

Combination of FRS-, PSP-, and LDV measurements to describe the velocity and pressure distributions in the flow around and on the surface of a hemisphere

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ABSTRACT

This article presents the combination of three optical measurement techniques—Filtered Rayleigh Scattering (FRS), Pressure Sensitive Paint (PSP), and Laser Doppler Velocimetry (LDV)—applied to a test object of particular interest for fundamental research: the hemisphere. In addition to the compelling measurement data, a comparison of the velocity data obtained via FRS and LDV is presented. The pressure distribution on the surface is recorded using pressure-sensitive paint (PSP) that is illuminated in the UV range. The dye emits light with a wavelength of around 650 nm, its intensity depends on the static pressure or the oxygen concentration. The velocity and pressure distribution in a cross-sectional plane behind the hemisphere is measured using the frequency scanning filtered Rayleigh scattering method (fs-FRS), which allows the planar detection of the velocity, pressure, and temperature distribution in the flow, see Doll et al. (2024). The reconstructed FRS velocity is validated with Laser Doppler Velocimetry (LDV) measurements.

1. Frequency scanning method for Filtered Rayleigh Scattering (fs-FRS)

The frequency scanning method for FRS (fs-FRS) is based on the evaluation of the Rayleigh scattering of the laser light on the gas molecules in the flow. The Rayleigh scattering occurring at the gas molecules has a spectral distribution of several GHz width and contains information about temperature, pressure, velocity and density in the illuminated measuring range. Reflections of laser light on walls (geometric scattering) or on particles (Mie scattering) are not broadened in frequency and can be filtered out of the measurement signal with the aid of a molecular filter, in this case an iodine cell. A schematic of the scattering process can be found in Fig. 1(left), the principle of frequency scanning is drawn in on the right.

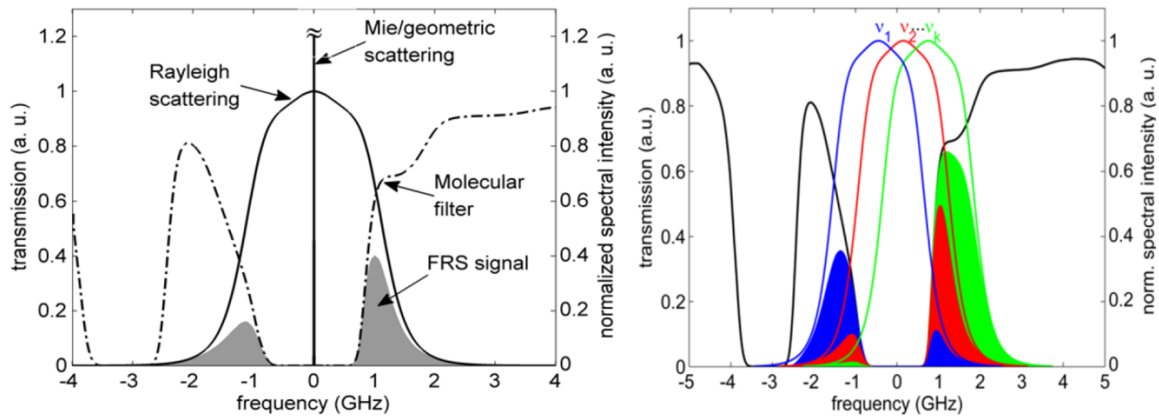


Figure 1. Left: The Rayleigh-scattered light from the narrow-band laser at the fluid molecules is filtered with an iodine cell, which removes reflections from surfaces and scattering from large particles (Mie scattering). Right: Frequency scan method: The laser frequency is set to discrete frequencies in the proximity of the transmission minimum of the iodine cell.

The light scattered by the molecules is imaged by the iodine cell onto a camera sensor and transferred into an intensity value. However, the spectral information on temperature, pressure, density and speed is lost as a result, because the camera captures only the integrated intensity values. In accordance with the fs-FRS method further developed by DLR Cologne, the frequency of the laser system is therefore varied in discrete steps along the filter curve of the iodine cell so that an intensity curve is created for each pixel.

Time-averaged pressure, temperature and velocity fields (Doppler shift) can be determined simultaneously from the resulting intensity spectra. The observing camera will detect the integrated convolution between the Rayleigh Spectra and the transmission curve of the iodine cell.

The temperature, pressure, speed and density can be reconstructed from this intensity curve using a suitable measurement model, which includes the Rayleigh scattering as well as the iodine absorption, compare Doll et al. (2018).

The FRS system consists of the components frequency-controlled laser, light section probe, light arm, camera module with iodine filter and CMOS camera as well as a multi-arm image fibre with individual front lenses. A schematic of the FRS system is depicted in Fig. 2. In order to allow simultaneous determination of three velocity components, the pressure and the static temperature, the measurement cross-section is viewed from six perspectives and imaged onto the sensor of a single camera. Due to the different observation direction of the individual cameras the observable Doppler shift which is dependent on the angle between the laser light and the observation, will be different, hence allowing for the reconstruction of the velocity vector. The FRS system with the dispersed fibre cameras at the testrig is displayed in Fig. 7. The viewing perspective of camera 5 is shown in Fig. 8. The FRS setup in working condition is depicted in Fig. 3.

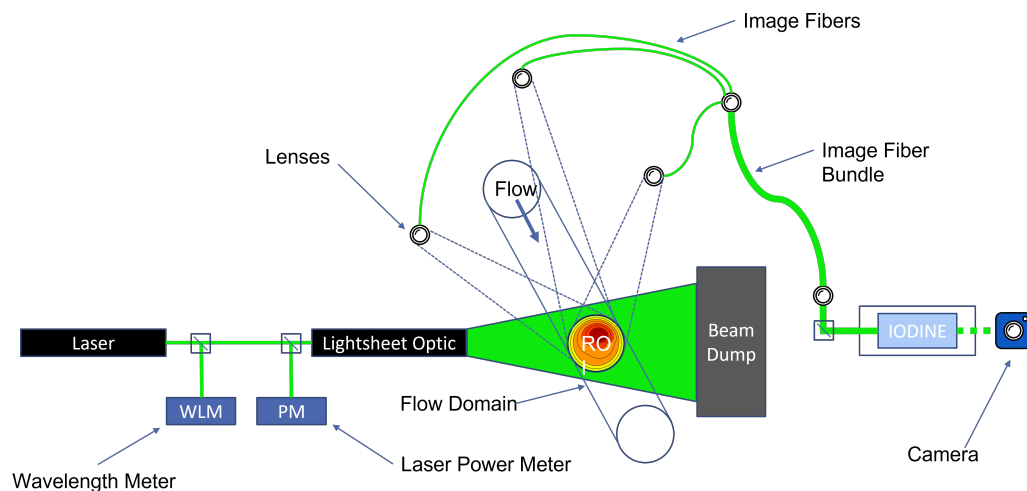


Figure 2. Schematic for the core components of the multiview fs-FRS system. For simplicity only 3 of the 6 image fiber branches with front lenses are displayed.

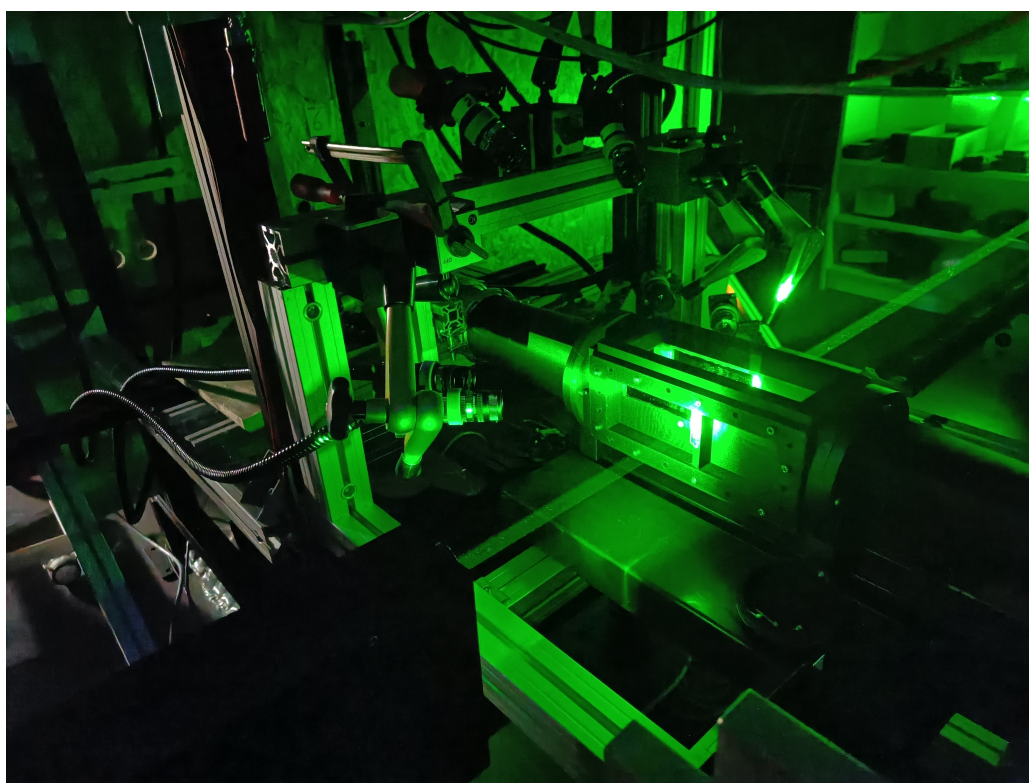


Figure 3. FRS setup capturing the flow situation downstream of the halfsphere. Flow direction right to left. Lightsheet generator in the lower left.

2. Pressure Sensitive Paint (PSP) Method

Coatings with pressure-sensitive paint (PSP) are the basis for imaging methods, allowing experimental determination of pressure distributions on a surface without influencing the investigated model surface. PSPs enable continuous measurement and visualization of flow and pressure fields with high spatial and temporal resolution. The photoluminescent PSP sensor is composed of a polymer binder (poly-4-tert-butyl styrene) with embedded dye molecule Pt (II)-tetrakis (pentafluorophenyl)porphyrine (PtTPFPP), which phosphorescence is quenched by oxygen. A detailed introduction to temperature-sensitive paints (TSP) and PSP techniques can be found in Liu et al. (2021). The governing equation for PSP measurements is the Stern-Volmer relation, compare Eq. (1):

$$\frac{I_{ref}}{I} = A + B \frac{p}{p_{ref}} \quad (1)$$

where:

- I_{ref} denotes the intensity at reference conditions,
- I is the intensity at measurement condition,
- A and B are constants determined during the calibration process,
- p_{ref} is the pressure at reference condition, and
- p is the pressure at measurement condition.

FH Münster (FHM) performed spectral calibrations with the PtTPFPP-dye covering the range from 10 *kPa* to 100 *kPa* at ambient temperature, see Fig. 4. To use the spectral calibrations in a imaging setup an integration of the curves displayed on the left side, respecting the applied filters is performed. As the phosphorescence lifetime of the dye is in the order of 50 μs , the exposure timing needs to be carefully controlled. The applied PSP dye also has a temperature dependency, however the here presented calibration and measurements were performed at ambient temperature, thus the effect can be neglected here.

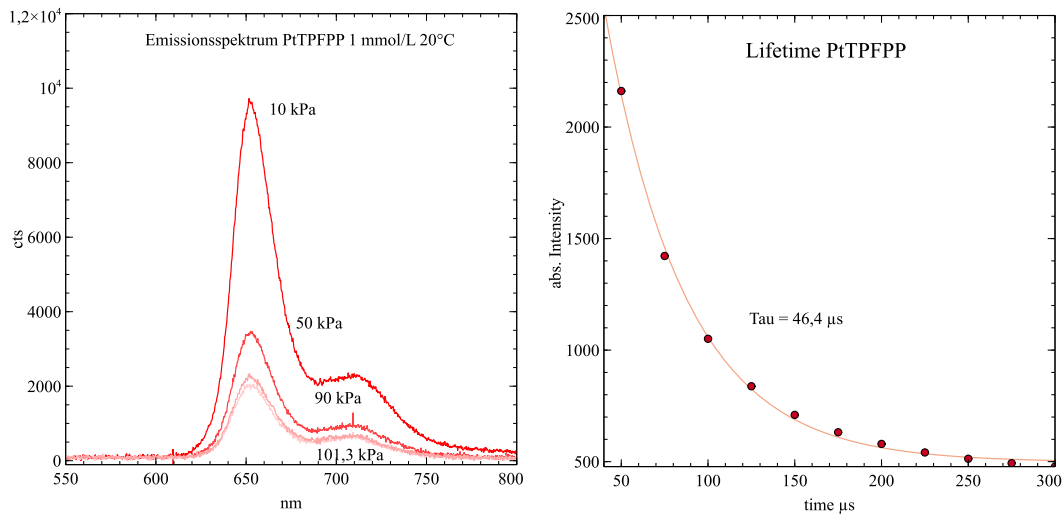


Figure 4. Left: Emission spectra of the applied PSP dye (Pressure calibration curves) at ambient temperature . The intensity of the emitted light is inverse proportional to the partial pressure of oxygen and hence also to the pressure of air. Right: Phosphorescence decay and calculated lifetime τ of the PtTPFPFPP dye.

The PSP measurement system consists of the following core components: sensor (PSP dye), lighting unit, synchronization unit, camera and evaluation software. The measurements shown were carried out using 3D printed thermoplastic models that were coated with the PSP color by FHM using a spray method. The experimental setup for performing PSP measurements is displayed in Fig. 5.

A modular LED unit by ILA R&D GmbH is used for illumination. This unit stands out for its short fall times ($<100 \text{ ns}$) and high light intensity. The PSP dye is excited with a 405 nm LED array. One LED array has a power of 12 W (cw). In pulsed operation emission at significantly higher power levels is possible. The effective maximum power for the pulse mode is essentially limited by the cooling of the LED.

The LED module allows for quick exchange of the LEDs, for example to adapt to another wavelength. Up to four LEDs/LED arrays can be controlled in parallel or individually. The parameterization and temporal sequence between lighting and camera are realized by a microcontroller-controlled synchronization unit. Optocouplers for the four digital input and output signals enable the application of the sequencer in industrial environments. The smallest adjustable time difference is $1 \mu s$. The shortest trigger time is $10 \mu s$. For even shorter timescales a FPGA-based synchronizer can be applied.

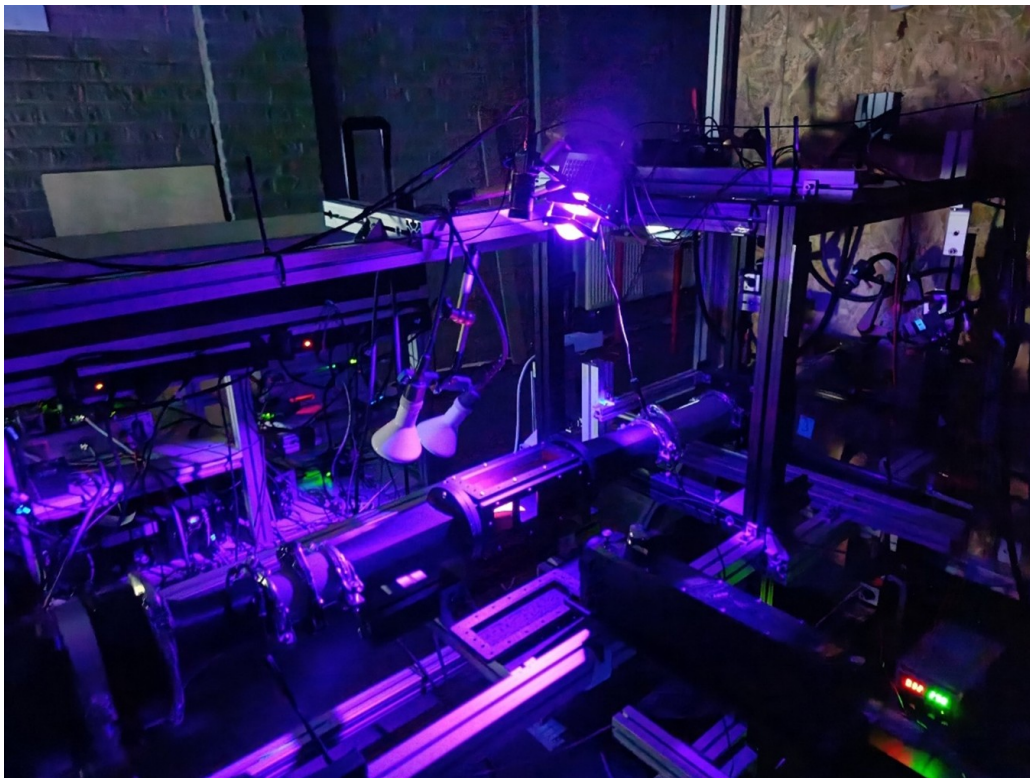


Figure 5. Teststand with the PSP setup and active LED illumination with $405nm$ from top. The flow direction is from left to right. The camera is located next to the illumination with a working distance of approximately 400 mm . In the lower right also the LDV Probe is visible.

The utilized global shutter camera (Backside Illuminated CMOS) allows frame rates of 55 Hz with a discretization of 12 bit at 2064×1544 pixels. At 8 bits, 115 Hz are possible in the same resolution. The pixel size is $3.45 \times 3.45\text{ }\mu\text{m}$. The quantum efficiency is specified as 65 % at 532 nm . The camera has a configurable output signal that can be synchronized with the active camera capture. This allows for documenting the actual time or time difference of the acquisition(s) in respect to the illumination. Exposure times range from $1\text{ }\mu\text{s}$ to 30 s . Noteworthy is that the camera also features a multi exposure mode, allowing measurements even at very weak signal levels (with reduced temporal resolution) to be carried out. The camera integrates multiple exposures directly on the CMOS chip in this mode.

3. Laser Doppler Velocimetry (LDV)

To obtain the velocity fields downstream of the halfsphere two different LDV systems are applied. A 2D LDV probe to capture the in-plane velocities and an industrial 1D probe (iLDV) to capture the main axial flow component. Both systems work in back-scattering configuration. The focal length for both systems is 250 mm . The LDV probes are mounted on a traversing system to reach the desired measuring positions inside the flow channel. For seeding Dioctyl sebacate (DEHS) droplets are inserted upstream of the flow conditioning section. The measuring positions for the measuring plane perpendicular to the axial flow direction are evenly spaced with a distance of $2.5 \times 2.5\text{ mm}$, totalling in 259 traversing positions. For the horizontal plane downstream of the halfsphere a $2 \times 2\text{ mm}$ grid has been applied with 438 sample positions.

The measurements have been carried out with a target of 500 Bursts per position. After recording the data for each measuring position is validated using additional quality criteria.

4. Experimental Setup

The test stand consists of an open wind tunnel with conditioned inflow. The wind tunnel is driven by a fan in suction configuration. Following the inlet nozzle, there is conditioning of the inflow through several strainers and subsequent narrowing of the flow cross-section, see Fig. 6. The cross-section of the square test chamber is $70 \times 70\text{ mm}$. The nominal wind tunnel speed in the measurement section is 60 m/s in the experiment. The flow in the test chamber can be observed through windows on up to four sides. Lateral insertions allow for positioning of airfoils or models at angles relative to the inflow between 0° and 15° .

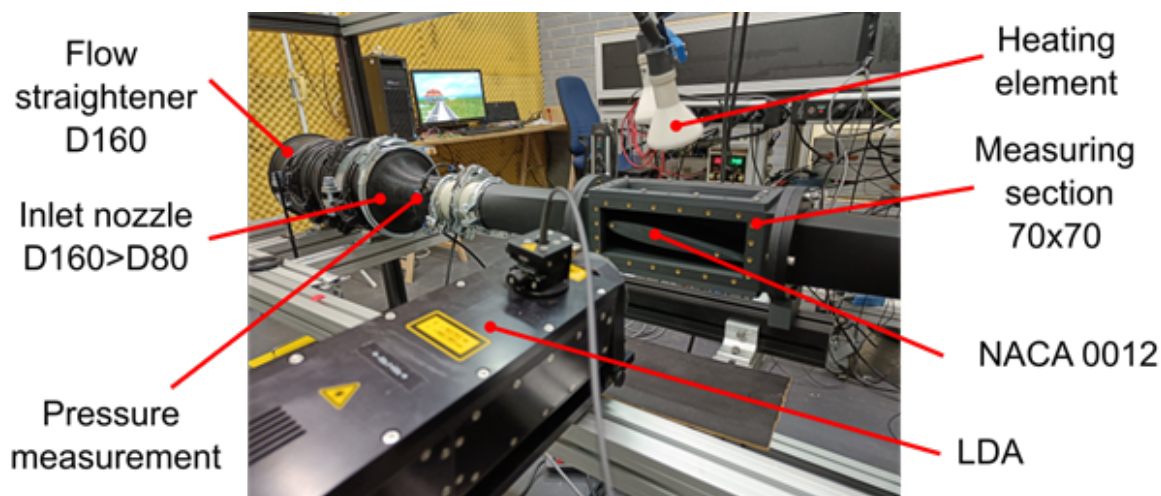


Figure 6. Overview of the flow section including LDV Setup for obtaining the reference velocity field. The displayed NACA 0012 profile is replaced with a flatplate with mounted semisphere in the measurements, compare also Fig. 9.

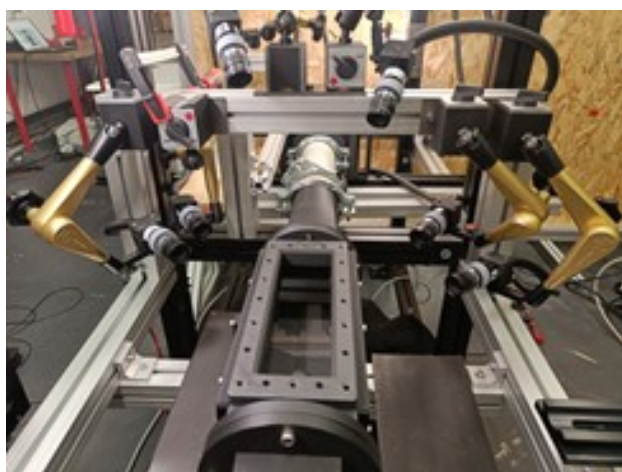


Figure 7. Optical setup of the FRS system with the 6 camera objectives and the corresponding image fibre. The view direction corresponds to the flow direction



Figure 8. Perspective view on the experiment through the right side window which is utilized by camera 5. Camera 6 offers a similar viewing angle albeit mirrored on the longitudinal axis.

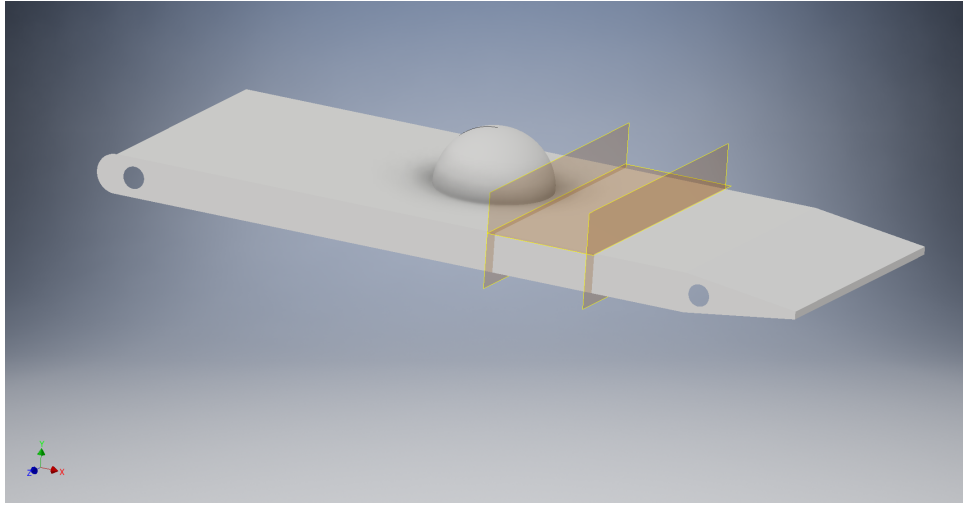


Figure 9. Geometric layout of the halfsphere experiment. The length of the mounting profile is 200 mm . The width is 70 mm . The diameter of the halfsphere is 30 mm ($1D$). The distance of the measuring planes to the trailing edge of the hemisphere are 3 mm ($0.1D$), respectively 30 mm ($1D$). The horizontal plane is located approximately 1 mm above the surface, starting 3 mm behind the semisphere. Flow direction from left to right. The flat plate is mounted with an angle of attack of 0° . For the PSP experiments the surface of the model is spray coated by with a PSP-dye by FHM. For the FRS and LDV experiments the model is replaced by an optical inert variant. The results from the upstream cross-section and the horizontal measurement plane are presented in this paper.

5. PSP Results

The retrieved surface pressure is displayed in Fig. 10. Flow direction is from left to right. At the start of the flat-plate (left) a pressure drop due to the acceleration of the flow can be located. In front of the semisphere a small stagnation area is visible. Over the surface of the halfsphere the tails of the horseshoe vortex system protruding to approximately $2.5 D$ downstreams are visible. This is consistent with the values shown by Wood et al. (2016).

The pressure above the sphere angle is displayed in Fig. 11. The overall shape of the pressure resembles roughly the shape of the c_p value as reported by Meas et al. (2021), compare Fig. 12. It is worth noting, that the c_p values presented by Meas et al. (2021) were obtained with a much lower blocking of the cross-section.

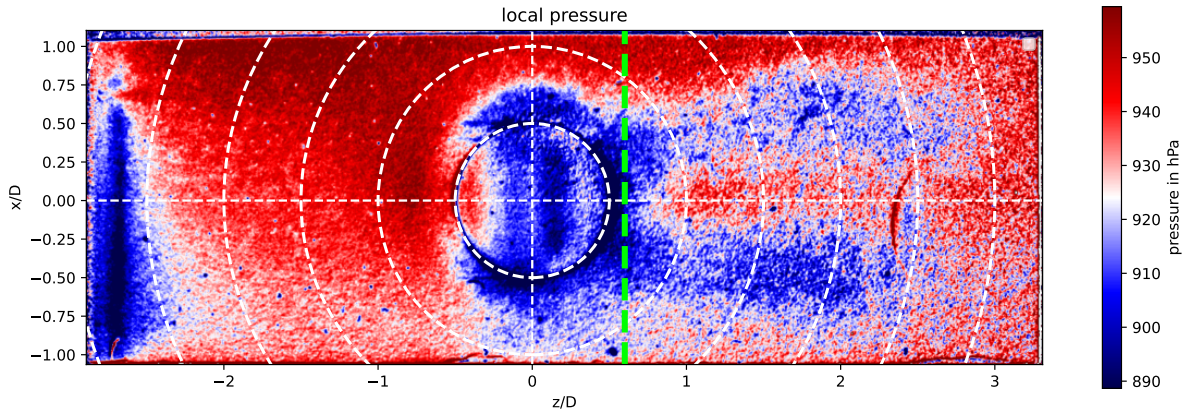


Figure 10. Distribution of surface pressure on the flat plate and the hemisphere, determined by PSP. Observation and illumination from the top. Flow direction from left to right. All coordinates in dimensionless sphere coordinates ($d=30\text{ mm}$). The green line denotes the position of the FRS- and LDV- measuring plane.

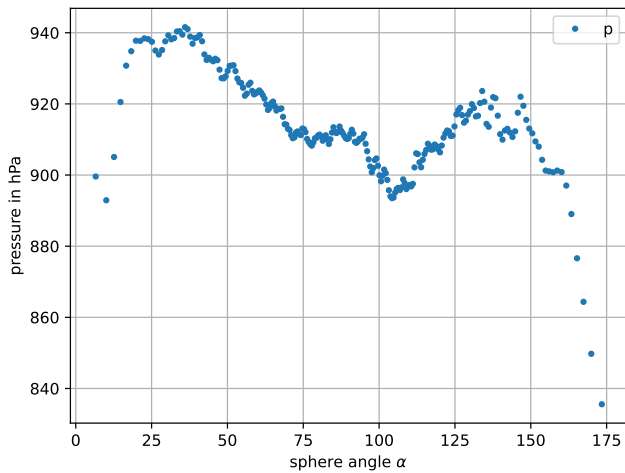


Figure 11. Plot of the observed pressure over the sphere angle α , at the centerline, derived by the PSP measurements.

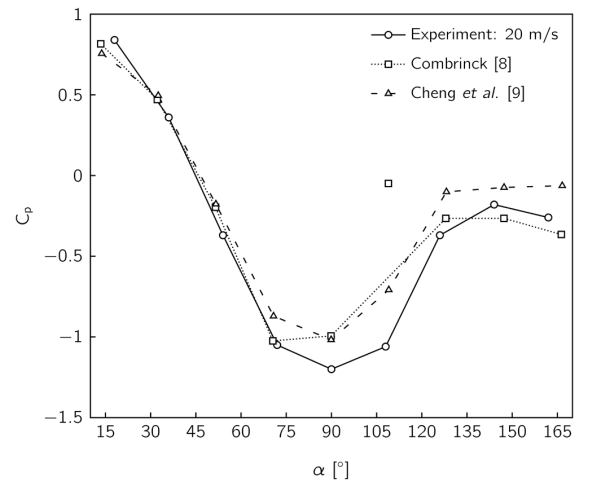


Figure 12. Plot of the observed c_p value over the sphere by Meas et al. (2021).

6. FRS Results

The axial velocity component in the cross-section $0.1D$ downstream of the hemisphere obtained with FRS is displayed in Fig. 13. The resolution in the computational domain is 2.5 pixel/mm . The central backflow region is observable. The position of the two wake systems at a x position of $\pm 10 \text{ mm}$ is clearly identified. Due to experimental constraints the lightsheet extended only to about 18 mm above the surface of the flat plate. However due to the blocking of the mie-scattering, measurements in the proximity of the wall were possible. The mean axial velocity in the FRS measurement region is determined to 47.6 m/s . The in-plane velocities are displayed as vectorplot in Fig. 15.

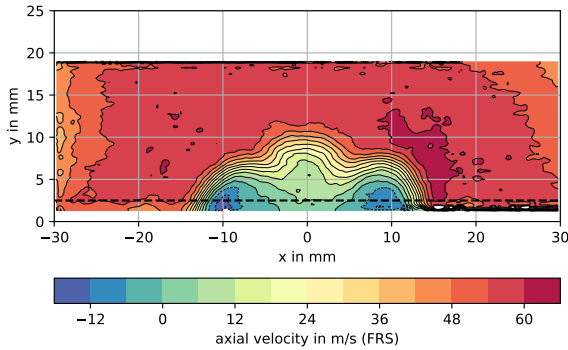


Figure 13. Contour-plot of the axial velocity obtained by FRS, in a cross-section $\approx 0.1D$ downstream of the hemisphere. The dashed line shows the section.

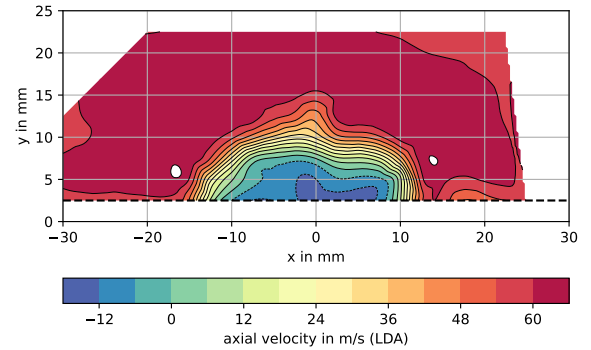


Figure 14. Contour-plot of the axial velocity obtained by LDV, in a cross-section $\approx 0.1D$ downstream of the hemisphere. The dashed line shows the cut section.

7. LDV Results

The axial velocity component in the cross-section $0.1 D$ downstream of the hemisphere obtained with LDV is displayed in Fig. 14. Within the validated measuring points a mean axial velocity of 51.04 m/s is determined. It is worth noting that the LDV and the FRS cover different portions of the cross-section. The mean axial ($1D$) turbulence is about 20% . The central back-flow region behind the hemisphere is clearly discernible. In comparison to the finer resolved FRS data, compare Fig. 13, the two wake systems are not resolved by the LDV data. In Fig. 16 a horizontal one dimensional cut through the LDV and FRS data is presented. The overall shape and the magnitude of the LDV and FRS velocity data show a high-degree of consistency. In general a slightly higher value for the magnitude of the velocity is present in the LDV-data. This effect is in the order of $3\text{-}5 \text{ m/s}$ for the main flow. For the core region behind the hemisphere higher values are observed. One possible

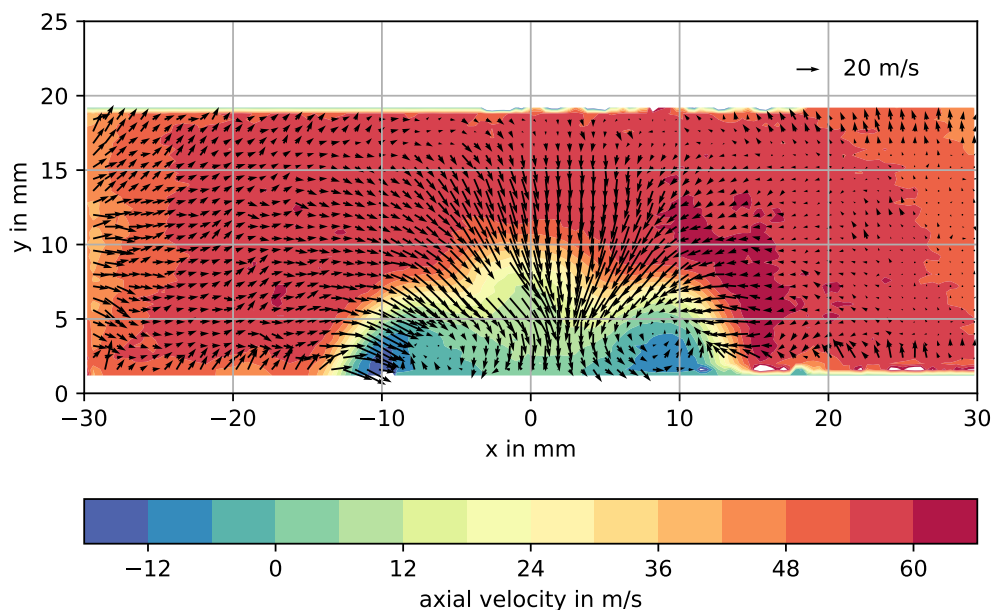


Figure 15. Vector-plot of the in-plane velocity obtained by FRS, in a cross-section $\approx 0.1D$ downstream of the halfsphere. The contourlines in the background are the axial velocity as depicted in Fig. 13.

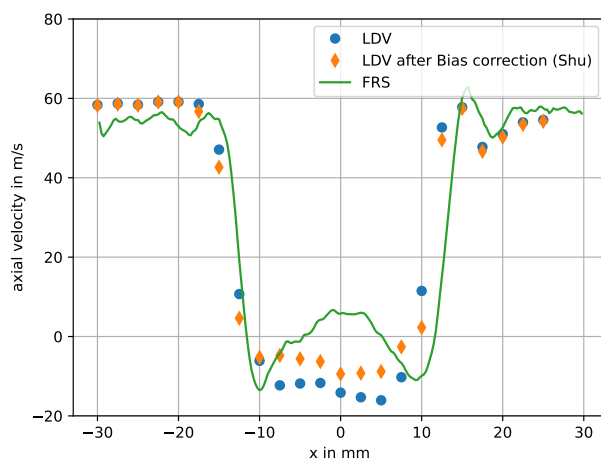


Figure 16. 1D cut of the axial velocity at $y = 2.5 \text{ mm}$. Raw LDV data is presented by the blue circles. The Bias-corrected axial LDV velocity according to Shu (2000) is displayed by the orange diamonds. The FRS velocity is denoted by the continuous green line.

explanation for this is the Velocity-Bias effect which is prone to appear at higher turbulence levels, especially at the core region. A rough estimation of the Bias effect based on the analytical solution by Shu (2000) is performed, compare Fig. 16. The Bias-correction is more pronounced in the core region where higher turbulence degrees are present. In the main region outside the 'shadow' of the halfsphere the shape and magnitude of the velocity vector remains nearly unchanged by the applied correction. The applied Bias correction method can not explain the remaining differences in the velocity field at the core region.

Although special care has been applied to enable a repeatable experimental setup, a slight change in the axial position remains possible. Even a small variation in the axial position will result in a visible change in the pressure and velocity field, compare also Fig. 10. Especially the trailing edges of the horseshoe vortex system can appear merged close to the halfsphere.

The axial velocity component in the horizontal plane downstream of the halfsphere is shown in Fig. 17. The mean axial velocity is here only 34 m/s , due to the proximity to the flat plate. The axial extension of the backflow region in the wake of the halfsphere is in the order 0.5 to $0.7 D$.

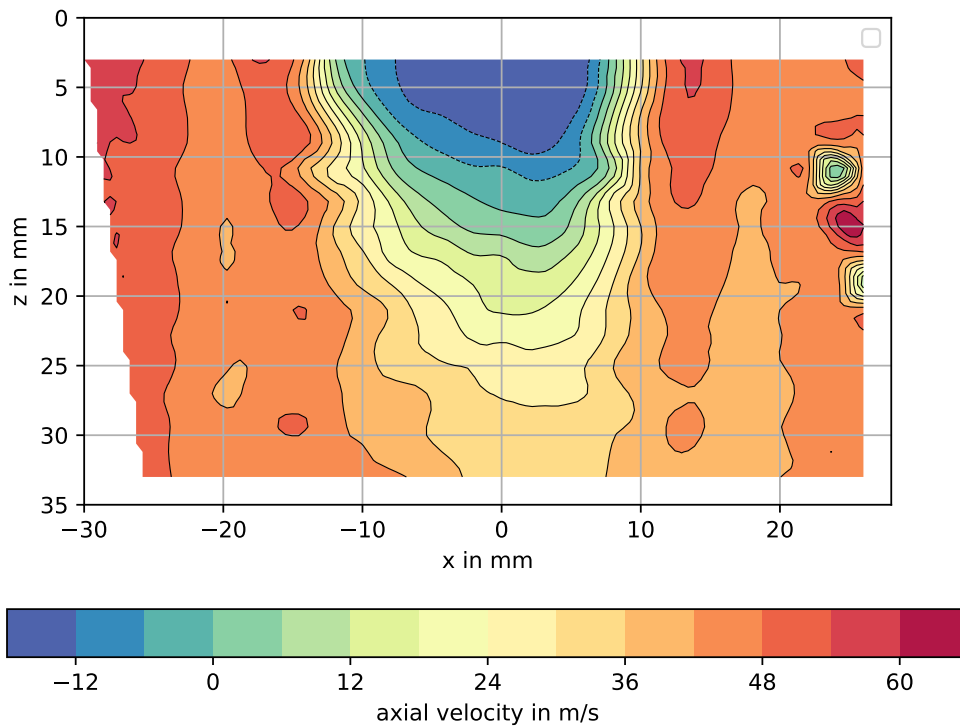


Figure 17. Contour-plot of the axial velocity obtained by LDV, in a horizontal plane 1 mm above the flat plate $\approx 0.1D$ downstream of the halfsphere.

8. A note on the interoperability of the applied techniques

The PSP and FRS techniques both enable the obtainment of planar data. PSP delivers data from the surface while FRS delivers data from within the respective measuring plane. For the results presented here the fs-FRS technique applies a frequency scan through 37 frequencies, resulting in 37 images. This limits the temporal resolution in comparison to the applied PSP technique. However, recent developments by Doll et al. (2024) and Doll et al. (2023) show single frequency measurements are feasible with only a moderate loss in accuracy. The PSP coating is very sensitive to contamination and can degrade due to overexposure. Therefore, the measurements with the relative high power FRS light sheet and the concentrated LDV beams are performed on an optical inert geometrical twin of the setup. Due to the seeding requirements of the LDV technique and the inevitable contamination of the test rig with seeding particles it is recommended to perform LDV measurements as a last step. The LDV technique can enhance the temporal resolution within a relatively small confined measurement volume, while delivering state of the art velocity uncertainty for regions of low turbulence. It is recommended to assure that the exchange of the model does not change the relative geometrical position by alignment pins or other means.

9. Conclusions

The here presented results of the pressure and flow velocity around and on the surface of a hemisphere are obtained with the optical PSP, fs-FRS and LDV techniques. It is understood that each of the applied technique can augment to the overall picture of the examined flow setup. While each of the methods has its strength and weaknesses in combination they enable a comprehensive mapping of the flow situation e.g., as reference for the validation of CFD simulations.

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