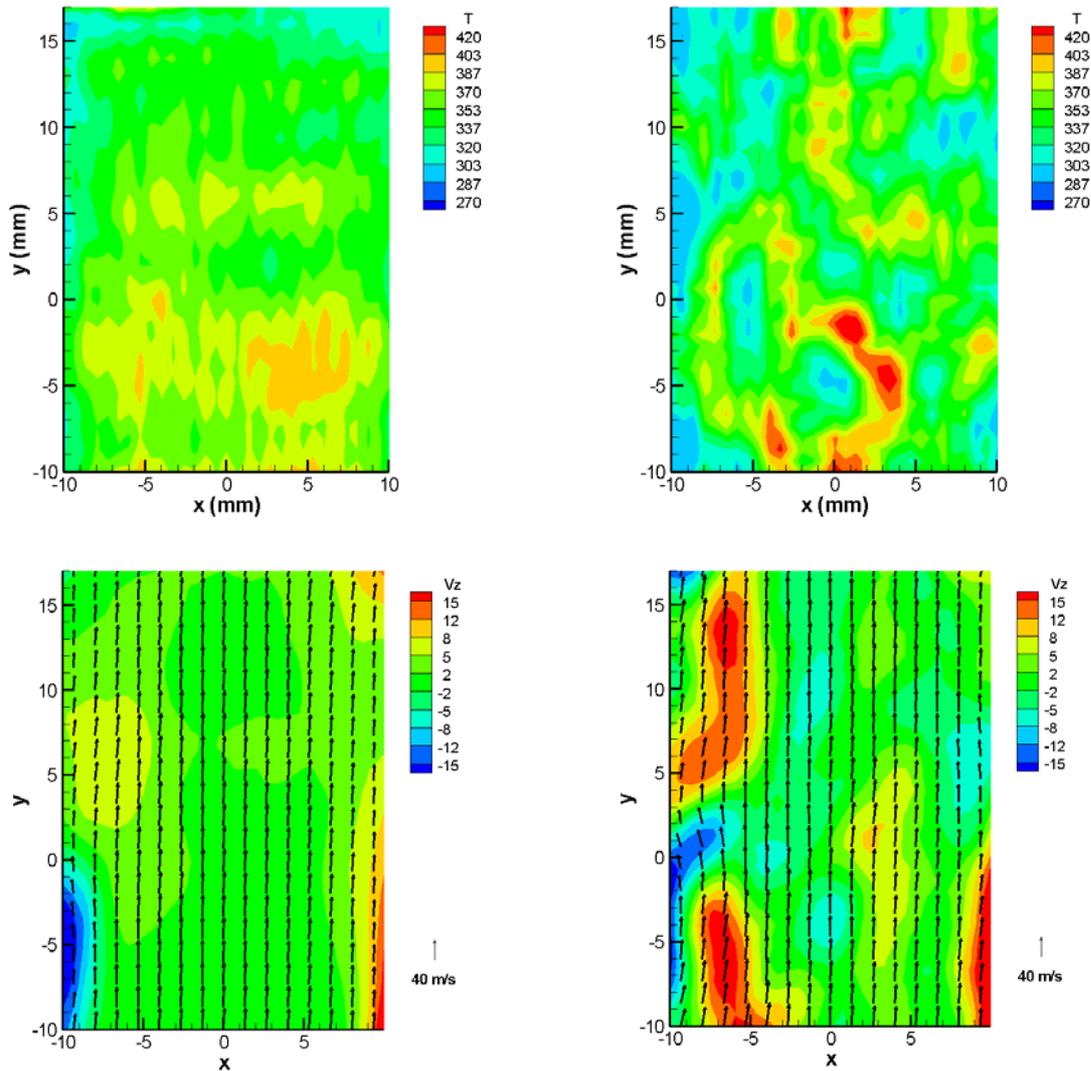


Fig. 6: Top row: Estimated average (left) and instantaneous (right) temperature distribution in a heated free air jet. Bottom row: corresponding average (left) and instantaneous (right) 3-C velocity maps. Colour coding represents the out-of-plane velocity component.

While the single-shot averaged PDV velocity data reasonably agree with the calculated value the quality of the FRS images were so poor that it couldn't be explained with a superimposed Mie signal alone. Further investigations lead to the detection of another severe problem. The windows of the FRS iodine cell were strongly polluted with an unknown substance originating from the isolating material due to the high operating temperature. This will be addressed in the future with a new heater for the cell containing no volatile material.

5. Conclusions

We presented a new approach to combine filtered Rayleigh and Mie scattering in order to measure simultaneously all three components of a velocity field and the corresponding planar temperature map. The combined setup includes a common laser source and thus reduces the overall complexity. Our key idea is to apply two different iodine cells with low and high vapor pressures for the PDV respectively the FRS detection system. This alone should facilitate combined measurements if the flow field velocity is high enough – i.e. the resulting Doppler shifted frequencies reach the slope of the transmission profile while the laser is stabilized in the absorption maximum.

To improve further the sensitivity of the PDV system the laser frequency must be detuned from this point. This decreases the absorption efficiency of the used transmission profile but is even possible above the point of complete extinction (transmission $< 3.10^{-7}$) if the viewing angles of the FRS system are chosen to record a frequency shifted Rayleigh spectrum back in the direction of the transmission minimum. If the investigated flow has a dominant component a suitable placement of the PDV observation directions results in a Doppler frequency shifted signal equal in magnitude and sign towards the transmission slope. Although the iodine cell used for the FRS system had an erroneous filling we tried to demonstrate the feasibility of combined measurements if the saturation temperatures of the PDV and FRS absorption cells would have been 36°C and 80°C.

One advantage of the combined technique is the reduction of the parameter space for the FRS signal since the measured velocity vector by the PDV system determines the otherwise unknown Doppler shift of the Rayleigh spectrum.

Another challenge is to push the laser frequency further away from the position of the minimum. If this working point reaches approximately the midway of the transmission slope there are no restrictions for choosing the PDV viewing directions since then positive and negative frequency shifts could be determined accurately. This might be possible with absorption cells having a higher saturation temperature or a greater length.

It should be emphasized that exact laser frequency, achievable PDV sensitivity and degree of Mie suppression are strongly dependent on the used iodine line and the arrangement of the viewing directions. Thus a combined FRS-PDV system offers several parameters to be designed for an optimization dependent on the flow properties.

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