CW LASER RADAR FOR COMBUSTION DIAGNOSTICS

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ABSTRACT

A CW-laser radar system developed for combustion diagnostics is described. The system is based on triangulation to attain range information. A portable system has been constructed and here we show some result from measurements in various flames, for example Rayleigh scattering thermometry and monitoring of particle distributions with high temporal and spatial resolution. The concept can equally well be based on pulsed lasers, allowing suppression of background emission through gated detection.

1 INTRODUCTION

Lidar is an interesting concept for practical combustion diagnostics, since it allows single-ended measurements, i.e. only one optical access is needed. This feature opens up for range-resolved *in-situ* measurements inside devices with intractable geometries, such as full-scale furnaces, boilers, and power plants. Our research group has in recent years developed a lidar system based on a picosecond laser as transmitter and an ultrafast detector (streak camera or MCP-PMT) to achieve adequate range resolution (~1 cm) [1]. The ps-lidar system has been demonstrated for Rayleigh thermometry (including two-dimensional) in flames [1] and full-scale room fire experiment [2], quantitative species detection based on differential absorption lidar (DIAL) [3,4], and measurements of soot volume fraction in flames [5].

Laser-induced fluorescence (LIF) is a very sensitive and highly species-selective technique, which therefore has been used extensively for combustion studies. Unfortunately LIF is difficult to utilize in ps-lidar. Since ps-lidar attains range resolution from the time-of-flight principle, the finite fluorescence lifetime (typically on the nanosecond scale in combustion environments), prevents adequate range resolution. This problem can, in principle, be circumvented if the recorded signal is deconvoluted with the fluorescence decay curve, but since the fluorescence lifetime generally is unknown and also varies along the measurement path, this is not a viable solution.

Based on the pioneering work by Brydegaard and co-workers, who has developed a novel continues-wave (cw) lidar concept based on the Scheimpflug principle [6,7], we intend to pursue this technique for combustion diagnostics. In cw-lidar, range resolution is achieved through triangulation instead of utilizing a time-of-flight approach as in conventional lidar. By positioning the detector, collection optics, and the laser beam in a configuration which fulfils the Scheimpflug condition, infinite focal depth can be obtained and the laser beam can thus be sharply imaged onto the detector. Since range resolution in this lidar configuration is achieved by imaging the laser-induced emission, instead of utilizing time-resolved detection, LIF is fully applicable. This new approach also opens up for the use of small inexpensive diode lasers, which may reduce the size, weight, and cost of the system, thereby also facilitating its mobility.

2 METHODOLOGY

The Scheimpflug-lidar setup currently under development in our laboratory is illustrated in Fig. 1. The detector is a linear array CMOS camera (Glaz-S, Synertronic Designs) with 2048 pixels (200×14 μm pixel size), providing a maximum scan rate of 4 kHz. The kHz-scan rate enables online background subtraction by modulating the laser output on and off in synchronization with the camera exposure. The high scan rate also opens up the possibility to study fast combustion processes. The signal is collected with a 2-inch spherical lens (f = 200 mm), and a bandpass filter is used in front of the detector to suppress background radiation. A tele-xenar objective (1:2.8/100, Schneider Kreuznach) expands and transmit the laser beam towards the region of interest. Diode lasers (O-like lasers) emitting at 445 nm (3-W output power) and 405 nm (0.5-W output power) are currently available for measurements.

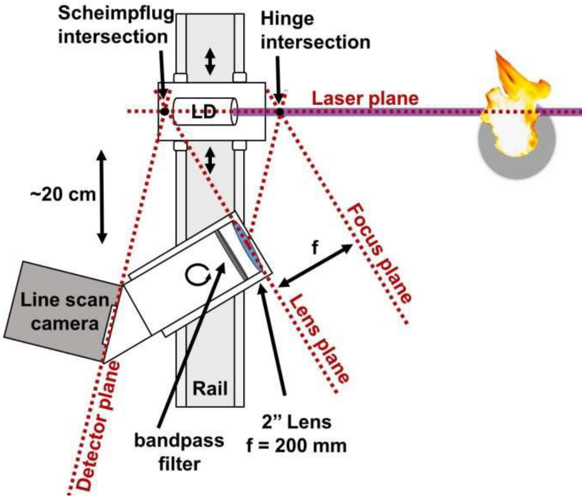

Fig. 1 Schemtaic setup of cw-lidar in Scheimpflug configuration for combustion diagnostics. The laser is a diode laser and the camera is linear array CMOS camera allowing a maximum scan rate of 4 kHz.

Figure 2 shows a photograph of the lidar system in operation. The bright blue spot, visible in the upper-middle part of the figure, is scattering from the beam termination trap.

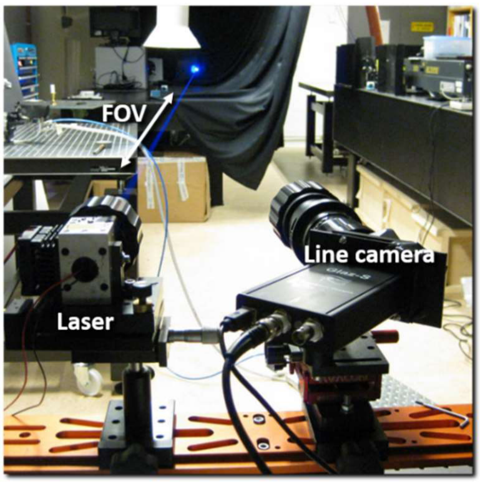

Fig. 2 Photograph of the cw-lidar system.

3 RESULTS

3.1 Elastic scattering from sooty flames and smoke

Elastic scattering from two highly sooty candle flames, placed in the lidar transect at 230 and 352 cm, was studied with the cw-lidar system. The data was collected with a 2 kHz scan rate and 400 µs integration time. Figure 3 shows the attained time-range map, after background subtraction. The mean intensity over the time window for each range is shown at the left of each map. As expected, strong echoes, due to scattering from soot particles in the flames, give rise to the distinct peaks at 230 and 352 cm. A closer view of the signal from the closest flame, i.e. the signal confined by the blue rectangle, is shown beneath the full time-range map. It is clearly seen that the instability of the flame can be resolved in time and space by the system.

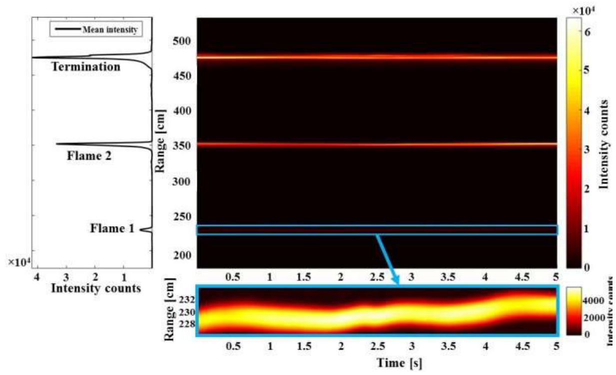

Fig. 3 Time-range map, covering a 5-second time window and a range interval of 187 – 530 cm, recorded with two sooty flames present in the lidar transect. The mean intensity over the full time window for each range is shown in the left panel, while the bottom panel is a zoom-in of the signal inside the blue rectangle.

In order to study particle distributions in smoke, the candle flame located at 350 cm was abruptly blown out, which resulted in the time-range map depicted in Fig. 4. Prior to extinguishing the flame, i.e. in the time interval 0 to 4 sec, the observed signal is elastic scattering from soot particles in the burning flame. After the flame has been blown out it is possible to monitor how the smoke is moving in time and space. This result suggests that cw-lidar in Scheimpflug configuration may deliver particle distributions with high temporal and spatial resolution, crucial information in combustion and environmental research.

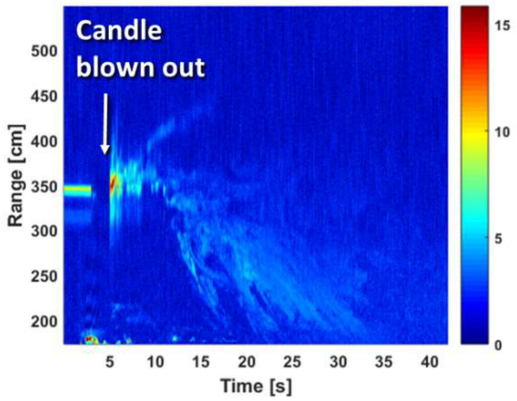

Fig. 4 Time-range map acquired in an experiment where a sooty flame was extinguished (at approximately the 4-sec mark). The spatio-temporal dynamics of the smoke is revealed by the recorded data.

3.2 Elastic scattering from non-sooty flames – thermometry

Two non-sooty flames were positioned in the lidar transect. A conical flame on a Bunsen burner was positioned at 181 cm, while a flat flame on a McKenna burner was placed at 194 cm. Since no soot is present in the flames, the scattering of the laser beam was pure molecular Rayleigh scattering. An example of a recorded lidar curve is shown in Fig. 5.

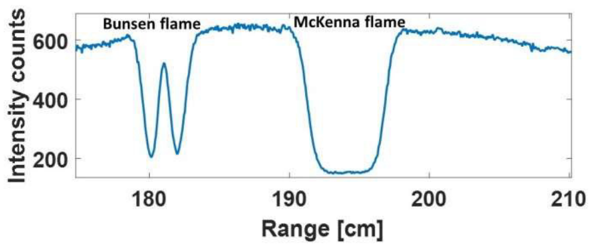

Fig. 5 Elastic lidar signal recorded with a non-sooty conical flame present at 181 cm and a non-sooty flat flame located at 194 cm.

The Rayleigh scattering intensity is proportional to the number density of molecules. From the ideal gas law it then follows that the Rayleigh scattering intensity is inversely proportional to the temperature, which explains the lower lidar signal intensities at the locations of the two flames. At the location of the McKenna burner, the lidar signal is fairly constant through the flame, which is expected since the flame is flat (i.e. temperature and species concentrations do not vary across the flame). At the location of the Bunsen burner two intensity dips are observed, which is expected since this flame is conical. The dips correspond to the reaction zone, i.e. the transition region between the unburnt reactants and the product gases. The lidar signal is significantly higher in the center of the flame, i.e. at 181 cm, actually only slightly lower than the signal level for the surrounding air. This is also expected since cold reactants (fuel and air) are present in the center of the flame.

Using the same McKenna burner, but positioned at a slightly shorter distance, a lidar curve was recorded through a slightly fuel-lean premixed methane/air flame, which corresponds to the blue curve in the left panel of Fig. 6. With identical system settings, a lidar curve was recorded with the flame turned off and room-temperature air flowing through the burner, which corresponds to the red curve in Fig. 6.

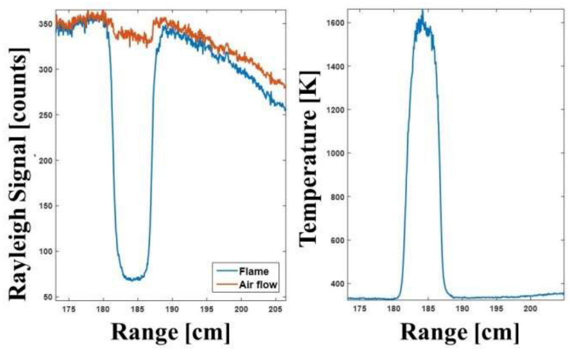

Fig. 6 Left: Lidar curves corresponding to molecular Rayleigh scattering in a slightly fuel-lean methane/air flame on a McKenna burner (blue curve) and with only air flowed through the burner (red curve). Right: Evaluated flame temperature profile.

The flame temperature can now be determined using Equation (1), where σ_{flame} and σ_{air} are Rayleigh cross sections of the flame and air, respectively, I_{flame} and I_{air} are the measured signal intensities in the flame and air, respectively, and T_{air} is the air temperature (295 K).

$$T_{flame} = \frac{\sigma_{flame}}{\sigma_{air}} \frac{I_{air}}{I_{flame}} T_{air} \quad (1)$$

Since the major flame species and their concentrations are known, the Rayleigh cross sections can be determined (relative values are sufficient). Using these cross sections and the data plotted in the left panel of Fig. 6, the temperature profile shown in the right panel of Fig. 6 was extracted. A flame temperature of ~1600 K is in fairly good agreement with previously reported results [1]. The reason why our measurement slightly underpredicts the flame temperature is, at least to some extent, due to uncertainty in the recording of the reference lidar curve (red curve in Fig. 6), which is related to difficulties in preventing dust particles from penetrating into the probe volume and stray light.

4 FUTURE WORK

Currently cw-lidar experiments utilizing LIF is under development in our laboratory. If successful, stand-off range-resolved detection of trace species with high temporal resolution can be added to the assets demonstrated here, making cw-lidar a very versatile tool for combustion diagnostics.

The Scheimpflug lidar concept is not restricted to cw lasers, but it can equally well be based on pulsed lasers. In fact, a pulsed laser source together with a gated intensified CCD camera is probably the best setup for most applied combustion experiments, as strong background radiation is anticipated. Therefore, such lidar configurations will soon be developed and investigated in our laboratory.

5 CONCLUSIONS

A cw-lidar system based on a Scheimpflug configuration has been successfully demonstrated in sooty and non-sooty flames. The results show that the method has the potential to monitor particle distributions with high temporal and spatial resolution and to remotely measure temperature profiles in non-sooty flames with high range- and time resolution. It is anticipated that the portable lidar system constructed will be a very useful tool not only for fundamental combustion studies, but in particular in numerous field campaigns at industrial sites.

ACKNOWLEDGEMENTS

The authors would like to thank the Swedish Energy Agency for financial support through the Center for Combustion Science and Technology (CECOST). Also acknowledged is the funding through the Advanced Grant TUCLA of the European Research Council (ERC).

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