Doppler Global Velocimetry in flames using a newly developed, frequency stabilized, tunable, long pulse Nd:YAG laser

by

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ABSTRACT

Laser anemometry is an important tool in modern combustion research and in the development of industrial combustors. Its purpose is to deliver data for code validation and to give an overview on the flow field to enhance the understanding of the burner and to identify flow phenomena. In the last two decades laser Doppler anemometry (LDA) and phase Doppler anemometry (PDA) were used for this purpose. LDA and PDA are both point techniques and therefore quite time-consuming to apply. Planar light sheet techniques like particle image velocimetry (PIV) and Doppler global velocimetry (DGV) offer much higher data rates.

Today there is high interest to use planar velocimetry techniques in flames. One further reason, why especially DGV might be the favourable technique for this purpose is, that LDA, PDA and also PIV are very sensitive against strong fluctuations of the index of refraction, especially at high pressures at which they often fail. DGV in contrast has not to image single particles and therefore is less affected by fluctuations of the index of refraction. In addition to this, DGV also does not require windows with brilliant optical qualities. Furthermore, DGV can –to a certain extend- distinguish between the velocity of the kerosene particles and the gas velocity, an important feature in optical diagnostics for combustion.

Despite these advantages of DGV, the technique was not used for combustion research yet. Measurements in flames were hindered by the fact that the scattering signal has to overcome the background luminosity of the flame and the incandescence of solid particles (soot as well as tracers). The light intensity of cw Ar+ lasers, which were often used for DGV, is normally not sufficient for this purpose, especially at high temperatures and high pressures.

To overcome this problem, pulsed Nd:YAG lasers can be used in combination with gated CCD-cameras. However, commercially available, pulsed Nd:YAG lasers have a rather wide bandwidth of about 100 MHz, or even more, due to their short pulse duration. This large bandwidth may result in a serious reduction of the measurement sensitivity. These lasers also tend to show an uneven frequency distribution over the light sheet height (Forkey, 1996; McKenzie, 1996), reducing the measurement accuracy even more.

A new kind of narrow band frequency stabilized, tuneable, long pulse Nd:YAG laser was developed in the frame of a co-operation between the German Aerospace Center (DLR) and the Laser Center Hannover (LZH). The new laser is capable to fulfil the requirements for a successful DGV application. This paper describes the set-up and the performance of this laser, with special emphasis on its frequency stabilization. Furthermore the DGV camera system with its intensified cameras is presented and the special aspects of the image processing are discussed. Finally results from an atmospheric kerosene combustor are presented. These first sucessfull DGV measurements in a combustion experiment demonstrate the capability of DGV and may open a new field of applicability.
PRINCIPLE of DOPPLER GLOBAL VELOCIMETRY

Like LDA or PIV, DGV also measures the velocity of tracer particles which need to be added to the flow. With one orientation of the laser light sheet and one direction of observation, one component of the flow velocity is measured. DGV takes advantage of the fact, that the frequency of the scattered light is shifted due to the Doppler effect:

\[ \Delta \nu = \nu - \nu_0 \]

\( \nu_0 \) : Laser frequency
\( \nu \) : Scattered light frequency
\( \Delta \nu \) : Doppler shift

This shift depends on the particle velocity \( \vec{v} \), the light sheet direction \( \vec{l} \) and the direction of observation \( \vec{o} \):

\[ \Delta \nu = \nu_0 \left( \frac{\vec{o} \cdot \vec{l}}{c} \right) \vec{v} \]

(2)

The basic idea of DGV is to measure the scattered light frequency \( \nu \) by transmitting the scattered light through an iodine cell (Fig. 1). Iodine has strong absorption lines, which are used as a frequency to transmission converter. These lines interfere with the 514 nm line of the Ar’ laser as well as the 532 nm line of the frequency doubled Nd:YAG laser. Assuming the frequency \( \nu \) to be on the slope of one absorption line, then \( \nu \) can be determined by measuring the iodine cell transmission of the scattered light. Therefore, two detectors are required to measure the light intensity before and after the cell. To correlate \( \nu \) and \( T \), the transmission profile \( T(\nu) \) of the iodine cell must be known.

![Diagram of Doppler Global Velocimetry setup and transmission profile of the iodine cell. Direction of the measured velocity component depending on the direction of laser light propagation and the direction of observation.](image)

The laser frequency \( \nu_0 \) has to be known and precisely stabilized, so that the Doppler shift \( \Delta \nu \) can be calculated according to equation (1). With equation (2), one component of the vector \( \vec{v} \) can be calculated. It is the component in the direction of \( \vec{o} \cdot \vec{l} \), the bisector of the angle formed by the direction of the laser light and the direction of observation (Fig. 1). At a scattering angle of 90° a velocity of 1 m/s corresponds to a frequency shift of 2.7 MHz. Since the frequency width of the slope of the absorption line is between 300 to 600 MHz (depending on the operation conditions of the gas cell), the dynamic range of velocity measurement is between 100 and 200 m/s.

Another basic idea of DGV is to use two CCD-cameras as detectors, both watching the same section of a laser light sheet. By pixel wise division of the two pictures and further post processing a map of one velocity component in the light sheet is obtained. Depending on the type of laser (cw or pulsed), the result is either a time averaged or a frozen velocity image.

The second and the third velocity components can be measured by changing the arrangement of the optical set-up. There are two alternative ways to accomplish this:
• With one light sheet direction and three synchronized camera systems in different positions which simultaneously capture momentary pictures, the momentary 3D-velocity distribution can be obtained. Such a configuration is needed to investigate instationary 3D-flow structures (Meyers, 1996).
• The second alternative is to use only one camera system in a fixed position and three light sheets with different orientations. The three pictures of the three light sheets have to be taken one after the other, with the consequence that this method is restricted to stationary flows only.

The second method is simpler than a set-up with three camera systems. It is well suited to measure mean velocities by long camera exposure times. When a pulsed laser is used - like in our case - a long exposure means that the cameras perform a so called “on chip integration” of a larger number of single-pulse images adding up the generated photoelectrons per pixel of each image. In this way, the turbulent velocity fluctuations are averaged and therefore the result is an image of the mean velocity distribution. Since the exposure times are typically in the order of several seconds, a weak seeding gives a sufficient amount of scattered light. Because of these reasons, a set-up with three light sheets and one camera system was chosen and is described below.

SPECIAL ASPECTS of DGV IN COMBUSTION ENVIRONMENTS

Doppler global velocimetry has been widely used in different environments, e.g wind tunnels (Beutner and Mosedale, 1998; Meyers,1996) and also in combustion chambers operated with air under isothermal conditions (Röhle, 1999). Up to now, DGV-measurements were restricted to cold flows, because the application in flames is hindered by the reduction of the signal to noise ratio due to background light originating from flame luminosity and incandescence of solid particles (soot as well as tracers). Under these conditions the light intensity of cw Ar⁺ lasers, which are usually used for DGV, is not sufficient. It is well known from previous experiments in kerosene combustion chambers, that the problem of flame luminosity and particle incandescence increases dramatically with pressure and temperature in the combustion chamber. This is especially true when preheated air is used. To overcome this problem, pulsed lasers can be used in combination with gated CCD-cameras. During the laser pulse the intensity of the scattered light is much higher than the mentioned background radiation intensity (Fig. 2). In the time between the pulses, the camera intensifiers are switched off, so that the cameras are not sensitive to light. This principle which is usually used for spectroscopic measurements in flames (e.g. laser induced fluorescence (LIF) and coherent anti-Stokes Raman scattering (CARS)) is here applied to DGV.

SETUP of the LONG-PULSE Nd:YAG LASER

To achieve a high measurement accuracy, it is advantageous, that the laser provides a narrow linewidth and is frequency stabilized. Tunability of the frequency over several iodine lines of different flank-slope is required to optimize the measurement system for different velocity ranges. These requirements are met by the resonator concept, choice of the cw single-mode ring-laser (=seed-laser) coupled to an iodine cell and the developed electronics (Fig. 3).

The linewidth (FWHM) of the Gaussian “single-mode” pulse with pulsewidth t_p (FWHM) is nearly Fourier-limited and described by \( \Delta \nu = 2 \ln 2 / \pi t_p \) (Koechner, 1992, p.235).

The pulse length is dominated by cavity length and power density in the active laser medium. If one considers the decay of stored photonic energy caused by laser emission and light losses, the decay time constant represents the mean lifetime of a photon inside the resonator. This mean lifetime is proportional to the cavity length and depends also on front and rear mirror reflectivity and light losses. Furthermore, the lifetime of the stimulated
emission is inverse proportional to its emission cross-section and to the power density in the Nd:YAG-rod (Koechner, 1992, pp. 81-86; Degnan, 1989). Therefore, the pulse length increases with increasing resonator length and decreasing pulse energy. The optimization of laser power and pulse length resulted in a cavity length of about 1.7 m and an IR pulse length of 400 ns, which corresponds to a linewidth of 1.1 MHz. After amplification and frequency doubling the pulse length is 300 ns corresponding to 1.5 MHz linewidth. At 532 nm a pulse energy of 1.6 mJ has been achieved (5.3 kW peak power). The repetition rate of the laser diode pumped oscillator-amplifier system is 1 kHz realized by an acousto optical modulator (AOM). The essential feature of the laser concept is, that the resonator oscillates driven on a single frequency mode provided by a monolithic ring-laser (Innolight). This seed-laser has a high stability of frequency and output power. It is resistant against influences from outside and its emission frequency can be tuned by cavity temperature (about 4 GHz/K) and the pressure on the cavity produced by a piezo crystal (about 1.7 MHz/V). Inside of the tuning range several iodine lines suitable for DGV-measurements were found (Fig. 4). For test purposes the laser was tuned to the arrow marked lines. The right hand line inside of the marked “three line group” was used for the DGV measurements. This line is composed of two transitions ((v′=32, v′′=0) P53 and (v′=34, v′′=0)P103, B-X band system).

During a measurement the seed-laser frequency is stabilized on the flank of an iodine line. This is accomplished by a closed-loop control circuit (“frequency controller” in (Fig. 3)). The laser-oscillation starts on the single-mode frequency if the optical axis of the laser resonator and the seed-laser beam are well aligned and the cavity length matches the seed-laser frequency. This adaptation of the cavity length is provided by a piezo on which the rear mirror is mounted. By the default of photons for the stimulated emission the laser pulse build-up time (BUT) is reduced by about 1.4 µs (Fig. 5) compared to a free multi-mode oscillation with mode competition (BUT=5.4 µs).

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Fig. 3: Setup of the long-pulse Nd:YAG laser.

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Fig. 4: Simulated iodine transmission and tested tuning range; iodine cell length 5 cm, 2.7 mbar, 338 K.

Fig. 5: Laser pulse build-up time as a function of rear mirror voltage.
The BUT-reduction is a measure of the quality of the single-mode operation and used to control the laser. Fig. 6 clarifies the function of the "cavity mode controller" (Fig. 3) in more detail. Synchronous to the opening of the cavity by the AOM, a TTL-Level is electronically set to "high" and reset (flipflop) by the trigger pulse of a photodiode, when the laser pulse is build-up in the cavity. The pulse length is proportional to the build-up time and is converted to a dc-voltage by a "time to amplitude converter" (TAC). Because the BUT is minimum at matched resonator length, this length can be identified and stabilized by the derivation of BUT with respect to rear mirror voltage. For that purpose a voltage of about ±0.25 V varying with the half laser repetition frequency (f/2 = 500 Hz) is added to the linearly tuned feedback voltage at the rear mirror. The produced variation of BUT enables to measure the derivative \(dU_{\text{BUT}}/dU_{\text{mirror}}\) close to the minimum of BUT. The derivation of \(U_{\text{BUT}}\) is carried out by a "lock-in" amplifier, which receives f/2 as reference frequency. The produced voltage is zero for optimum single-mode operation and serves as input signal of a PID controller (PID1). A deviation from zero is counteracted by the output signal of PID1 which is amplified to a high voltage and tunes the rear mirror.

In case of resonator length perturbations, e.g. by acoustic waves or externally induced vibrations, the build-up time increases and the frequency control starts to work more intensely. To suppress multi-mode laser operation in case of heavy perturbations, a discriminator electronics was developed. Exceeding a maximum accepted \(U_{\text{BUT}}\) a constant voltage is switched to the PID1-input line. This forces the PID to continuous counteraction and leads to a fast underrun of the upper limiting value \(U_{\text{BUT},\text{max}}\), which activates the regulation. In this way longer periods without single-mode operation are prevented, which could appear if the control loop does not find a derivation unequal to zero between two minima (see Fig. 5).

During a short transgression of the maximum accepted \(U_{\text{BUT}}\) the discriminator electronics generates a trigger signal which is used to suppress regulation actions of the seed-laser frequency stabilization. During this short time the seed-laser frequency is nearly stable (± a few kHz). The remaining frequency drift of the temperature stabilized seed-laser without iodine-cell control loop (Fig. 3, Fig. 7) was determined to be about 3MHz/min by the help of a confocal scanning etalon.

The control loop named "frequency controller" is shown in Fig. 7. The frequency control is based on the generation of an actual voltage-value by the division of two transmission signals (Fig. 8, Fig. 7).

The actual value is compared to a set-value and the difference is used as input signal for the PID-control. Because the frequency positions of the iodine lines are well known and their slope can be calculated or experimentally calibrated for known iodine concentrations, a measured value \(U(I/I_0)\) can be correlated to absolute frequencies. \(U(I_0)\) corresponds to the reference-transmission without iodine absorption and \(U(I)\) to the transmission \(T\) through the iodine cell. The peak voltage generated at the diodes during a laser pulse is detected and converted to a dc-voltage. Because the frequency drift of the ring-laser is extremely slow a low pass filter (10 Hz) can be used. After that a divider creates the voltage equivalent to \(I/I_0\). The comparison of set-value and actual value is realized by subtraction of an offset-voltage (set-value) from the actual voltage \(U_{\text{PID}}\). To render controlled single-mode operation for hours the

Fig. 6: Block diagram of the "cavity mode controller".
control loop was split in a fast reacting loop (PID2) and a slowly acting loop (PID3). The output signal of PID2 is amplified and directly used to regulate the ring-laser-frequency fast and linear by a piezo crystal. An additional slow control loop (PID3) provides that the piezo voltage stays inside of the linear frequency tuning range and that PID2 does not leave its regulation range. For slow, continuous ring-laser frequency drift PID3 counteracts to the output-voltage of PID2 and keeps PID2 in the center of its regulation range. In this way, the fast piezo response is step by step replaced by the temperature change. If the maximum \( U_{\text{BUT}} \) is exceeded the input signals of PID2 and 3 are switched to ground and the last valid output voltages are kept by a sample hold circuit. They are released after a short delay as soon as single-mode operation is sure (trigger level low, \( U_{\text{BUT}} < U_{\text{BUT, max}} \)).

To check the frequency stability of the laser, the variation of \( U(I/I_0) \) during stabilized single-mode operation was measured. For this purpose the laser was stabilized to a set-value corresponding to 50 % iodine cell transmission. The remaining variation of \( U(I/I_0) \) was about ±25 mV, or ±0.25 % related to 10 V for maximum transmission. At 50 % transmission the frequency changes by 3.2 MHz/1 %. Therefore, ±0.25 % corresponds to a frequency stability of about ±0.8 MHz and is equivalent to about ±0.3 m/s velocity-uncertainty.

To process DGV measurement, a look-up table is needed which correlates frequency and transmission. Therefore, the iodine cells of laser and DGV measurement system were calibrated against each other. The laser frequency was scanned by a voltage-ramp generator coupled to the temperature-offset input connector and iodine transmission spectra were measured simultaneously. The frequency range is shown in Fig. 9.

Using a code published by Forkey (Forkey, 1996) the vapour pressures were fitted to the experimental results to reproduce the transmission ratio of the lines. Because of the smaller transmission, the left line in the line-group shown in Fig. 9 is sensitive to this procedure. The resulting vapour pressure of 4.5 mbar (DGV-cell) corresponds to 56.7°C recalculated by the vapour pressure formula. This result is in good agreement with an
independent calibration (57°C), performed by a measurement of the transmission as a function of cell temperature. With the known gas phase concentration the slope of the right hand iodine flank (marked in Fig. 9) was determined and a look-up table was created to evaluate the flame measurements. Calibration measurements on flow fields with well known velocities are in progress.

![Graph showing transmission as a function of wavenumber](image)

**Fig. 9:** Simulated iodine transmission for laser iodine-cell and DGV-camera iodine cell at 5 cm cell length and 338 K. Pressures fitted to experimental results.

Laser cell: 2.2 mbar vapour pressure. DGV-camera cell: 4.5 mbar vapour pressure.

**EXPERIMENTAL SETUP**

To generate the light sheet the laser beam is guided through a fibre to a light sheet box which contains the complete light sheet generation optics (Fig. 10). The height of the light sheet and the distance of the waist can both be adjusted. The maximum height for a parallel light sheet is 140 mm. The distance of the waist from the light sheet box can be changed by the position of the collimating lens behind the fibre. The attainable diameter of the waist is a function of this setting and the diameter of the fibre. In the experiments described below, the fibre core diameter was 200 µm, the working distance was 1 m and the waist had a thickness of about 3.5 mm. The separation of laser and optics facilitates the alignment of the laser light sheet relative to the object of investigation.

![Diagram of light sheet generation](image)

**Figure 10:** Generation of the scanning light sheet. Side view (top) and top view (bottom).

The light sheet optics is also optimized for long exposure times. The light sheet has a flat top-hat intensity profile, generated by a scanning technique with a modulation frequency of 10 to 100 Hz. A top-hat profile minimizes the intensity dynamics in the measured images with positive influence on the measurement accuracy.
To prevent the appearance of stimulated Brillouin scattering (SBS) (Labudde et al, 1980; Agrwal, 1995) and other non-linear optical effects in the fiber, a fiber with 200 µm core diameter was used. SBS reduces the transmitted intensity drastically for single-mode lasers if smaller core diameters are used (increase of power density). In pre-experiments fibers with different core diameters were tested. At, e.g., 50µm core diameter about 70% of the incident power was lost by back-scattering. Due to multiple SBS and four wave mixing (FWM) processes a “paling” of transmitted lines with line distances in the order of 34 GHz (bulk silica, 514.5 nm) can appear (Labudde et al, 1980). This can be excluded for our measurement for two reasons. Firstly, the transmitted intensity corresponded well to the fiber attenuation and secondly it would have been impossible to absorb the laser light by strong iodine lines because the coincidence of iodine line positions and additional laser lines would be randomly.

The arrangement of the light sheets relative to flame and cameras is shown in Fig. 11. To facilitate the optical access a “nearly cubic” combustion chamber (about 100x100x113 mm$^3$) made of steel was designed. One wall was substituted by a glass window for the camera access. Rectangular window flanges with vertical slits in the combustion chamber wall for the light sheet passage were fitted to the chamber. The window flanges are air purged to protect the windows from particles. The tracer particles (SiO$_2$, 0.8 µm diameter, Merck) were added to the air flow near to the air blust nozzle with co-rotating air swirls also shown in Fig. 11. The dimensions of the sketch are not in scale but chosen for clearness of the representation. In reality the inner diameter of the nozzle is 7 mm.

Fig.11 : Experimental setup showing the orientation between light sheets, camera and flow direction.

The DGV camera system (Röhle, 1999) uses one collecting lens which generates an intermediate image. This is transferred by a transfer lens to the chips of the two cameras. A non polarising beam splitter plate is used to reduce polarization influences. A laser line filter is used to reduce ambient light. The images are taken by a pair of intensified, 12-bit, cooled, slow scan CCD cameras (LaVision). Intensified cameras were needed, because they can be synchronised with the pulsed laser in the way that the image intensifier is only switched on during the laser pulse. In addition, these cameras can perform long exposures of several seconds without integrating too much dark current. Therefore, they are a good choice for a DGV system which is optimised for time averaged measurements.

In order to get identical images from both cameras, the cameras are mounted on micro positioning devices to allow precise alignment. By an additional software correction the alignment can be further enhanced. The image processing is performed by using a program written in the language IDL. The steps of the post processing were described in (Röhle, 1999). This post processing only takes a few seconds and can be started immediately after the DGV pictures are taken. In this way the technique is nearly on-line.

The enlargement of the build-up time by 1.4 µs as a consequence of multi-mode operation is used to simplify the DGV-data acquisition. We used cameras with gated image intensifiers providing the possibility to set the appearance of the light pulse near to the end of the amplification period. In multi-mode operation the light pulse appears after the gate period (width about 800 ns) and the corresponding flame-image is not intensified. In this way images are only measured in case of a correct frequency stabilized operation of the laser thus enabling correct averaging.
Fig. 12: Background image.

Fig. 13: Kerosene image.

Fig. 14: Kerosene and tracer image.

Fig. 15: Kerosene image without background.

Fig. 16: Tracer image without kerosene and background.

Fig. 17: Droplet velocities.

Fig. 18: Tracer velocity.

Fig. 19: Extract from figure 18.

Fig. 20: Slip of droplets.

Fig. 21: Result without separation between tracers and droplets.
MEASUREMENT of the FLUID VELOCITY and the VELOCITY of the KEROSENE PARTICLES

An important difference of DGV measurements in kerosene flames to conventional DGV measurements is the presence of kerosene droplets in the flow. In contrast to the small tracer particles the droplets can be a lot larger in size and inhomogeneously distributed. The small tracer particles (usually $>1 \mu m$) are supposed to follow the flow, so that their velocity represents the flow velocity, while the kerosene droplets (size of up to 50 $\mu m$ in the beginning of the evaporation phase) do not follow the flow. To a certain extent, it is possible to measure the velocities of this two kind of particles separately:

First of all a DGV measurement is performed to measure the velocity of the kerosene droplets. The cold flow and the laser are switched on and the so called back ground images are taken for each camera and each light sheet direction. These images should contain the complete ambient light and reflexes of the laser light sheet, but no light scattered by particles or droplets. Then the combustor is ignited and a further set of images is acquired. These images contain the light scattered by the kerosene droplets and the superimposed back ground light. The influence of the background light is than eliminated by subtraction the background images from the images with combustion. In this way the pure kerosene-Mie images are obtained. An example of such a kerosene image is shown in Fig. 15. This set of images is later on used to calculate the velocity field of the kerosene droplets.

In the next step tracer particles are added to the air flow of the burner and another set of images is acquired. These images contain basically three different kinds of light: The background light, the light scattered by the kerosene droplets and the light scattered by the tracer particles. With other words, these images are the sum of the light sheet images of the kerosene flame (including the background) and the pure Mie-signal from the tracer particles. The first post processing step to determine the velocity of the tracers is therefore, to subtract the images of the kerosene flame (before background correction) from the flame images measured with kerosene droplets and tracer particles. The result is a pure tracer image (Fig. 16).

Then these two sets of images, the kerosene images and the tracer -Mie images undergo a standard post processing:

- Dewarping of the images
- Division of the content of each image pair
- Pixel specific sensitivity correction
- The mapping $T \rightarrow v (T)$ using a look up table
- The mapping $v \rightarrow v (v) : Equation (2)$
- Combination of three one component measurements to one 3-component-measurement, according to the direction of illumination and observation.
- Vector or false colour representation of the results
- Generation of structured ASCII-files for processing with further software

The Fig. 17 and 18 show an example for the vector field of the droplet velocities and the flow field measured with the added tracers, e.g. the flow velocity. From the difference of these two vector fields, the slip velocity of the large droplets, that means the velocity of the droplets relative to the surrounding air can be calculated (Fig. 20).

The procedure of taking the “kerosene image” as a background image for the image containing scattering light from tracers and kerosene droplets only works, when the scattered light intensity of the droplets is not extremely large compared to the scattered light of the tracers. In Fig. 18 this requirement is fulfilled everywhere except very near the fuel atomisation swirl nozzle. Because of this, there are some drop outs in the tracer velocity in that particular region.

Aside of these procedures of measuring the flow and the kerosene droplet velocity separately, there is of course another possible way to process the acquired data, which is to subtract the background images from the images of the flame with droplets and tracers and than continue with the post processing mentioned above. Then the resulting vector field will consist of three regions. The first region will be dominated by the droplet velocities – this will usually be near the point of the fuel injection – a second region dominated by the tracer velocities which should equal the flow velocity and a third, transient region between these first two where the measured velocity is somewhere between the flow velocity and the velocity of the droplets. An example for this is shown in Fig. 21.
DISCUSSION of the RESULTS

The flow fields shown in Fig. 17 and 18 are quite typical for a burner, except that there is no axial recirculation. The shape of the axial velocity distributions is also quite typical, but the velocity is not negative on the symmetry axis. Since a recirculation region is essential for a continuous combustion, the interpretation has either to be, that the flame is stabilized by its corner vortices only – Fig. 18 gives a slight impression of such a vortex on the left hand side – or that the recirculation can only be visualized in the instationary flow field.

The Fig. 20 shows the slip velocity between the droplets and the flow. The long vectors are caused by the large droplets, which do not follow the flow. These droplets are sprayed out of the strongly swirling flow field. After they left the region with large circumverential velocities, they continue to fly straight on through nearly resting air. Thereby they evaporate more and more. This can be seen quite clearly in the kerosene. The evaporated fuel is than sucked into the sheer layer of the swirling jet. It is in this sheer layer where the combustion takes place. This can clearly be seen from OH-LIV measurements (Fig. 22)

![Fig. 22: OH-LIF image of the flame.](image)

There is a lot of OH in the sheer layer while there is no OH in the middle of the flow. From this we can derive that the combustion takes place in the sheer layer only. That means that this flame is only stabilized by the corner vortices and the small vortices in the sheer layer of the jet. This gives us confidence in the DGV measurement which did not show an axial recirculation.

In the middle near the symmetry axis the slip between the droplets and the flow is a lot smaller, so it can be assumed that the droplets there are small enough to to follow the gas flow. The atomisation process in the swirl nozzle generates small droplets as well as large once. These small droplets are carried with the flow to the region in the middle above the nozzle, instead of leaving it due to centrifugal forces. In this way the flow acts like a cyclone separator.

The SiO$_2$ tracer particles tend to stick to walls and the windows. Therefor it was necessary to clean the window during the experiment. Since the intensity distribution in the kerosene images is extremely large, a lot care needs to be taken to keep the cameras in there dynamic range. After the presented experiments it turned out that the images could still have been improved in that respect. This is probably the reason, why the vectors in the corner regions of the burner do not show a nice structure. Future measurements will probably be give much better results over there. The vertical light sheet causes problems because of reflections of the laser light at the bottom plate of the burner. It was necessary to introduce a slit in this plate to hide the reflex.

CONCLUSION

A new frequency stabilized, tunable long-pulse Nd:YAG laser was developed and successfully applied a kerosine burner. The flow field of the gas phase and the liquid phase could separately be analysed. The established frequency control renders possible accurate and reproducible measurements.

OUTLOOK

Flows in technical environments often show a periodic behaviour, for example the flow inside a piston engine or the flow in the compressor or in the turbine of a turbo engine. Sometimes flows also show periodic structures due to pure fluid mechanical reasons. An example for this is the von Karmann vortex street or the phenomenon of a preceding vortex core. If a trigger signal can be derived from such a flow, for example the signal of a pressure sensor or - in the case of a rotating machine – a trigger signal from the rotating axis, one can trigger the data acquisition to perform a phase averaged DGV measurement. Such a -successful- measurement is described in the paper of (Willert et al, 2000), who used a cw Ar laser and a bragg cell to strobe the laser light. The applicability of this technique is limited by the fact, that most of the laser light is lost, because the bragg cell blocks the laser most of the time. Therefore in future applications it is planned to use the pulsed Nd:YAG laser phase locked to the experiment. New insights in the flow physics of periodic flows are expected from time resolved measurements in, e.g. compressors, turbines and piston engines.

Pulsed DGV with the long-pulse Nd:YAG laser shows a high potential also for combustion research. The technique is able to provide large quantities of velocity-information in a short time, which makes new -quasi-evolutionary- parameter studies possible at reduced costs. The coupling of 3-component velocity information with high measurement point density to temperature measurements (by e.g. CARS, LIF) is expected to enhance...
the understanding of reacting flows. Further activities will be aimed to apply this technique to combustion under high pressure. This is of particular importance because this light sheet technique is less sensitive to beam steering effects than point measurement methods.

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More information on DGV can be found on our homepage: www.dlr.de/en-at/tm

REFERENCES


Forkey, J.N.: Development and demonstration of filtered rayleigh scattering – a laser based flow diagnostic for planar measurement of velocity, temperature and pressure; Dissertation; Department of mechanical engineering; Princeton; 1996.


