NEW CHALLENGES IN THERMO-FLUIDDYNAMIC RESEARCH BY ADVANCED OPTICAL TECHNIQUES

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ABSTRACT

In order to develop computer codes describing phenomena in Thermo-Fluiddynamics, sophisticated measurement techniques are needed to give a data base of the global and local behaviour of complex thermodynamic systems. Therefore optical methods have been prefered for many years due to their inertialess and non-invasive mode of operation. New high-energy laser, electronical cameras and data processing devices, do not only allow to develop new measurement techniques, but also offer new possibilities for some classical optical measurement methods. A short introduction to holography, holographic interferometry, as well as Rayleigh, Raman and LIF scattering show, together with examples from several fields of Thermo-Fluiddynamic research work, the importance and capabilities of optical measurement techniques. The possibilities of new high speed video camera systems used in combination with optical measurement methods are shown by examples of highly transient combustion processes.

1. INTRODUCTION

Optical methods are used in Thermo-Fluiddynamic research for many years due to their big advantages. As they work in a non-invasive and inertialess way they do not influence the process that has to be investigated and can be used for highly transient processes.

The development of optical methods is supported by the availability of new equipment like high energy light sources, intensified electronical camera systems, and electronic devices as well as new software. This fact allows to reduce the time of data processing which has been very time consuming in the past.

It can be distinguished between imaging and non imaging techniques. Imaging techniques (global methods) provide simultaneous information over a larger area and use any kind of conventional or electronic photographic material to store this information. Non imaging optical methods work with a measurement volume often smaller than 1 cubic millimeter, and therefore are also called pointwise methods. In table 1 examples are given for modern, optical measurement techniques to determine temperature, concentration, density, velocity and droplet size - which are mainly the interesting dimensions in Thermo-Fluiddynamics. The table also gives information about the physical effect of the methods, as well as the recording dimension and the application. It can be seen that a parameter which is interesting in Thermo-Fluiddynamics can often be measured by various techniques. For example the velocity in a droplet spray can be measured by double-pulse holography, particle image velocimetry (PIV) or laser doppler velocimetry (LDV). For each application a different method might be prefered. In our example, a pulse hologram contains the full three-dimensional information about the process in one moment. Using PIV a two-dimensional image of the moving droplets can be recorded continuously, whereas the application of LDV only provides (three-dimensional) velocity information in one single point, but with a data-rate of up to several kHz, depending on the spray.

As it is not possible to discuss all optical techniques known from the literature in detail here, emphasis is given to

- Holography
- Holographic Interferometry and

light scattering methods like

- Rayleigh scattering
- Raman scattering and
- Laser-Induced Fluorescence (LIF, LIPF)

Some examples will show, how classical measurement-techniques like

- Self Fluorescence and the
- Toepler-Schlieren technique

can become very interesting again with newest high speed video camera devices.

2. HOLOGRAPHY

In 1949 Gabor found a new technique to record and reconstruct three-dimensional pictures, called holography ("complete recording"). But it needed the invention of the laser as a coherent light source, 10 years later to discern the large variety of this technique. The general theory of holography is so comprehensive that for a detailed description one must refer to the literature [14],[18],[19].

Therefore only the principles, necessary for understanding the holographic measurement technique can be mentioned.

measuring technique	physical effect	application	dimensions
schlieren and shadowgraph	light refraction	density, temperature	2D (integ.)
holography	holography	particle size, velocity	3D
interferometry	change of light velocity	density, temperature	2D (integ.)
laser Doppler velocimetry	Mie scattering	flow velocity	point
phase Doppler	Mie scattering	particle size	point
particle image velocimetry	Mie scattering	flow velocity	2D
dynamic light scattering	Rayleigh scattering	density, temperature	point – 2D
Raman scattering	Raman scattering	mol. concentration, temperature	point – 1D
coherent anti-stokes Raman spectroscopy	CARS scattering	mol. concentration, temperature	point
laser induced fluorescence	fluorescence	concentration, temperature	point – 2D
absorption	absorption	concentration, temperature	point – 2D (integ.)
pyrometry	thermal radiation	temperature	1D
thermography	thermal radiation	temperature	2D (integ.)
self fluorescence	therm. fluorescence, chemoluminescence	concentration, temperature	2D (integ.)

Table 1: Examples of optical measurement techniques used in Thermod-Fluiddynamics

The main idea of the principle is, to store the whole wave field, emerging out of the object in the hologram-plane H-H. Figure 1 shows the principle of storing the phase of a wave. The spherical wave coming from an object point P (= object wave - shown as circles in figure 1) would only darken a film in the hologram-plane (figure 1a (4)). This is caused by the permanent change of the phase distribution of the light in the hologram-plane (figure 1a (1), (2), (3) with a phase difference of $\lambda/4$ each). By superposing a coherent reference wave (in this case a planar wave, with the same wavelength as the object wave) a constant distribution of the interference-minima by time (figure 1b) is produced. This is caused by the same velocity both waves pass the holographic-plane, and so the relation between the phases keeps the same. On the film microinterference-lines are created[1] which lead to a hologram after developing a plate which can be illuminated in this holographic plane.

This hologram is now a tool to reconstruct the original waveform. In figure 2, a record and a reconstruction of an off-axis[2] hologram is shown. By illuminating a hologram with the reference wave again, the ringsystem on the photographic emulsion works like a diffraction grating, with a decrease of the grating constant by increasing diameter. Because of the diffraction of the reference wave at this grating, one zero-order wave plus two first-order waves appear. One of these first-order waves travels in the same direction as the original object wave and has the same amplitude and phase distribution. This spherical wave corresponds to the recorded object wave and creates the virtual image P'. The second first-order wave goes to the opposite direction and creates a real image of the object behind the photographic plate. This real image can be studied by means of various reconstruction devices, like a microscope.

In order to create a hologram of a complex object, this object has to be illuminated by a monochromatic light source. The reflected, scattered light (object wave) obviously has a very complicated waveform. According to the principles of Huygens, it can be regarded as the superposition of many elementary spherical waves. The microscopic pattern of the hologram (which consists of up to 3000 lines/mm) now contains all information (amplitude and phase) about the complete wave.

Holograms have some interesting characteristics:

- Due to the fact that the reference wave which is coming from one object point P, covers the whole hologram the total information of the object is also recorded in a small part of the hologram. Observing a part of the hologram, one just has to come closer as if looking through a window.
- By changing the view angel, also the perspective changes when different reconstructed waves reach the eye.
- On a hologram a couple of exposures can be made, without changing the position of the plate. By reconstructing the hologram a superposition of the images takes place. This can be used either for a double-pulse technique to determine velocity-fields or for

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[1] In this case of the superposition of a spherical wave with a planar wave, a system of circles, with decreasing distances by increasing diameter is created, called "Fresnel-zone-system".

[2] In an "off-axis" holographic set-up, the objective wave and the reference wave come from different directions, in an "in-line" set-up the objective wave concides with the reference wave, as shown in figure 2.

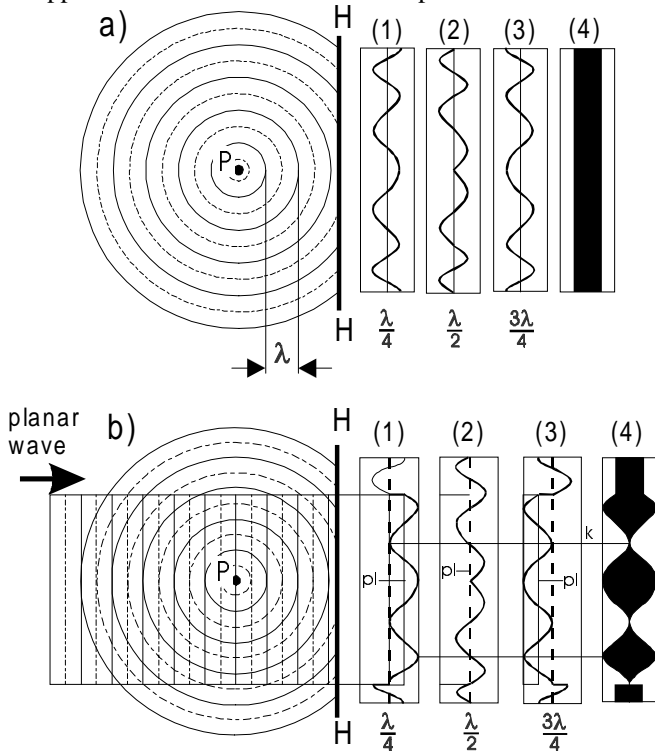holographic interferometry [19]. These two special application will be described in chapter 2.1. and 3.

Figure 1: Principle of recording a holographic-plate: a) without a reference wave the whole plate is illuminated with the same intensity, b) by the superposition of the wave coming from point P (object wave) with a reference wave, the phase of the interference-minima is constant by time. pl = planar reference wave, k = interference-minima.
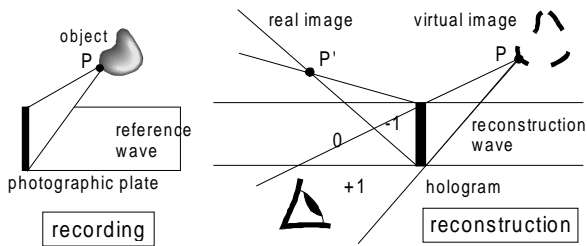

Figure 2: Record and reconstruction of an off-axis hologram. The microscopic pattern on the holographic plate acts like a diffraction grating with a local variable grating constant.

For conventional application of holography, lasers, emitting continuous monochromatic light, can be used. The recording of very fast moving or changing objects needs ultra-short exposure times, which can be achieved by a pulsed laser. A holographic set-up, using a pulsed laser is shown in figure 3.

In this arrangement, the light, emitted by a pulsed ruby laser (wavelength • = 693 nm, pulse duration 30 ns) travels through a system of a beam splitter, lenses and mirrors,

where it is expanded, divided and guided through the measuring object onto the holographic plate. This set-up is suitable for studying particle flow or phase distribution in multiphase mixtures. It allows to visualize dispersed flow – like in post dry-out heat transfer with droplets down to 10 times the wavelength of the laser light.

For evaluating the hologram it first has to be reconstructed, as demonstrated in figure 2. After the chemical processing the holographic plate is illuminated by a continuously light emitting helium-neon laser. If the holographic plate is replaced in the same orientation as during the recording process, a virtual image of the droplet cloud can be seen exactly at the place where it was produced previously. For a quantitative evaluation an enlarging lens or a microscope can be connected to a camera. To do this, the holographic plate has to be turned by 180°, so that the real image which has a three-dimensional extension appears in front of the camera.
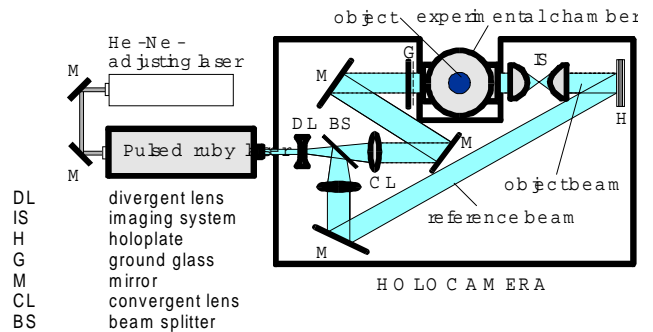

Figure 3: Holographic set-up for ultra-short time exposures with a pulsed laser. As the puls duration of a ruby laser is about 30 ns, a continuous light emitting He-Ne-laser has to be used for the optical adjustment.

With a macroscopic lens, only a very narrow area of the spray will be well focused and by moving the camera forwards or backwards, the image can be evaluated plane by plane. The decision about the sharpness of a contour is made by a digital image processing system described in detail by [6], [20]. An example of the result of such an computer-aided image processing is shown in figure 4. The upper row in this figure shows the region of the spray near the nozzle, and the lower one, a region further downstream, where the veil is already disintegrated into a droplet swarm. By applying specially developed algorithms [7], the cross-section area, the diameter and the concentration of the droplets can be determined automatically.

Figure 4 gives an impression how the numerical procedure changes the original photographic picture into a computerized one which contains only information of particles being exactly in the focus plane, a slice, which is in this case thinner than 0.5 mm. The first module of the software transforms the original image (A), seen by the videocamera into a binary image. This original image of a holographic reconstruction is smoothed (B) and treated with a gradient filter (C). Sharply imaged structures are detected, edged and filled. Finally the image is binarized (D). An

additional tool in this module allows to analyse either the big structures like the liquid veil (E, above) or only the smaller structures like droplets (E, below).

velocity of droplets as well as their changes in size and geometric form can be evaluated [6].

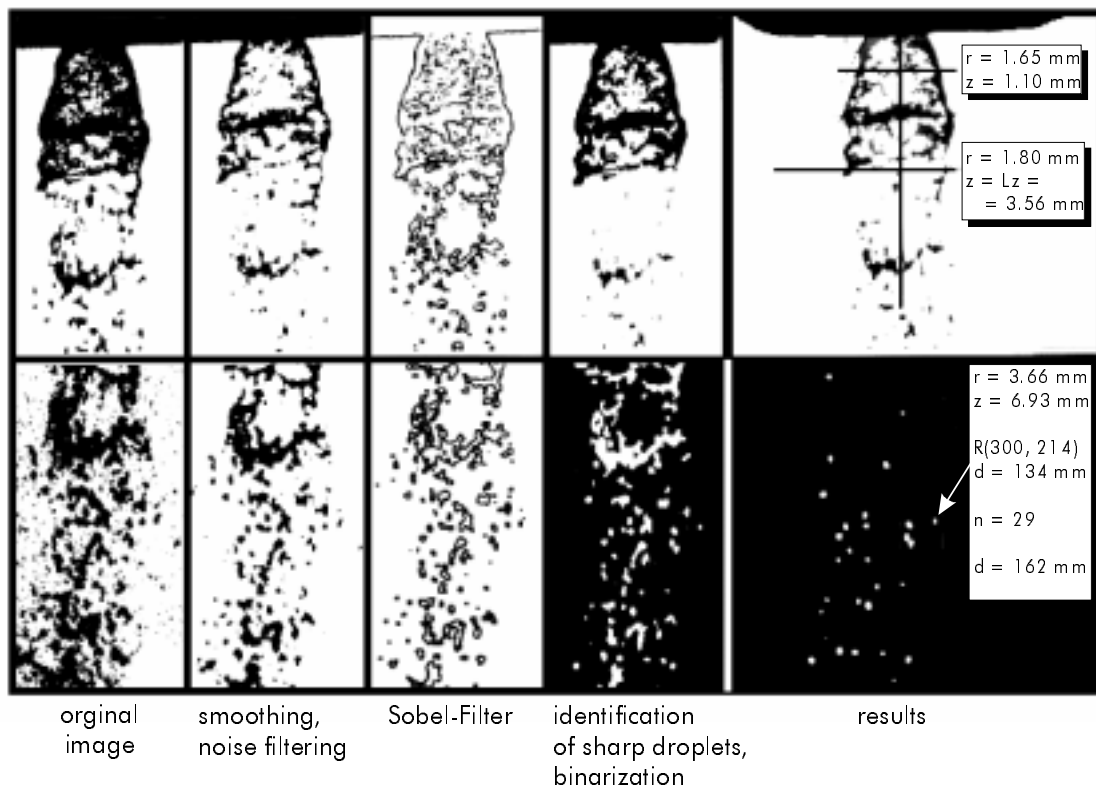The method of velocity measurements becomes

| orginal image | smoothing, noise filtering | Sobel-Filter | identification of sharp droplets, binarization | results |

Figure 4: Steps of image-processing of hologram. Upper row: Spray near the nozzle. Lower row: Spray downstream the nozzle.

2.1. Double-pulse holography

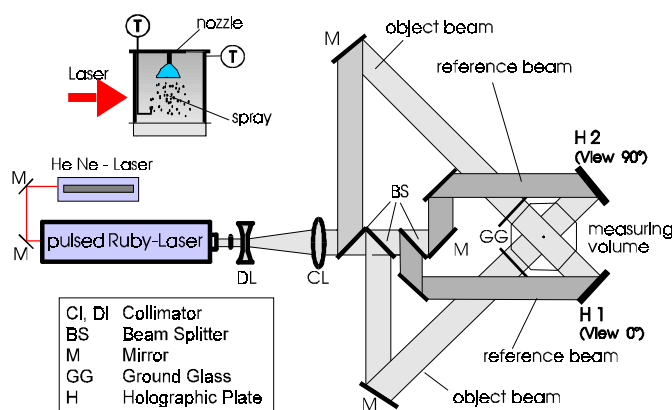As mentioned above, it is possible to illuminate the

Figure 5: Holographic set-up for stereomatching of strongly three-dimensional measurement problems. The two holographic plates are exposed at the same time.

photographic emulsion of a holographic plate sveral times before processing. For example, this can be done with a ruby laser which allows to emit more than one laser pulse within a short period of time (1-800 •s). Using this method the

complicated, if the motion of the particles is strongly three-dimensional. In such a case, pictures of a series of focus planes have to be scanned, digitized and correlated to each other to find the same droplets which were exposed at different times and are located in different focal planes. A computer code using a Fourier analysis to do the evaluation algorithms can be found in literature [15].

Nevertheless, this technique becomes more and more difficult when the droplets of the spray have different directions as usually within technical applications of sprays. Hence a new method called "stereomatching" was developed in which two holograms are recorded simultaneously and perpendicular to each other. The optical set-up is shown in figure 5, for the evaluation, both holograms have to be scanned and digitized by a camera, which is still focused stepwise along the depth co-ordinate in order to record the entire three-dimensional information contained in the holographic image. For the handling of this huge amount of data, the software described above was extended for stereomatching, which is described in [12].

3. HOLOGRAPHIC INTERFEROMETRY

Up to the 70th mostly the Mach-Zehnder-interfermometry [19], was used for optical investigation of temperature fields, temperature gradients and heat transfer

coefficients. A planar light wave, coming from the left side is divided into two object waves by a semipermeable mirror. The first object wave passes through the test section, while the second object wave is going the way around the test section. Caused by a temperature or density gradient in the test section, the phase distribution of the first object wave changes. The two waves are superposed after another semipermeable mirror. This leads to a macroscopic interference which shows the temperature or density field in the test section. This macroscopic interference caused by a temperature gradient must not be mixed up with the microscopic interference, we use for holography (as mentioned in chapter 2). The optical set-up for this technique has to be very precise and all optical devices have to be best quality, as a small difference of the refraction index on the way of the two light waves leads to an unintentional interference. In the case of a closed test section with windows, two equal chambers, have to be applied, to ensure two equal beam paths.

The holographic Interferometer avoids these problems of Mach-Zehnder-Interferometrie, as for the second object wave the holographic reconstruction of the test section is used. Thus two waves are superimposed which pass through the same test section at different moments, and changes which occur between the two recordings are interferometrically measured. In order to determine for example the heat transfer, the recording of the first wave is made, when all desired processes in the test section are in operation (fluid flow, pressure and mean temperature) but not that process (the heat transfer from a plate or from a bubble) which is of interest. In the following, two techniques doing this are explained:

- double exposure technique and
- real time technique.

As described before several object waves can be recorded, one after another, on one single holographic plate before the photographic emulsion is being developed. By illuminating the plate with the reference wave, they are all reconstructed simultaneously (figure 6). If they differ slightly from one another, the interference between them can be observed (figure 6, lower part). In this example the first recording was done, when the test section (tube) had a constant temperature distribution. After that a temperature field was established by heating up the wall of the tube. Now the incoming light waves received a continuous, additional phase shift, due to the temperature field. This wave front (measuring beam) was recorded on the same plate. After processing and illuminating the hologram, both waves were reconstructed simultaneously and they interfered.
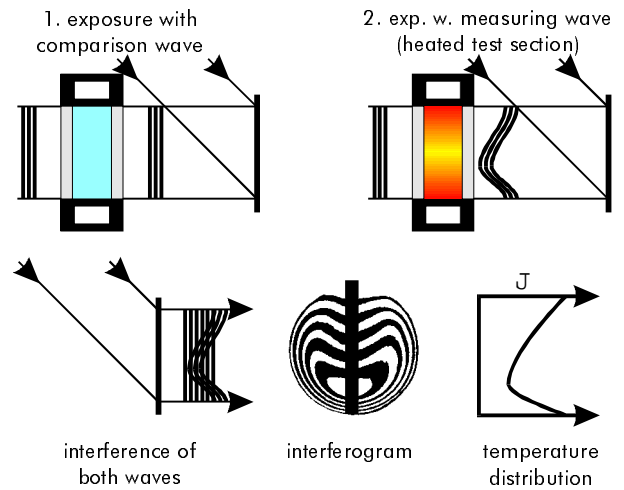

Figure 6: Principle of the double exposure technique

By means of this method – in comparison to conventional interferometry techniques – the same object beam is compared at different times. Since both waves pass through the same test section, any imperfections of the windows, mirrors and lenses are eliminated. Examinations even at very high pressures can be made, because the deformation of the windows can be compensated.

This method of double-exposure technique is simple to handle, however, the investigated process cannot be continuously recorded and the result of the test can only be seen after developing the photographic emulsion. Hence a more sophisticated recording process for holographic interferometry, the real-time method, was developed, illustrated in figure 7.
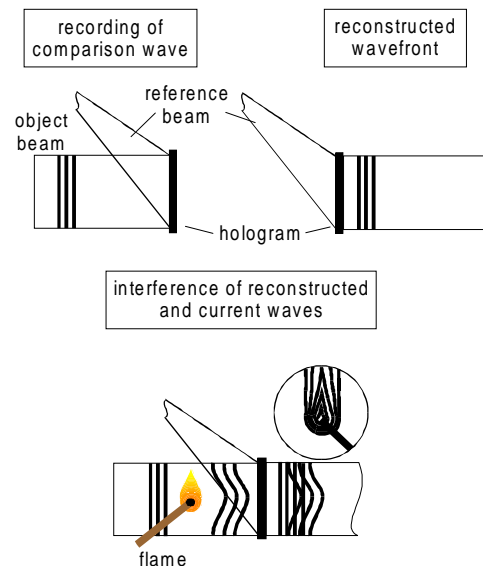

Figure 7: Principle of the real time method

After the first exposition of the hologram, during reference conditions of the test chamber, the hologram is photographically developed and fixed. The plate is exactly repositioned to the former place in the optical set-up. This can be done with piezo quarz positioning devices with an accuracy of half a wavelength. By illuminating the hologram the comparison wave can be reconstructed continuously. This wave can now be superimposed to the momentary
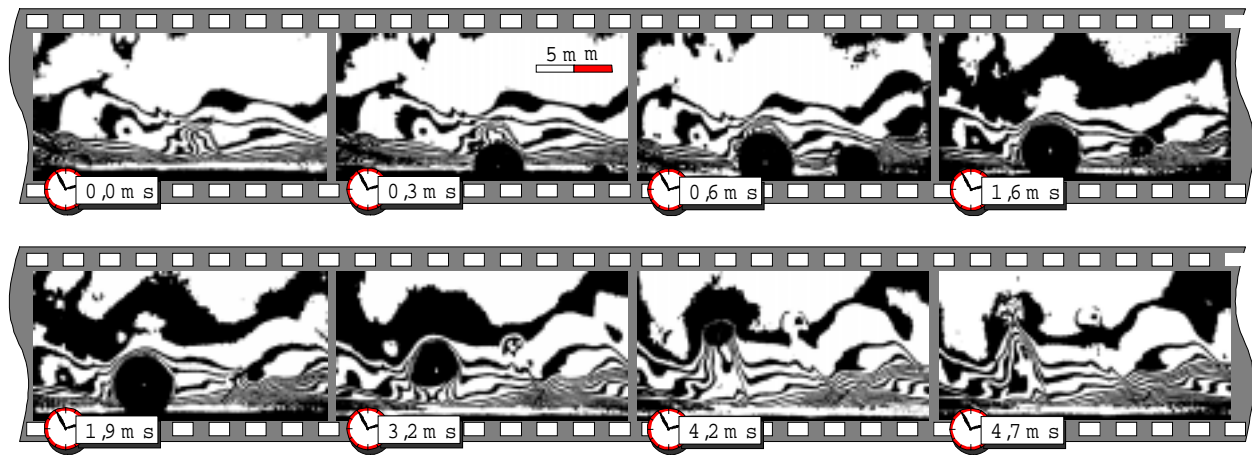
Figure 8: Detachment and recondensation of bubbles from a heated wall

object wave. If the conditions in the test section are not changed, compared to the situation of the first exposure, no interference fringes will be seen on the hologram. This indicator can be used for replacing the hologram exactly to its old place. By starting the heat transfer process, the object wave receives a phase shift, due to the temperature field in the examined fluid. Both waves interfere with each other, and the changes of pattern can be continuously observed or filmed.

In figure 8 an example of detachment and recondensation of bubbles from a heated wall is shown. The black and white lines – called fringes – in these interferograms represent in a first approximation isotherms in the liquid. So if the fringes are close together, there is a steep temperature gradient, fringes far apart from each other show a plateaux of almost constant temperature. One limitation of this optical measurement method can also be seen in figure 8. The light passing the test section is not only shifted in phase,it is also deflected, depending on a positive or negative temperature gradient, to the wall or from the wall. Hence a thin zone very near to the wall appears as a grey pattern without interference fringes.

3.1. Evaluation of the interferograms

As described before, the physical principles of the interference effect of the holographic interferometry are similar to Mach-Zehnder interferometry. The difference of both methods is the origin of the reference beam which has no influence to the interference effect due to a temperature field in the test section. Thus the evaluation of both methods is quite similar to each other and can be found in the literature [20],[21]. However, to obtain absolute values for the temperature field, the temperature at one point of the cross section has to be determined, for example by thermocouple measurements. This is usually done in an undisturbed region or at the wall of the test chamber.

All examples of measurements discussed by now are of two dimensional nature, but also three-dimensional temperature fields, for example, spherical and cylindrical temperature fields, can be measured by holographic

interferometry. In this cases, the Abel correction has to be used, which is described in [8], [16].

3.2. Finite Fringe Method

As the boundary layer at a heat-transferring surface becomes very thin with higher heat transfer coefficients, it is quite difficult to evaluate the interference pattern. In such a case it can be helpful, to create a pattern of parallel interference fringes after producing the reference hologram. This can be done by tilting a mirror in the reference wave or by moving the holographic plate within a distance of few wavelength. The direction and distance of the pattern depends only on the direction of movement of the holographic plate or mirror. The result of the so called "finite fringe method" is compared to the earlier described "infinite fringe method" in figure 9. By imposing a temperature field, due to the heat transfer process, the parallel fringes are deflected which is a measure for the temperature gradient. This allows to deduce the heat flux and consequently the heat transfer coefficient. The detailed evaluation process is described well in [9].
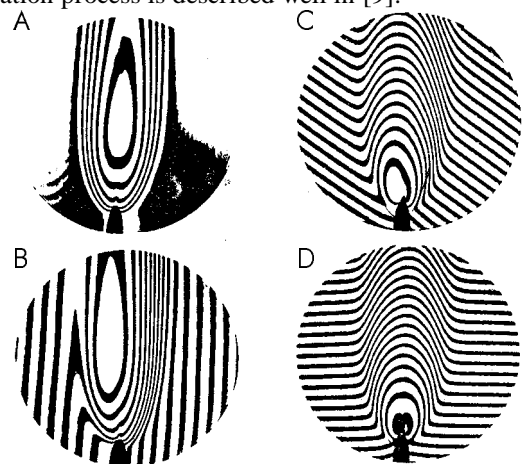

Figure 9: Interferograms of a Bunsen-burner flame - Infinite fringe method (Picture A)
and Finite fringe method with different orientations of the undisturbed fringes.
B: vertical, C: inclined, D: horizontal

The light passing the measurement volume cannot only be phase-shifted by a temperature field but also by locally different densities, caused by concentration gradients. In these cases two unknown variables – temperature and concentration - have to be found, by solving the interferometric equations. This can be done by using two laser simultaneously, emitting light of two different wavelengths. As the refractive index is depending on the wavelength of the light (as known from the rainbow phenomena), two sets of equations are available – one for each wavelength – and the system is solvable for two unknown variables. The problem of this method, described in detail by [22], is that the two interferograms originating from these two beams of different wavelengths have to be superimposed very accurately. As already described, it is possible to record different interference pattern on one and the same holographic plate which is done by means of the two-wavelength method.

4. LIGHT SCATTERING METHODS

The lower part of table 1 shows some of the most common light scattering techniques, used for thermo-fluiddynamic investigations. A summarisation and detailed explanation of various light scattering methods can be found in [11]. This methods are based on the principle that photons are in interaction with particles which are lifted to a higher rotational, vibrational or electronic level. After a certain time - depending on the special technique - the particle drop back (but not always exactly to the same level as before) and emit light of a special wavelength. In order to get a high light flux and a well defined wavelength of the incoming light, mostly laser are used as light sources. Scattering processes having the same wavelength as the exciting light wave are termed elastic processes, if a shift of the wavelength occurs, the phenomena is termed inelastic scattering process.

4.1 Mie scattering

The elastic scattering process, where the size of the scattering particle is bigger or not much smaller than the wavelength of the incoming light is called Mie scattering, which is a very strong process. Unfortunately it is not dependent on the density, temperature or species concentration and hence cannot be used for the measurement of these dimensions. But this type of scattering can be used for some other very important techniques like particle image velocimetry (PIV) or laser Doppler velocimetry (LDV). PIV is a two dimensional method, where a laser beam is formed into a thin light-sheet illuminating a plane within the volume of interest. The radiation scattered by the particles in the illuminated area is recorded by a camera. LDV [10] is based upon the principle that two laser-beams of the same origin are focused to a small measurement volume. When a particle passes this measurement volume, the Doppler frequencies of the Mie-scattered light can be directly transformed to velocities. With three different coloured pairs of laser beams, all three velocity dimensions can be determined simultaneously. As the datarate, depending on the particles in the flow, is very high this method can be used very well to determine turbulence parameters.
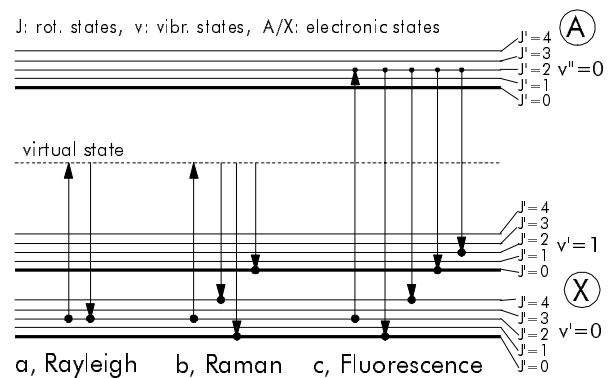

Figure 10: Energy diagrams for Rayleigh scattering (a), Raman scattering (b) and laser induced fluorescence (c).

Scattering processes of light quanta from molecules or small particles (with a diameter much smaller than the wavelength of the incoming light like molecules) are for example Rayleigh scattering, Raman scattering or Fluorescence (figure 10).

4.2 Rayleigh scattering

Rayleigh scattering can be observed, if after the interaction with incident light quanta the molecules return to the same state in which they have been previously. As it is an elastic process, the scattered photons have the same frequency as the incoming light, hence, the scattered signal is not specific to the species in the measurement volume. Therefore this method can be used to measure densities, and by using the gas law in constant pressure situations, also temperatures can be determined.
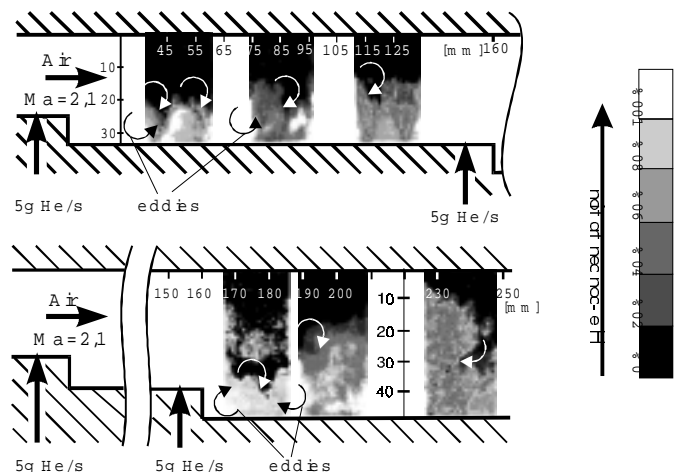

Figure 11: Helium distribution in a supersonic flow, measured by Rayleigh scattering

By using a two dimensional optical set-up, this can be compared basically to the one used for laser induced fluorescence as shown in figure 15, keeping in mind that different lasers, lenses and camera systems might be used. A laser beam is formed into a thin light-sheet by two lenses, and the Rayleigh scattered light is recorded perpendicular by

a CCD-camera. It can be assumed, that having particles in the test region leads to an additional Mie scattering process which cannot clearly be distinguished from Rayleigh scattering. So the experiments, examined with this method have to be of a clear, fundamental nature like the example shown in figure 11 [13], where helium is added from two positions at the wall into a supersonic flowfield. These experiments were made to investigate the mixing processes in supersonic flows for future aircraft propulsions, in this case a scramjet, with hydrogen as fuel.

4.3 Raman scattering

The principle of Raman scattering as an example of an inelastic scattering process is shown in figure 10 b). By exciting a molecule with a photon, it is shifted to a non stable virtual state from which it drops back within a time of 10^{-12} sec or less. But contrary to Rayleigh scattering, the molecule turns into a higher or lover level than the original one. Therefore the scattered radiation is shifted from the incident light wave by the characteristic frequencies of the media. For historical reasons, a downshift in frequency is called Stokes, an upshift is called anti-Stokes. The fact that the Raman scattered signal is species specific and linearly proportional to the number of species makes it a very useful tool for the examination of species concentration in combustion processes. Figure 13 shows an example of Raman scattering in a burner before and in an hydrogen air flame [3]. As the concentration of nitrogen can be assumed as being mainly constant, the different scattering intensities of nitrogen in this example can be used to determine the local temperature.

Figure 12: Typical Raman set-up with two alternative detection systems. Usually only one of the shown possibilities is used.
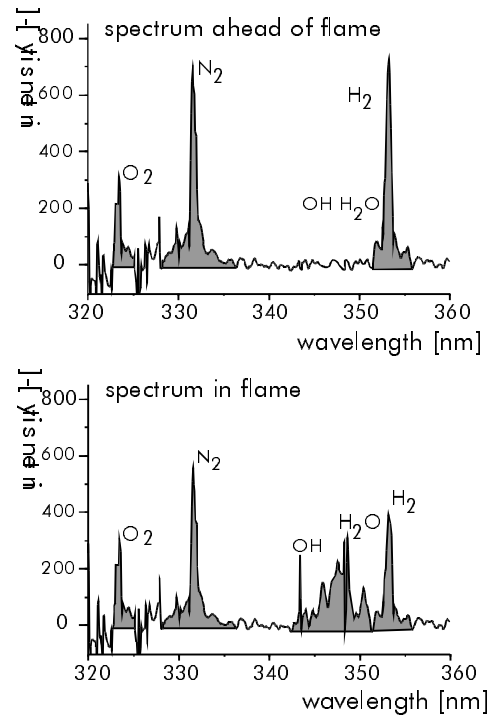

Figure 13: Typical spectra from a representative point in a burner. Left: unburned mixture with 12 % hydrogen in air. Right: spectrum from the turbulent reaction zone.

So far, Raman seems to be a perfect tool for the examination of concentrations and temperatures. Unfortunately, for practical use, Raman spectroscopy has also a couple of disadvantages compared to other scattering methods described here. The optical set-up is quite complicated, as the emitted light has to be spectrally analysed to identify the single species. By using a spectrometer as shown in the lower part of the optical set-up in figure 12 a point or one-dimensional spectral analysis can be realized. Interference filters (shown in the upper part of picture 13) allow the observation of only one species per filter. However, the collected Raman signal to laser energy ratio in flames is about 10^{-14}, which leads to a very poor signal (even by using high energy lasers and specially intensified cameras) and bad signal to noise ratios.

4.4 Laser induced fluorescence (LIF, LIPF)

By choosing a laser wavelength which allows to lift the molecule even to a higher electronic energy state the so called laser induced fluorescence can be observed (figure 10 c) when the molecule drops back to a lower level again. As the level the molecule is lifted to is not a virtual state - as used with Rayleigh or Raman scattering - but a semi-stable state, the lifetime of the molecule in this excited state can be much longer (10^{-10} to 10^{-5} sec). The fact that the laser induced fluorescence is species specific and the intensity of the scattered light is many orders of magnitudes stronger than those for Raman, makes it a very important tool for flame diagnostics.

However, radiation is not the only possibility for an excited molecule to loose energy. Also dissociation, energy transfer to another molecule, energy transfer to other internal energy states within the same molecule and chemical reaction can take place and can summarised
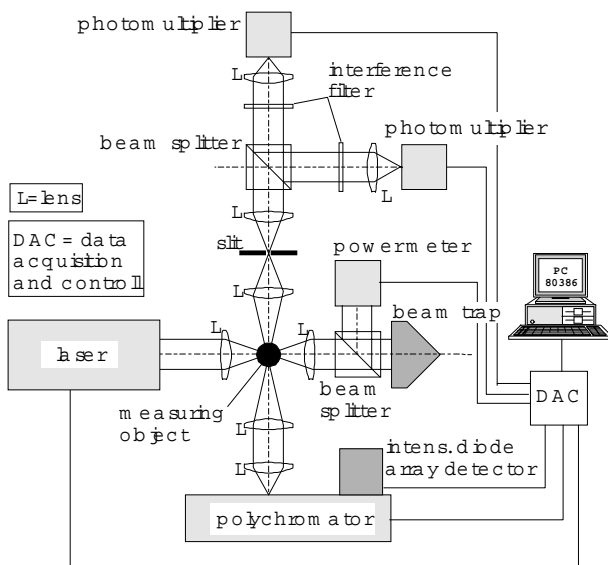
termed quenching effects. One can imagine that the main problem of these quenching effects is not only that they reduce the amount of fluorescence, but mainly that an quantitative interpretation of the observed fluorescence is nearly impossible, as the quenching rates are hardly ever known. However an analytical correction as far as possible can be found in literature [1], [2], [11]. There are several special techniques where there is no need for quenching corrections like the laser induced predissociation fluorescence.

The optical set-up can be simplified as drawn in figure 14. As described before, a thin laser light-sheet is formed by two lenses, a camera with a special lens and filter is recording perpendicular one or more fluorescence lines of one single species.

Figure 15 shows an example spectrum of laser induced fluorescence. This can be realised by using a pulsed excimer laser run with XCl, which has a wavelength of 308 nm, and an extremely short pulse duration of 17 ns. Two of these very short shots of a flame in a burner are shown in the right pictures of figure 15. In the upper picture, the flame is separating from the injection spot of the burner, in the lower picture a non reacting zone – in spite of a homogeneous mixture of fuel and air – can be observed over a long flowpath of the flame.
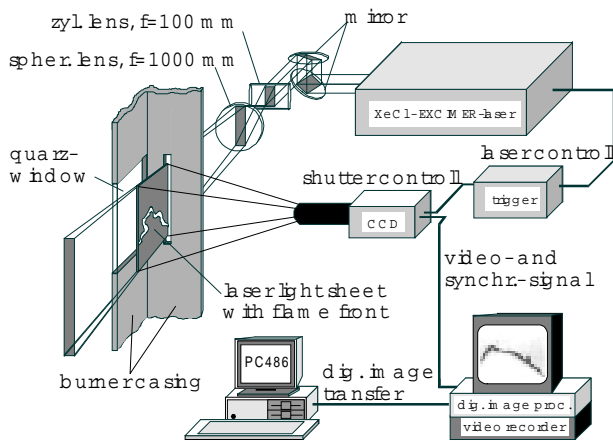
Figure 14: Optical set-up for laser induced fluorescence

Using this method, one has to be aware of the fact that the laser induced fluorescence as used in such a manner with an excitation wavelength of 308nm for OH is an elastic scattering process, thus the scattered signal can be interfered by Mie scattering of particles or reflection at windows or walls.
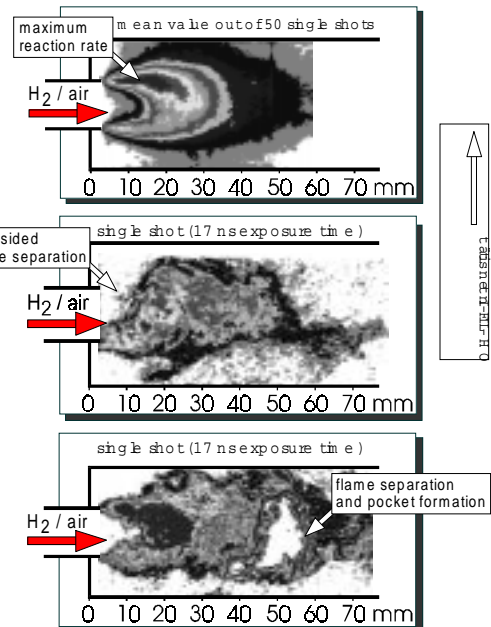
Figure 15: Laser-induced Fluorescence at a Hydrogen-Air Diffusion Flame

One possibility to get quantitative species concentration out of an fluorescence signal is the so called laser induced predissosiation fluorescence (LIPF). Hereby a state with a very high dissociation rate is excited with light of a special wavelength. This dissociation happens that fast, that the other quenching effects mentioned above can be neglected. To excite the OH-radical in that way a KrF-excimer laser (wavelength • = 248 nm) can be used. As this transition dissociates strongly, the scattered fluorescence signal is much lower than using LIF with 308 nm, but the signal can be quantified much easier. For practical use, due to the relative low signal, the experiment has to be as clean as possible. The test chamber should be free of reflection (as with all light scattering processes), and due to the fact that ordinary glass is not transparent for light of 248 nm (as well as for 308 nm) the windows have to be made out of quartz glass. When using this wavelength for excitation, the fluorescence signal appears frequency shifted with a wavelength of 295 – 304 nm as shown in figure 16. When using a filter, interfering signals can be almost tuned out. In figure 17 a propane diffusion flame is shown to demonstrate the effects of laser tuning and block-off filters.
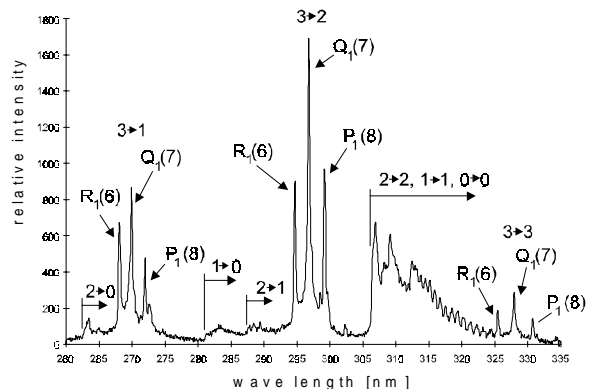
Figure 16: Spectrum of the emission of OH after the excitation with an KrF-excimer laser
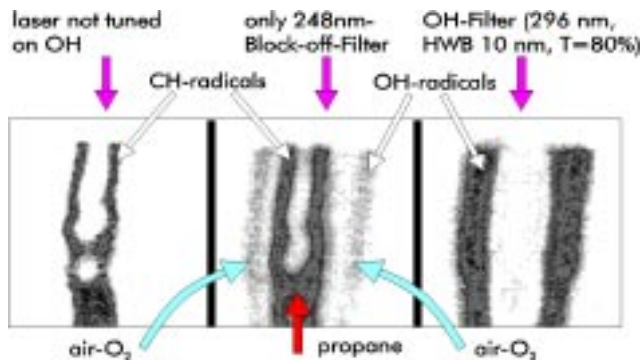

Figure 17: OH - / CH - LIPF at a propane diffusion flame

In order to demonstrate the capability of this optical method, the influence of the hydrogen concentration on the flame structure in an unsteady smooth tube burner is shown (figure 18).
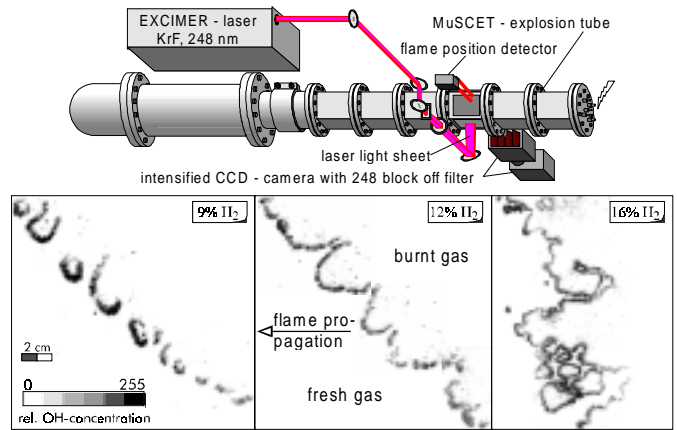

Figure 18: LIPF images of hydrogen air flames in an instationary tube burner

At a low hydrogen concentration, the single flamelets are not able to work against the buoyancy in the tube, so the flame is locally quenched. With 12% hydrogen in air, this effect is not that strong anymore, but still quenched zones can be determined at the negative curved areas of the flame. Adding more hydrogen (16%), a pocket separation at the flamefront takes place, which leads to bigger surface of the flame and to higher flame velocity.

5. CLASSICAL OPTICAL MEASUREMENT METHODS COMBINED WITH NEW CAMERA DEVICES

The camera equipment which is on the market nowadays opens new opportunities for classical measurement
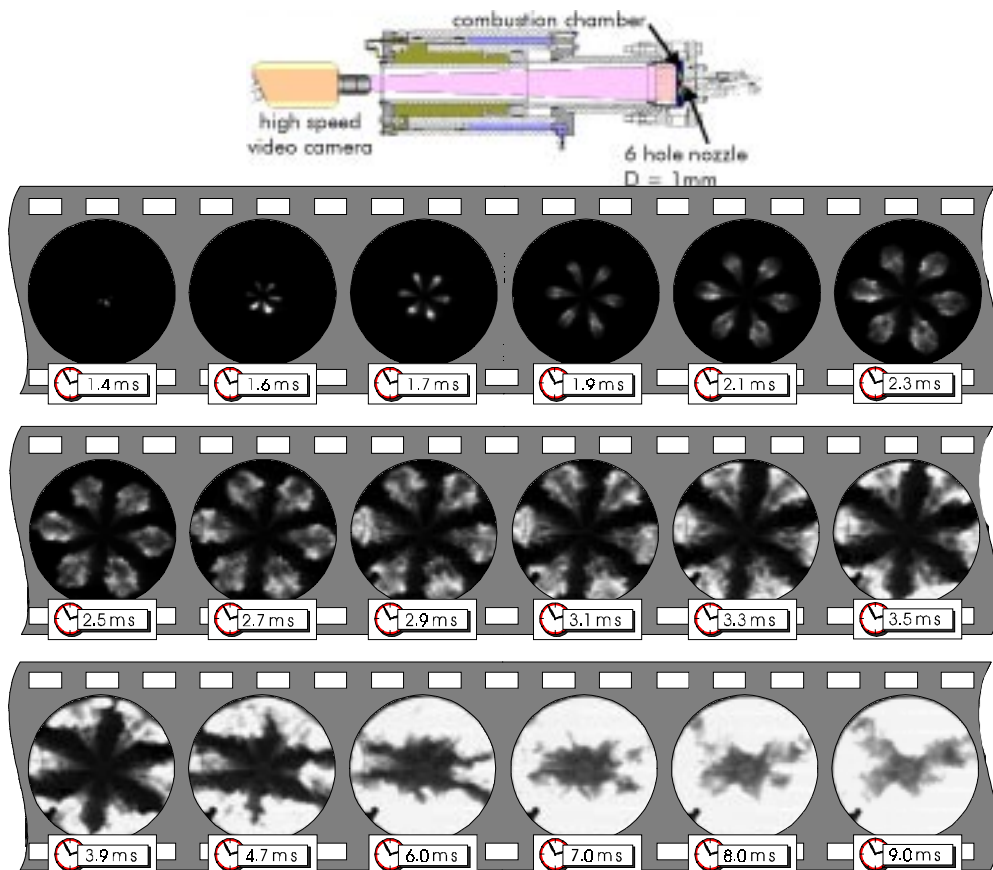

Figure 19: Self-fluorescence in a single-stroke engine with a piston diameter of 250 mm

techniques like the Toepler-Schlieren method or even the oldest known measurement technique, the examination of the so called self-fluorescence. This appears with reacting gas-mixtures undergoing high enthalpy differences, and can be observed even with the naked eye. It is based on the fact, that during a chemical reaction some of the particles already arise in an electronically excited state. A part of these excited particles radiate energy by spontaneous emission of photons in connection with a change in the energetic state of the molecule which is refered to as chemo-luminiscence. In figure 19 an example of the burning process in a ship engine driven with hydrogen is shown in which self-fluorescence occurs mainly during the OH-production [23].

Years ago, drum cameras - using photographic film material - were used to produce such high speed photographs. Depending on the spatial resolution repetition-rates of some 10.000 images/sec could be realised, by using a pulsed light source like a flash lamp. . One of the main disadvantages of this method was the handling of the photographic material. Due to the whole film developing process, the result of an experiment could be seen only half an hour after the experiment itself.

With modern high speed videocameras, it is possible to record sequences with repetition-rates of 45.000 images/sec and to store several thousand images in the internal memory of the system online. Immediately after the experiment, the result can be seen as a video film. Storing images in the computer for further processing works mainly automatically and is done within a few seconds per image. Another big advantage of this new high speed videotechnique is, that the internal image memory of the system can be overwritten continuously. By setting a trigger signal the camera stops recording and the last for example 1000 images taken before the trigger signal are kept in the memory. It is also possible to set the trigger signal in the middle of the experiment and to keep 500 images before and 500 images after the trigger. By investigating self-igniting combustion processes this is a very helpful tool, as the ignition time can not always be predicted precisely. Nevertheless the resolution of such a video system is 256 times 256 pixels, which is only a very small part of the resolution of classical photography.

By means of such a high speed video camera system the schlieren method developed by Toepler 1864 can be used in a new way for highly transient processes like the combustion in a closed tube (figure 20). The combination of an old but very sophisticated optical measurement technique with newest recording devices gives a very good insight into the dynamic processes of flame acceleration by obstacles as horizontal tubes, plates and wall-openings. The principles of the schlieren-technique itself, the optical set-up and the evaluation of the data can be found in the literature [16]. As the sequence shown in figure 19 and figure 20 can only give an idea about the effects of flame acceleration during the burning process, the authors have to refer to the internet homepage of the chair, where several Mpegs (computer video films) can be downloaded, including the examples shown in figure 19 (http://www.thermo-a.mw.tu-muenchen.de/ Lehrstuhl/Projekte/h2diesel/) and figure 20 (http://www. thermo-a.mw.tu-muenchen.de/Lehrstuhl /Projekte /puflag/).

6. CONCLUDING REMARKS

Advanced optical techniques offer new perspectives in the measurement of transport phenomena in Thermo-Fluiddynamics. The better understanding of these processes will give a push in the design of modern heat and mass transfering systems, such as heat exchangers, burners or combustion engines, and will result in an improved efficiency and reliability or reduced manufacturing costs of these components. Reliable measurements of important parameters in heat and mass transfer like temperature, density, velocity or species concentration are the basis for the mathematical modelling of transport processes. By including this knowledge into computer codes, it is possible to take advantage of the huge capabilities of modern computer systems for the prediction of the thermo-fluiddynamic behaviour of complex systems. In order to perform these measurements, sophisticated inertialess optical techniques are necessary, to examine for example the temperature field, the velocity and the heat transfer in the boundary layer or the temperature and local species concentration just ahead of a flame without disturbing the thermodynamic processes itself. The development of these techniques was influenced mainly by the availability of special light sources, cameras and evaluation devices. Nowadays, various types of lasers as coherent light source are on the market, each suitable for a certain technique, depending on special characteristics as high energy, ultra short pulse duration or tunable wavelength. For the visualization of thermodynamic processes intensified CCD (charged coupled device) - cameras were developed during the last years to detect the - often very weak - scattering signals with a high local resolution. High speed video cameras allow the detection of physical processes with a very high resolution in time and can give an overview on the dynamic behaviour of transient systems. Nevertheless, the huge amount of data, generated by optical, often three-dimensional, measurements, requires computer aided data processing and evaluation.

Figure 20: High speed Schlieren video technique, showing the flame acceleration by obstacles during the combustion process of hydrogen in air in a closed tube.

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