Development of an optical multi-purpose sensor using filtered scattered light

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Technical breakthroughs and rapid progress in laser science and related optical components like fibers, filters and detectors have enabled the development of various optical sensors. Especially velocity measurement techniques like LDA or L2F are state-of-the-art techniques and also as probes available. Therefore they are suitable to determine physical properties even in environments with limited access. Another advantage of these optical sensors is the non-intrusive use in the sense that they don't disturb the flow environment through the presence of a probe body. While these velocity sensors are widely used a compact and reliable optical probe capable of measuring the temperature or pressure inside a given flow volume is still work in progress.

One possible solution is the extraction of the temperature information from the spectral profiles of Rayleigh and Brillouin scattered light from gases and liquids respectively as demonstrated by LiDAR systems [1, 2]. To eliminate the disturbing influences from surfaces, dust or suspended particles we propose the use of a molecular filter in form of an iodine absorption cell in combination with these spectroscopic methods. Together with scanning the frequency of the used laser source through the extended minimum of a suitable absorption line filtered Rayleigh and Brillouin scattering (FRS and FBS) are capable of rejecting high levels of stray light from unwanted sources while preserving the spectral information about the physical properties to be measured [3]. When tuning the laser frequency to the slope of the absorption line the velocity component along the line of sight can be obtained by analyzing the Doppler frequency shift from the scattered Mie signal of particles carried with the flow [4].

Fig.1 Layout of the optical multi-purpose sensor for collecting backscattered light

Fig. 1 outlines a possible realization on of an optical sensor for temperature and velocity measurement in a backscatter mode of operation. Laser light is transported via a single-mode polarization maintaining photonic crystal fiber PF, collimated and focused with lenses L1 and L2 into the measurement volume V. Due to the use of a single lens for both focusing and collection, light scattered only from this volume can be refocused with L3 into a second multi-mode receiving fiber RF which transports the collected signal light to the analyzer unit. This confocal arrangement works as a spatial filter to enable measurements in the presence of high background light levels such as in near wall environments. The analyzer unit contains an iodine absorption cell and a pair of photomultiplier tubes to allow density normalization for Mie signals. The use of an interference filter with a FWHM of 1nm blocks all unwanted contributions from broadband background light sources and also most of the Raman components.

Filtered Rayleigh scattering (FRS)

For determination of gaseous flow properties the laser frequency is tuned to a sufficiently strong absorption line to reject all possible contributions from particles. Only the spectral wings of the Rayleigh part reach the detector unit. Scanning the laser frequency through the regions where the absorption is sufficient strong to suppress all disturbing Mie signals the recorded FRS spectrum can be used to extract temperature and pressure values by applying a least-square-fit procedure to describe the experimental data with a suitable model (e.g. Tenti S6 [3]).

Filtered Brillouin scattering (FBS)

The scattering spectrum in liquids like water consists of two pronounced Brillouin peaks accompanied by a much weaker Rayleigh signal. The latter signal and the contributions of suspended particles are effectively blocked analogous to the Mie signals in case of FRS. Furthermore the typical Raman signal which is shifted around 100nm from the laser line is easily blocked by the interference filter in the analyzer unit. The distance from both Brillouin lines to the laser frequency and their width are dependent on the temperature and therefore the remaining signal can be used to measure this property of the liquid.

Filtered Mie scattering (FMS)

Although Rayleigh and Brillouin spectra are also shifted by the Doppler effect the possible frequency resolution with FRS and FBS is not sufficient due to their spectral width especially for resolving small shifts in the order of a few MHz. But in the presence of suitable particles in the flow the laser frequency can be tuned to the slope of the absorption line while decreasing the sensitivity of the detectors in order to account for the stronger Mie signals. This allows the operation as a velocity sensor since a frequency change due to the Doppler Effect can be measured as a transmission change in the analyzer unit. With this backscatter arrangement the sensor determines the line-of-sight component of the flow velocity.

Table 1 summarizes the performance of the sensor with respect to different test cases. The best accuracies were obtained for temperature measurements in water. The results for air are also encouraging and we will further characterize the probe in future applications like near wall measurements or duct experiments.

<table>
<thead>
<tr>
<th>Tech.</th>
<th>Medium</th>
<th>P(bar)</th>
<th>T(K)</th>
<th>V(m/s)</th>
<th>Rel.Acc.(%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>FRS</td>
<td>air</td>
<td>1</td>
<td>300-350</td>
<td>0</td>
<td>1-2</td>
</tr>
<tr>
<td>FRS</td>
<td>air</td>
<td>1-10</td>
<td>300</td>
<td>0</td>
<td>2</td>
</tr>
<tr>
<td>FRS</td>
<td>water</td>
<td>300-350</td>
<td>0</td>
<td>&lt;0.3</td>
<td></td>
</tr>
<tr>
<td>FMS</td>
<td>air+seed</td>
<td>300</td>
<td>0-100</td>
<td>1</td>
<td></td>
</tr>
</tbody>
</table>

Table 1 Summary of the sensor performance for different test cases