100-kHz rate Rayleigh Imaging for Combustion and Flow Diagnostics

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Two-dimensional (2D) Rayleigh scattering (RS) imaging at an ultrahigh repetition rate of 100 kHz is demonstrated in non-reacting and reacting flows employing a high-energy burst-mode laser system. Image sequences of flow mixture fraction were directly derived from high-speed RS images. Additionally, a 2D instantaneous flow velocity field at 100 kHz was obtained through optical-flow-based analysis of the RS images. The technique was also applied to study turbulent flames having a near-constant Rayleigh cross section. The demonstrated high-speed RS technique in conjunction with optical-flow-based analysis provides non-intrusive, simultaneous measurements of the flow mixing and velocity field, extending the measurement capability of the RS technique to high-speed non-reacting and reacting flows.

Simultaneous measurements of multiple parameters of flow fields, such as density (ρ), temperature (*T*), and velocity (*v*), are highly desired for the characterization of high-speed turbulent flows. However, such measurements often involve multiple laser diagnostic techniques, often making their experimental setups and procedures complicated. For example, simultaneous particle imaging velocimetry (PIV)/planar laser-induced fluorescence (PLIF) [1, 2], Rayleigh/PLIF [3, 4], and PIV/Raman scattering [5] have been used to quantitatively measure simultaneous velocity/species concentrations, density/species concentrations, and velocity/temperature, respectively. The velocity field, one of the most important flow properties, is typically obtained by PIV, which requires particle seeding and often needs delicate optical arrangements for compatibility with other optical diagnostic tools. Other velocimetry techniques such as molecular tagging velocimetry (MTV) [6] normally need multiple laser beams as well as the seeding of gas into the flow, or they do not provide the 2D velocity field [7–9].

Rayleigh scattering (RS) has been widely used to provide non-intrusive, spatially and temporally resolved measurements of flow density, temperature, velocity, and mixture fractions in non-reacting and reacting flows [10]. This technique has been employed extensively as a diagnostic method in flow and combustion facilities for the following reasons: 1) ease of experimental setup with a single-beam approach, 2) high spatial resolution, 3) possible extension from 1D (line) to 2D or even 3D measurements, and 4) single-ended detection capability. The flow density or mixture fraction can be directly derived from the scattering intensity. By adding an atomic vapor filter or etalon, the Doppler shift of the scattered light can be detected from filtered RS images to obtain the 2D flow velocity fields [10]. Because of the small Rayleigh cross-section and low molecular density in the gas phases, a high-energy laser beam (approximately hundreds of millijoules) is required for RS gas sensing. Typical gas-phase RS measurements were performed at a repetition rate of 10–20 Hz by using high-energy, low-repetition-rate, pulsed Nd:YAG lasers. However, these measurement rates are insufficient for investigating highly turbulent and transient

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flow dynamics to provide valuable data for high-speed flow modeling. Typically, for supersonic and hypersonic flow diagnostics, an RS measurement frequency of 100 kHz or higher is required to track the flow dynamics.

High-speed RS is limited by the availability of laser sources. High-speed diode-pumped solid-state (DPSS) lasers normally have pulse energies of 2–20 mJ/pulse at a repetition rate of 10 kHz, which is insufficient for 2D RS measurements in gases. Continuous-wave (CW) lasers have been applied for kHz-rate RS flow measurements with relatively long time-integration (30 µs) [11], but instantaneous (e.g., with time exposures <100 ns) RS measurements at a rate of 100 kHz or higher for resolving the time scales associated with high-speed turbulent-flow phenomena is a challenge. To our knowledge, high-repetition-rate, high-energy burst-mode lasers are currently the most suitable laser source for high-speed 2D Rayleigh imaging because of the high laser energy required. Several burst-mode-laser-based measurements have been reported, including measurements of scattering in seeded CO_2 ice fog with 0.4 mJ/pulse [12] and 10-kHz Rayleigh scattering in combustion [13]. However, the measurement of flow structure evolution in the pure gas phase at a repetition rate of 100 kHz or higher, which is necessary for supersonic and hypersonic flow diagnostics, has not been reported yet.

In this paper, we demonstrate 2D Rayleigh imaging at a 100-kHz rate in various flow conditions to simultaneously measure flow mixture fraction and velocity fields by using a burst-mode laser and a high-speed camera. With a burst duration of up to 10 ms, hundreds of consecutive images were obtained. A 2D mixture fraction profile was directly derived from the RS intensity image. Furthermore, with high-speed RS detection, a 2D velocity field was obtained by using optical flow methods [14]. The method can be regarded as Rayleigh scattering imaging velocimetry (RIV). The technique is applied to a turbulent jet flame as a further application.

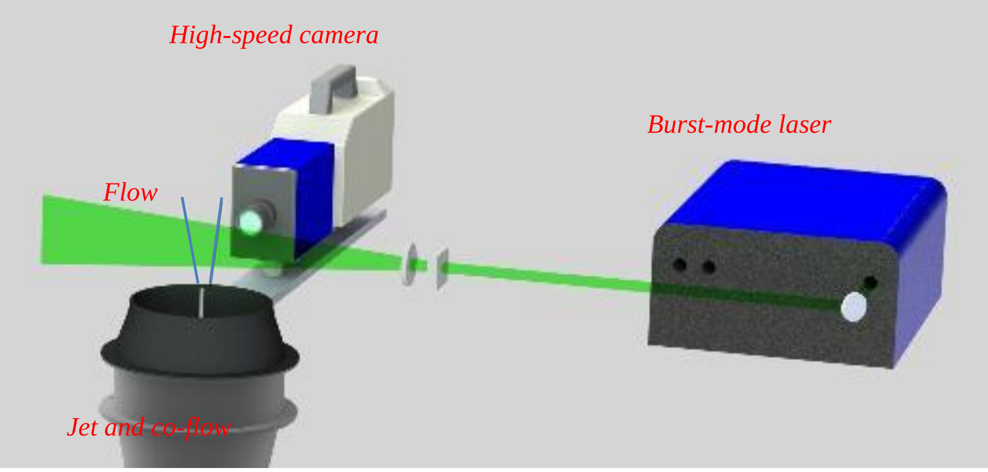

Fig. 1. Schematic diagram of the experimental setup for 2D Rayleigh scattering at a repetition rate of 100 kHz.

As shown in Figure 1, a burst-mode laser (Quasimodo, Spectral Energies) with second harmonics at 532 nm was used for Rayleigh scattering. The repetition rate of the laser was set at 100 kHz, and the pulse energy was ~100 mJ/pulse. A cylindrical lens (f1 = -75 mm) and a spherical lens (f2 = +400 mm) were used to generate a laser sheet, 100 mm in height and 100 µm in thickness, focusing inside a free jet. Only the uniform center part, ~40 mm in height, of the beam was selected for Rayleigh scattering. A high-speed 12-bit Photron SA-Z camera and a LaVision IRO intensifier were used for capturing the high-speed RS images. The camera featured Nikon f/1.8 lenses with a focal length of 50 mm. An 8-mm circular tube was used to generate the free jet. The jet is surrounded by low-speed 0.3-m-diameter co-flow to eliminate the dust particles and other disturbances from the room. Propane and helium were used to prepare gases with varying densities by mixing with air. Other gases and flow conditions could be used as well in supersonic or hypersonic flows as long as sufficient flow patterns are created for velocity-field analysis. The optical flow method was used here for flow velocimetry analysis since it has a better accuracy for short displacements [14, 15] than for long displacements of the flow structures between two consecutive images, and high-speed (100-kHz rate) Rayleigh imaging is advantageous for the optical flow analysis. In contrast, conventional low-speed (10 Hz – 10 kHz) imaging cannot provide the required correlations (< 3 pixels) for optical flow analysis among RS images, except in low-speed flows.

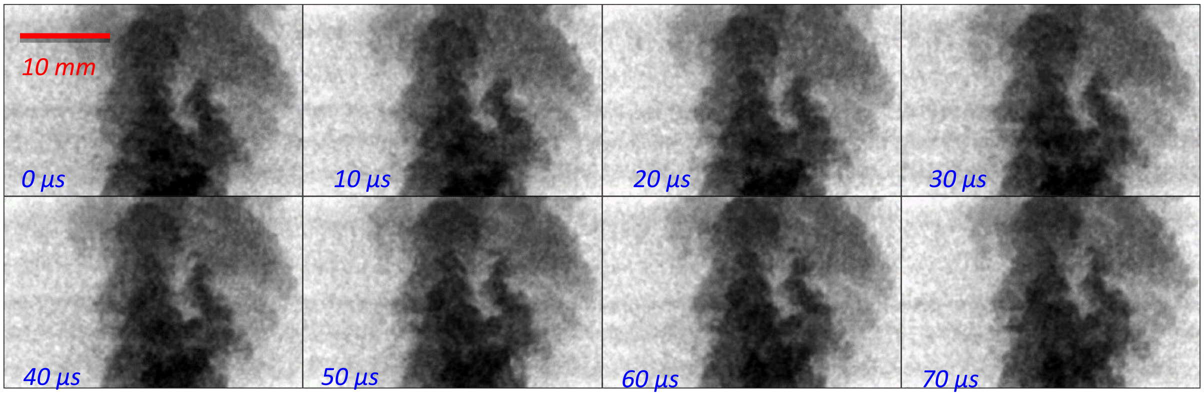

Fig. 2. Raw 100-kHz rate RS image sequence of a helium jet flow into air.

Figure 2 shows raw sequential images of 100-kHz-rate RS from the free helium jet into ambient air. RS images with 10-µs time separation are selected here to show the movement of flow structures. The flow rate was set at 400 SLPM (standard liters per minute). Experiments were conducted for helium flow rates of 100–500 SLPM, corresponding to an average estimated flow speed of 33–165 m/s at the nozzle exit. The field of view is ~20 mm (H) × 30 mm (W), and the jet exit is ~20 mm away from the bottom of the images. With ~60% of the maximum intensifier gain, the air co-flow signal intensity reaches 90% of the camera's saturation intensity level of 4096 counts. The mean signal-to-noise ratio (SNR) is ~30:1. The helium flow structures could be easily tracked from the Rayleigh image sequence. The helium air mixture fraction could be easily calculated from these RS images. Rayleigh scattering cross sections for helium and air [12], background subtraction, and beam-profile normalization were counted for mixture fraction calculation. Figure 3 shows an example of the mixture fraction image sequence. To show the movement of the flow structures, different images were selected and shown here from the same sequence. The flow structures indicated by red circles could be easily tracked by optical flow analysis.

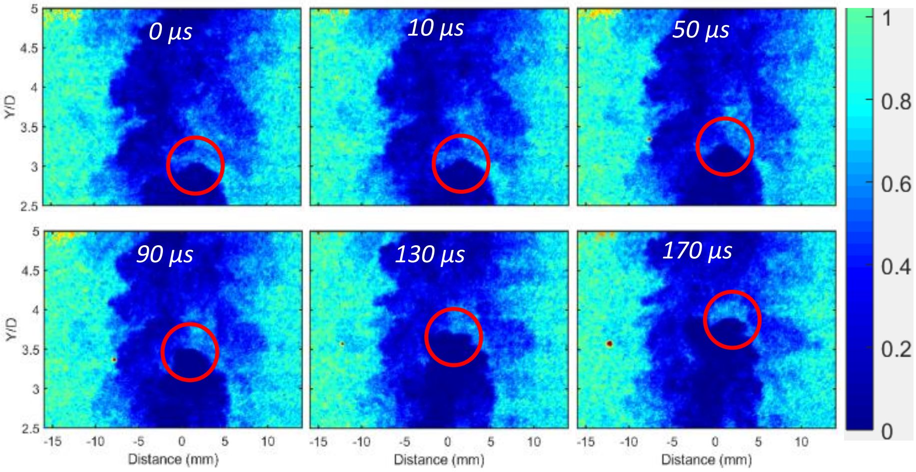

Fig. 3. Image sequence of mixture fractions of a helium jet flow into air.

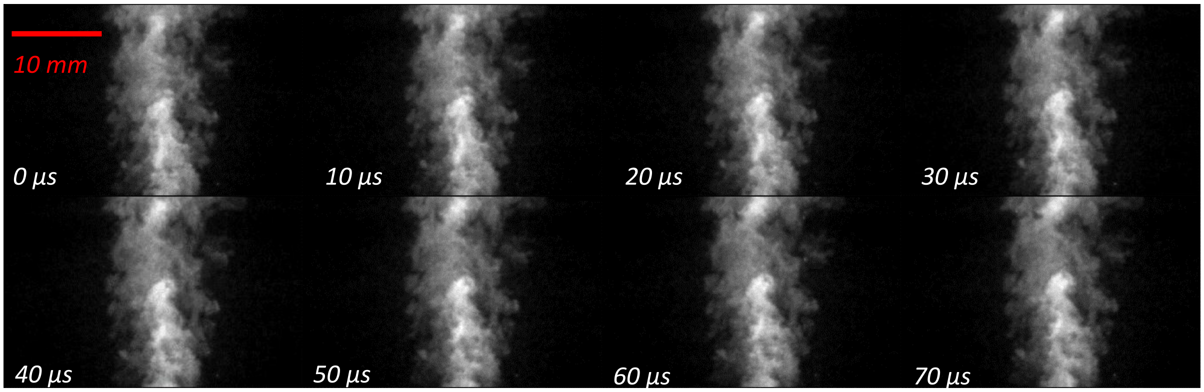

Fig. 4. Image sequence of a propane jet flow into air at a repetition rate of 100 kHz.

Figure 4 shows sequential images of 100-kHz-rate RS from the free propane jet into ambient air at 20 SLPM. Here as well, the maximum Rayleigh signal intensity of propane is kept at ~90% of the camera's saturation intensity level with a lower intensifier gain (~50%), and the SNR is ~50:1. Similar processing procedures were conducted to obtain the mixture fraction of propane-jet into air. Helium and propane have significantly different Rayleigh scattering cross sections at 532 nm: σ_{He}:σ_{air}:$\sigma_{C3H8} \approx$ 1: 63: 856.[16, 17]. Thus, helium induces a low Rayleigh scattering signal, and the SNR for propane flowing into air is high.

Figure 5 shows the overlap of propane-air mixture fraction and 2D velocity field of the free jet based on the optical flow analysis of the image sequence. Sixteen images with different time separations are shown with their velocity vectors, which are calculated between two consecutive images separated by 10 µs. The colored background shows the gas mixture fractions. The optical flow analysis is similar to the principle of PIV, in which the pattern of apparent motion of objects, surfaces, and edges in a visual scene caused by the relative motion between an observer and the scene is analyzed by the optical flow flux of the image sequence. The first optical flow governing equation proposed by Horn and Schunk [18, 19] for machine visions in the 1980s is based on the conservation of brightness of a particular point and is later improved by many other researchers [20–23]. By adding additional smoothness constraints, a two-dimensional velocity field can be determined linearly.

Figure 6 shows the averaged flow mixture fraction and velocity of the propane jet with over 300 consecutive image pairs within a single burst. Clearly, the propane concentration is higher near the nozzle exit than further downstream. There are no velocity vectors obtained in the surrounding air region because no moving structures exist here for optical flow analysis. The asymmetrical mixing layer on the upper part of the image is most likely due to the small number of images used to compute the average. From the individual velocity frames, the velocity vectors show a clear pattern of turbulence. However, the average velocity vectors become more vertical, indicating that the averaged X-component velocity (i.e., radial direction) is relatively small (<< 1 m/s whereas the velocity at the core of the jet is ~15 m/s).

100-kHz Rayleigh scattering imaging are also applied in reacting flow measurements. Figure 7 shows raw sequential images of 100-kHz-rate RS in a DLR-A flame. Since the Rayleigh scattering cross sections are uniform (±3%) in DLR-A flame [25], the flame temperature is inverse to the Rayleigh scattering intensity. Therefore, the raw images shown in figure 7 directly indicates the 2D flame temperature field. Optical flow analysis could also be applied in these Rayleigh images for flow velocity calculation. Simultaneous flow temperature and velocity imaging could be directly obtained by 2D Rayleigh scattering. We are currently working on the image processing and optical flow analysis for the Rayleigh scattering images in DLR-A flame and the results will be shown in future.

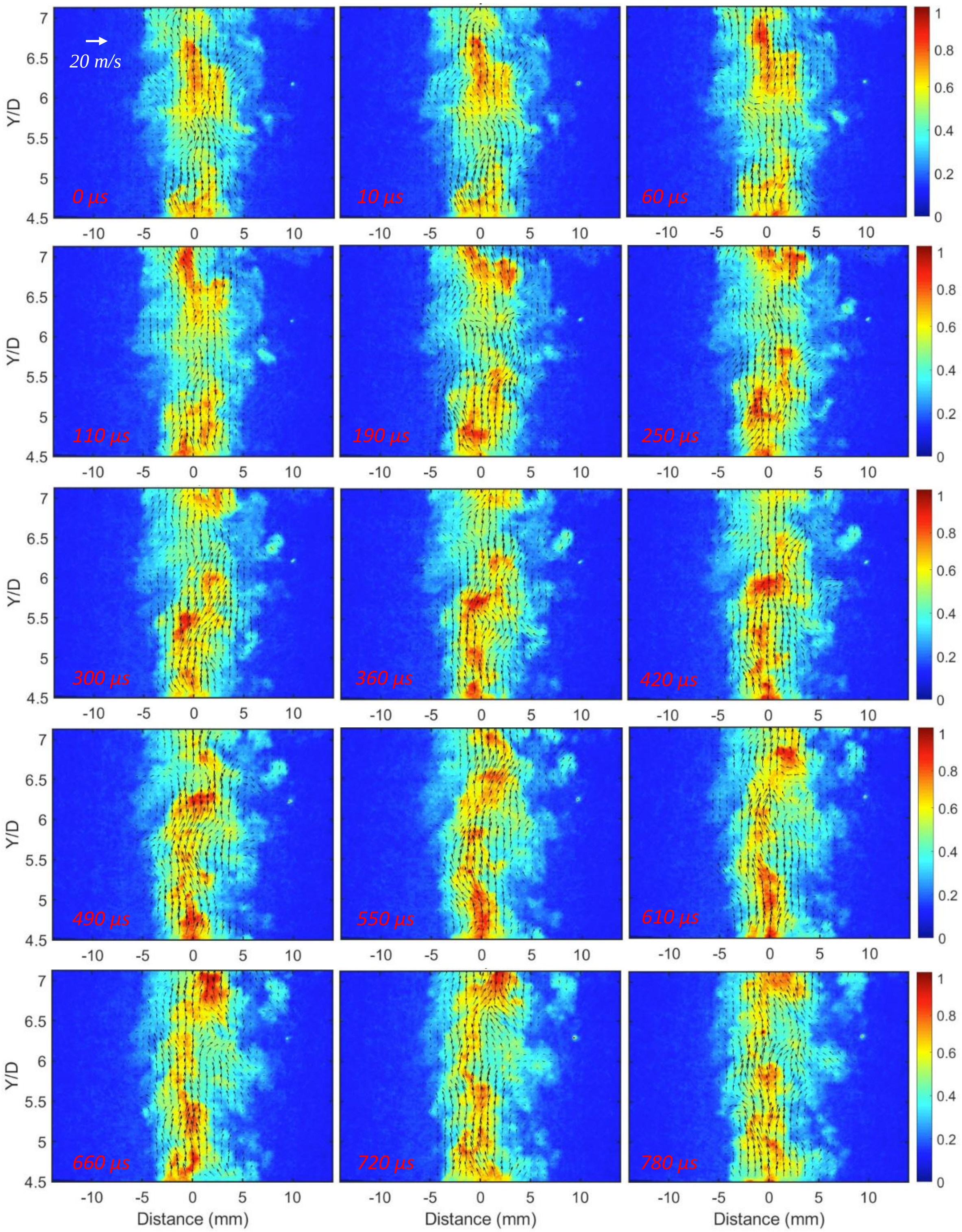

Fig. 5. Overlapped images of propane-air mixture fraction and velocity field for free propane jets into ambient air. Velocity was computed using the optical flow methods. The propane flow rate was at 50 SLPM, corresponding to ~16 m/s at the jet exit.

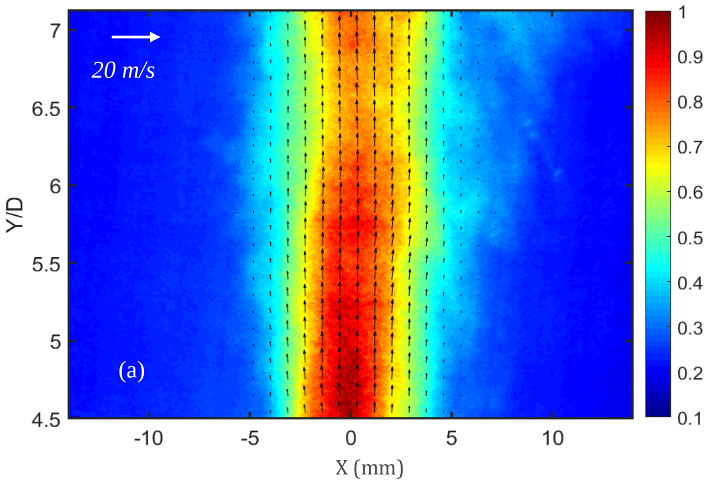

Fig. 6. Averaged mixture fraction and flow velocity field of propane jets at 50 SLPM.

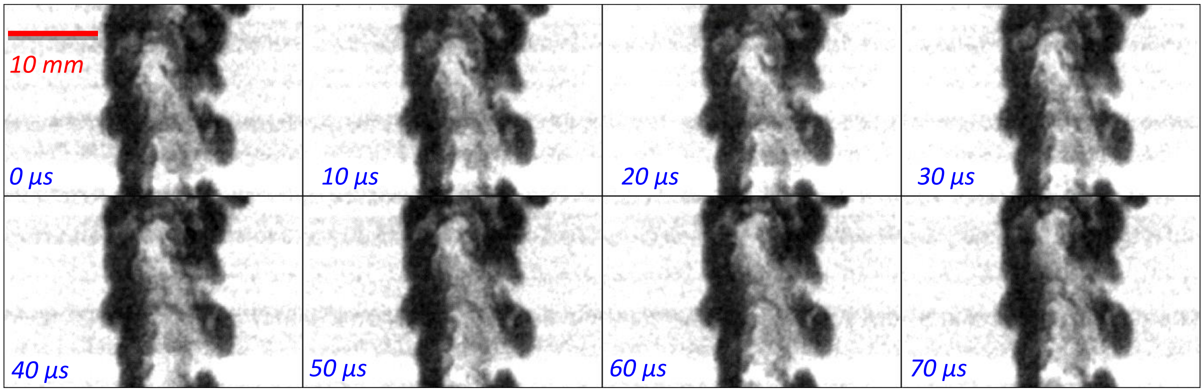

Fig. 7. 100-kHz Rayleigh scattering image sequence in DLR-A flame.

In conclusion, we demonstrated 2D RS at 100-kHz repetition rate in various flow conditions for simultaneous measurement of mixture fraction and velocity fields. Optical flow analysis was applied for flow velocimetry. The 100-kHz RS imaging along with optical flow analysis yields quantitative insights of the flow field, extending the measurement capability of 2D RS technique to high-speed flows.

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