Application of the structured laser illumination to planar optical diagnostics of the flows with nonuniform density

D Sharaborin1,2, R Tolstoguzov1,2 and E Frolova2

1Kutateladze Institute of Thermophysics, 1 Ak. Lavrentyeva Avenue, Novosibirsk, 630090, Russia
2Novosibirsk State University, 2 Pirogova Str., Novosibirsk, 630090, Russia

E-mail: sharaborin.d@gmail.com

Abstract The aim of this work was to develop a method of panoramic optical diagnostics of the inhomogeneity of the density field in stratified flows based on the registration of the distribution of the Rayleigh scattering intensity using structured laser radiation. Several approaches have been implemented for organizing spatial modulation of laser illumination, intended for use with various values of the incident radiation energy density. To test the processing and reconstruction algorithms of the experimental data, a series of measurements was carried out using the method of planar laser-induced fluorescence. The distribution of local density in a jet of carbon dioxide flowing into atmospheric air was measured experimentally using a method based on the registration of Rayleigh scattering.

1. Introduction

Nowadays, numerical simulation is widely used for modeling of flows in the development and design of efficient and environmentally friendly combustion chambers and burners. The calculation of flows with combustion is a nontrivial problem, which requires the simulation of the hydrodynamic structure of the flow, taking into account local thermal emissions and non-uniform densities fields. In addition, this task is motivated by the fact that it is necessary to carry out calculations of tens and hundreds of intermediate chemical reactions occurring in the combustion process at each node of the computational grid. Such complications of the models lead to a significant increase in the required computing power and calculation time. Also, it should be noted that the introduction of new numerical models is impossible without their precise verification. Thus, the use of experimental research methods is a more effective approach (in terms of time and resources) in case of turbulent flows with combustion, rather than numerical simulation methods. Currently there are several approaches based on the use of laser radiation to measure temperature or density distribution in combustion systems: Rayleigh scattering [1], spontaneous Raman scattering [2], laser fluorescence [3]. The LIF method uses generally OH radicals [4, 5], also NO [6, 7] or the addition of labeled molecules/atoms [8] as temperature indicators. All these methods have their limitations for use in technical systems with combustion, in case of at least one of the following factors: spatial resolution, measurement area size, pressure, the presence of particles, toxicity, and often underestimated high price.

The structured illumination method of visualization was first introduced in 1997 in microscopy [9]. A distinctive feature of this method is ability to eliminate defocused light, which impairs the
partitioning ability of optical devices within the line of sight. Over time, this technique has gained rapid development and widespread use in other areas [10-12]. Gustafsson illustrated that the method can be used to overcome the diffraction limit, reaching theoretically unlimited resolution [13, 14]. Most publications about structured illumination are concerned with a microscopic image, but the technique has also found popularity outside of this area. Cortizo et al. used a structured light source to study the topography of the sole of the foot during a walk [15], while Kristensson et al. implemented a method for studying the dynamic flow of water droplets [16] and Rayleigh scattering thermometry [17].

The main aim of present paper is to develop a method of planar optical diagnostic of the nonuniformity of density and temperature fields in stratified flows based on the registration of the Rayleigh scattering intensity distribution.

2. Experimental setup

For the purpose of testing the reconstruction algorithms and processing of experimental data measurements were performed using the methods of planar laser-induced fluorescence (LIF) and Rayleigh scattering in combination with a structured laser illumination. In the first case, a drop of a fluorescent dye Rhodamine 6G dissolving in pure alcohol as a test object was investigated using the LIF method. In the second case, the method of Rayleigh scattering was used to study a round jet of carbon dioxide flowing into the atmospheric air at constant temperature.

Sketch of the experimental setup for LIF and Rayleigh measurements is shown in figure 1. The second harmonic of a pulsed Nd:YAG lasers Beamtech Vlite 200 and Quanta-Ray was used as excitation radiation. The energy of 6 ns laser pulses was monitored by an energy meter (Coherent LabMax-TOP). On average, the energy was 60 and 700 mJ for LIF and Rayleigh measurements, respectively, with 5% RMS fluctuations. A system of focusing and collimating optics was used to form a laser sheet 50 mm wide and less than 0.8 mm thick in the measurement area. For registration the LIF signal, a 16-bit ICCD camera (Princeton instruments PI-MAX-4, resolution: 2560 × 2160 pixels) equipped with a multi-notch holographic filter to block the emission at laser wavelength. The intensity of the Rayleigh scattering signal in the jet was recorded using an image intensifier with a multichannel amplifier (LaVision IRO) with a S20 photocathode (multialkali). After amplification, the phosphor coating of the intensifier illuminated a hybrid CCD-CMOS matrix (Imager sCMOS) of a 16-bit camera (resolution: 2560 × 2160 pixels, pixel size: 6.5 × 6.5 μm).

Two Ronchi grating with different line spacing were used to create a structured laser illumination in the first experimental study. The grating was placed close to the measurement area in the path of the laser sheet after collimating optics. Line spacing of 50 lines/inch and 5 lines/mm allowed to collect

**Figure 1.** Sketch and photography of the experimental setup for LIF (left) and Rayleigh (right) measurements.
several data sets necessary for the development of the processing algorithms. Examples of LIF signal raw data in a drop of Rhodamine 6G excited by structured laser sheet are shown in figure 2.

A round jet of carbon dioxide flowing into the atmospheric air was organized using a contraction nozzle (with the exit diameter $d = 10$ mm). The Reynolds number $Re$ was 5300 with volumetric flow rate. To protect the Rayleigh scattering signal recording system from the negative effect of the Mie scattering on dust particles around the carbon dioxide jet, an air co-flow was created. Spatial modulation of laser illumination using Ronchi gratings in the case of Rayleigh scattering measurements was impossible because the high density of laser energy in the sheet leads to the destruction of the grating (the grating bands evaporated from the substrate). Thus, to create a structured laser illumination, a diffraction grating placed between the focusing lens and the collimating optical system.

![Figure 2](image)

**Figure 2.** Raw data examples of LIF signal of a drop of Rhodamine 6G (left) and profiles in the selected image area with periodic signal (right).

3. **Data processing and reconstruction approach**

In most practical applications of Rayleigh scattering, for example, in engines, gas turbines or other combustion techniques, where a laser beam passes through optical windows. The main source of errors and the limiting factor for Rayleigh scattering is associated with the detection of scattered light – interference, including all the parasitic light obtained by the camera [18]. Rayleigh scattering is particularly sensitive to extraneous light noise for two reasons: (1) the Rayleigh signal is not wavelength shifted (this means that using optical filters to suppress, for example, laser light reflections is impossible) and (2) Rayleigh scattering is relatively weak compared to scattering from particles of dust and droplets (i.e., Mie scattering), which significantly exceed Rayleigh scattering intensity. In addition, the complexity of applying the LRS method in combustion processes caused by high temperature and, consequently, low numerical density, that lead to a low signal-to-noise ratio. Thus,
all intensity contributions from other sources – reflections, flame emissions, Mie scattering on dust particles, etc. – have strong impact on the accuracy of measurements. The accuracy of the method depends on (1) the ability to accurately subtract the representative two dimensional field of background intensity, (2) preventing the creation of this unwanted light source. Unfortunately, none of the solutions are easy to use.

To provide a structured laser illumination, a laser sheet first passes through the Ronchi grating and then goes to the sample. The grating leaves a structural imprint on the profile laser sheet – sinusoidal modulation with a well-defined spatial frequency and phase. Photons that are scattered from the laser sheet directly to the camera (signal photons) retain this structure, while all background sources are displayed as offset (sharp or scattered) in the recorded image. The different characteristics of the two components of the image allow to remove unwanted offsets, which can be achieved in two ways. It is common practice to record three modulated images of a sheet of laser radiation, between which the modulation phase shifted by 120 degrees [9]. In another way, an image with a periodic signal component can be processed to eliminate background and noise using a discrete Fourier transform. The resulting spectrum shows peaks corresponding to the superimposed frequency of the structured laser illumination. For the presented data, the background, highlights, reflections and noise in the image is in the low-frequency range of the spectrum. Figure 3 shows an example of a sequence of image processing steps with a structured laser illumination. In the first step, using a discrete Fourier transform, we create a spectrum, figure 3 (left). Further, on the basis of the obtained spectrum, the frequency of the superimposed modulation is extracted. Sources of background are contained in the region of the spectrum between the peaks corresponding to the superimposed modulation, figure 3 (center). The spectral regions with a frequency equal to the frequency of the superimposed modulation and higher are shifted in such a way that the modulation peak takes the position of the zero mode, figure 3 (right). At the last stage of the data processing, the image is reconstructed using the inverse Fourier transform.

Figure 3. An example of processing stages of the Fourier spectrum. Original Fourier spectrum (left), low frequency region of the spectrum that contains the background signal (center) and Fourier spectrum after shifting superimposed modulation peaks into the position of the zero mode (right).

4. Results

Using the approach described before, the experimental data obtained by the LIF method of a drop of Rhodamine 6G in pure alcohol were processed and reconstructed. Raw data of LIF signal, processed Fourier spectrum and reconstructed image of a drop of Rhodamine 6G with spacing of Ronchi grating 5 lines/mm and 50 lines/inch are shown in figure 4 and figure 5 respectively. For both cases, a series of peaks are observed in the Fourier spectrum with frequency multiple to the frequency of the superimposed modulation. The presence of additional peaks in the spectrum leads to the formation of the same structure of the modulated signal as in the original data in the reconstructed image. In addition, the reconstructed image shows a significant decrease in signal intensity and the presence of
large blurry spots (bright areas that are not in the original image). In order to eliminate the effect of additional peaks on the reconstructed image, a narrowband low-pass filter is imposed on the spectrum before applying the inverse Fourier transform. An example of a reconstructed image without and with filtering is shown in figure 6.

Figure 4. Raw data of LIF signal (left), shifted Fourier spectrum (center) and reconstructed image (right) of a drop of Rhodamine 6G with line spacing of Ronchi grating 5 lines/mm.

Figure 5. Raw data of LIF signal (left), shifted Fourier spectrum (center) and reconstructed image (right) of a drop of Rhodamine 6G with line spacing of Ronchi grating 50 lines/inch.

Figure 6. An example of a reconstructed image without (left) and with filtering (right).

Raw data of Rayleigh scattering signal and reconstructed image of a jet of carbon dioxide flowing into atmospheric air are shown in figure 7. Scales normalized to the same value of the signal intensity
are shown below the images. In contrast to the results obtained for the LIF measurements, the reconstructed image for the Rayleigh scattering method shows an extreme decrease in signal intensity. The reason for this loss of signal intensity may be that the structured laser sheet is formed using diffraction grating. The interference pattern that is formed in the study area distributes the laser energy, and hence the signal intensity, not over a single modulation frequency, but over the set. Only one frequency is selected in processing and information about the others is lost.

![Figure 7](image)

**Figure 7.** Raw data of Rayleigh scattering signal (left) and reconstructed image (right) of a jet of carbon dioxide.

5. Conclusion

In this work, several approaches have been implemented for organizing spatial modulation of laser illumination, intended for use with various values of the incident radiation energy density. To test the processing and reconstruction algorithms of the experimental data, a series of measurements was carried out using the method of planar laser-induced fluorescence. The distribution of local density in a jet of carbon dioxide flowing into atmospheric air was measured experimentally using a method based on the registration of Rayleigh scattering. These results were used to debug the measuring system and data processing algorithms under conditions of high energy density of laser radiation and to record a low-intensity signal. The results indicate the need for further development of the method, including approaches for the formation of structured laser illumination. In this study, the use of a diffraction grating led to an excessively low signal intensity, comparable to the noise level in the reconstructed image.

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