APPLICATION OF NON-INTRUSIVE DIAGNOSTIC METHODS TO SUB- AND SUPERSONIC H_2-AIR-FLAMES

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1. INTRODUCTION

Combustion is still the most important way to provide thermal energy. Therefore investigation of the behavior of combustion processes in general and the structure of flames in particular remains a challenging task. The interest of research focuses on the spatial and temporal behaviour of the reaction front characterized by the temperature and concentration distributions as well as the composition of the exhaust gases yielding the combustion efficiency and pollutant content. The agressive environment in combustion systems, as well as the high sensitivity to any kind of disturbance of the combustion process by conventional probes, requires non-intrusive diagnostic methods which are best provided by optical measurement techniques.

At Institute A for Thermodynamics of the University of Technology in Munich a wide variety of optical techniques such as holographic interferometry, shadowgraph imaging, laser Doppler velocimetry (LDV), Raman scattering, self fluorescence and laser-induced fluorescence (LIF) have been employed in investigations of various H_2-air combustion processes for many years. The aim of this paper is to demonstrate the capabilities and limitations of comparatively simple qualitative techniques, which in many cases deliver sufficient information for understanding the overall behaviour of combustion processes and serve as important tools for the reduction of the effort required by more sophisticated techniques. The qualitative techniques used are the shadowgraph and the self fluorescence from the flames, supported by Raman scattering and holographic interferometry. The latter are quantitative methods for the determination of concentration and temperature distributions.

2. NON-INTRUSIVE COMBUSTION DIAGNOSTIC METHODS IN H_2-AIR FLAMES

2.1. Shadowgraph Method

The shadowgraph technique is a useful tool to visualize turbulent shear layers, mixing jets and shock wave patterns in the vicinity of rearward facing steps in combustion chambers. The principle of shadowgraphs is based on elementary optics, and presupposes, that the refractive index of gases is a function of their density, temperature, concentration and pressure. [1,2] The expanded, parallel beam of a polarized light source (e.g., He–Ne–Laser) penetrates through the transperent object of measurement (for example a combustion chamber equipped with windows) and is projected onto a screen or camera. Inhomogeneities of the refractive index distribution inside the combustion chamber lead to deflection of some of the rays in the parallel beam. In the same manner, strong local changes in the refractive index caused by mixing jets, shock waves or flames, cause a strong deflection or even extinction of the rays penetrating them, which means that those rays do not hit their original projection location on the screen or camera. The light pattern created by the deflected and undeflected rays of the beam, is thereby a precise visualization of the flow field in the combustion chamber.

Monitoring and recording the highly turbulent flow structures in the combustion chamber was realized with an intensified CCD–camera with an extremely short exposure time of 100 ns and a frame frequency of 25 Hz. For recording the shadowgraphs, an ordinary video recorder was used. Fig. 1.1a shows the structure of the flow field around a supersonic H_2–air flame downstream of the exit of the combustion chamber. The picture shows the location of the oblique shock waves and the highly turbulent surface of the flame. More details of this combustion experiment will be given in Chapter 4.

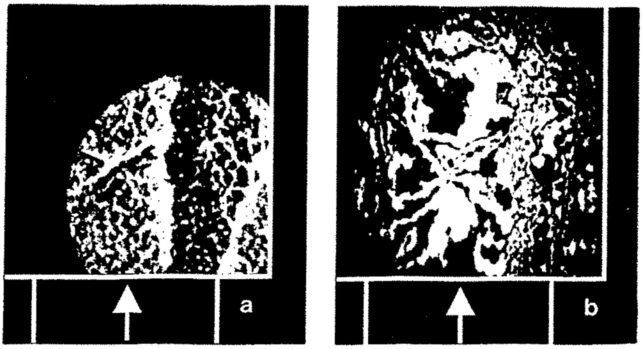


Figure 1.1. Visualization of high speed H_2–air flames by means of shadowgraph (a) und holographic interferometry (b) in the vicinity of the exit cross section of the combustion chamber. The Mach–number of the air flow is Ma = 1.2. H_2 ($\dot{m}_{H_2} = 0.25$ g/s) is injected perpendicular to the air flow. The shadowgraph picture (a) shows the location of the oblique shock waves and also the behaviour and the turbulent structure of the flame. The holographic interferogram (b) indicates the pressure distrubution around the flame with a set of oblique shock waves.

2.2. Holographic Interferometry

Holographic interferometry is an optical measurement technique for quantitative determination of pressure–, temperature– and concentration–profiles in gaseous flows. The principle is based on the superposition of a wave front of coherent laser light, which is deformed when passing through a transparent medium with a spatial distribution of the refractive index caused by changes of temperature, pressure, density or concentration with the original, undeformed wave front of the laser light. The experimental setup and the quantitative evaluation is discussed in detail by e.g. Hauf and Mayinger. [1,3]

To examine the mixing processes of the injected fuel jet in a H_2–fired combustion chamber, the beam of a He–Ne–laser is expanded and split into two beams, the object beam and the reference beam, respectively. The object beam penetrates the combustion chamber and is projected onto the transparent holographic plate. The reference beam interferes directly with the object beam on the holographic plate without passing the combustion chamber. Before starting the experiment, the holographic plate is exposed to the two interfering beams, so that all optical inhomogentities of the utilized optical elements (i.e., windows, lenses, mirrors, etc.) are recorded on the plate and therefore compensated. After development the holographic plate is repositioned to the original optical path and illuminated again with the object and the reference beam, and the interfering beams are monitored with the intensified CCD–camera described in the first subsection of this chapter. When the conditions in the combustion chamber are changed, for example by the injection of gaseous fuel, a fringe pattern caused by the interference of the deformed object beam and the non–deformed reference beam on the holographic plate is captured by the camera. Each fringe represents a certain change of the fuel concentration, so that evaluation of the whole fringe pattern gives the overall concentration profiles inside the combustion chamber. Fig. 1.1b. shows an example of a supersonic H_2–air flame in the vicinity of the combustion chamber exit, recorded by means of holographic interferometry.

2.3. Self Fluorescence

Self fluorescence (i.e., spontaneous emission) observation is a qualitative non–intrusive measurement technique used to visualize the dynamic structure and behaviour of flames. It is based on the principle that during combustion processes the molecules of intermediate reaction species are electronically excited by collisions (thermal energy) as well as by the chemical reaction itself. This excitation leads to an emission of light at wavelengths characteristic to the regarded species. Emissions from thermally excited molecules are referred to as thermal fluorescence; emissions from chemically excited molecules are referred to as chemiluminescence. In general, the spectrally selected acquisition of the emitted light yields information about the quantities of the participating species in the combustion process.

Looking at the combustion of hydrogen in air, the governing chemical reaction steps are the oxidation reactions of the fuel. The reaction front can be divided into an induction and a reaction block, where in the first steps intermediate products (like H and O atoms or the OH radical) are formed in endothermal reactions which then react to the final product (H_2O) under strong heat release. Since the intermediate species appear in significant concentrations only within the reaction zone, their emissions clearly mark this zone of strong chemical activity. In hydrogen flames the OH radical is a strong emitter, with the main emissions from the (0,0) band in the A-X system. The band head is at 306.4 nm, with the band shifted to the red. Monitoring the light sent out by the OH radical provides information about the distribution of the reaction fronts in a H_2–air–flame. [3,4] The self fluorescence is recorded with a standard 8-bit CCIR-video camera equipped with an image intensifier. A commercial quartz lens with a focal length of 105 mm suitable for the ultra-violet radiation is used to produce clear images on the sensor surface of the camera. The spectral selection of the light is achieved with an interference filter with the central wavelength at 307 nm and a bandwidth (FWHM) of 10 nm. The recorded intensities are converted to false color images with an on-line image processing system.

The big advantage of combustion investigations by means of self fluorescence is the simple experimental setup and the possibility to use self fluorescence even in large–scale technical objects (gas turbines, furnaces, ect.). The major disadvantage, similar to that of shadowgraph and holographic interferometry, is the integrating character of the technique. Chapter 4 of this paper will present a number of examples of how self fluorescence is used in combustion chamber diagnostics.

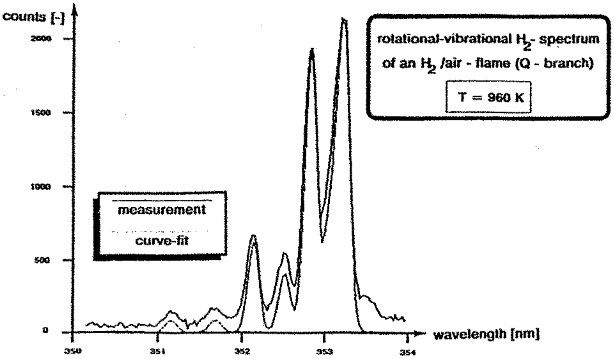


Figure 2.1. Spectrally resolved rotational-vibrational Raman lines of $H_2$from a H_2-air diffusion flame, excited with a narrow-band excimer laser (XeCl) at 308 nm. From the computer-fitted theoretical curve the system temperature is obtained.

2.4. Raman Scattering

Raman scattering is a quantitative non–intrusive diagnostic method to determine temperatures and species concentrations in flames simultaneously. The technique is either performed in point or in line measurements (i.e., 0- or 1-dimensional). Upon excitation by the laser beam the molecules emit light, which is frequency shifted in comparison to the exciting line. Each species exhibits a characteristic shift in frequency, therefore several molecules can be investigated with a single system simultaneously. The intensity of the Raman signal is proportional to the number of molecules of the measured species in the measuring volume, i.e., its absolute concentration.

In the setup used for the investigations presented in this paper, the laser is focused into a single point and the Raman signal is spectrally resolved with a polychromator coupled to an intensified diode array detector. All spectra are averaged data from 75 laser shots. With a highly dispersive grating installed in the polychromator, it is possible to resolve the rotational lines of the $v = 0 \rightarrow v = 1$ transition of the H_2 molecule to obtain the rotational temperature by a computer fit of theoretical curves to the obtained spectra (Fig. 2.1.). If all species, i.e., O_2, N_2, H_2O and H_2 are to be observed simultaneously, the spectral resolution of the system has to be reduced, and the temperature measurements are performed by scaling the absolute concentration of the inert N_2 with the aid of the law of ideal gases where the assumption of isobaric conditions may be applied.

Fig. 2.2. shows an example of typical Raman spectra in a H_2–air flame with the low resolution system. Three different positions of the flame are shown: before, in, and after

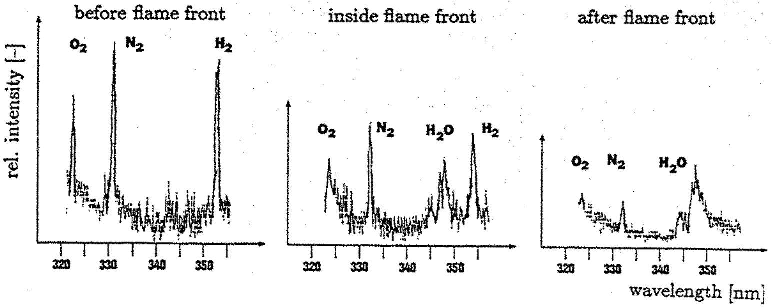


Figure 2.2. Raman spectra from a premixed H_2–air flame, obtained in a closed tube type burner with the flame stabilized behind a perforated plate. The spectra were obtained by excitation from a narrow-band excimer laser at 308 nm. Compared to Fig. 2.1., a polychromator grating with lower dispersion was used to reduce the spectral resolution. The background noise is increased significantly in comparison to open burners due to diffuse reflections from the windows. The spectra show the gas composition in three characteristic locations of the flames: before, in, and behind the reaction zone of the turbulent subsonic premixed, lean H_2–air flame. The absolute nitrogen concentration (represented by the area under the peak) decreases due to the increase in temperature. O_2 and H_2 concentrations decrease due to both the increase in temperature and the reaction as the steam content increases.

the reaction zone. For the evaluation of the spectra, a code was developed yielding the absolute scattering intensities (i.e., concentrations) for all spectra without modification, making a fully automatic evaluation of large numbers of spectra obtained at any location in the combustion system possible. A detailed description of the Raman scattering technique and probe as well as additional examples of evaluated spectra providing concentration and temperature profiles in premixed H_2–air flames is given in Reference 3.

Even though Raman scattering provides the strong advantage of great versatility in detectable species and simultaneous concentration and temperature measurements, it has two major disadvantages. First, it is only applicable in 0- or 1-dimensional measurements, requiring a large number of spectra in order to capture a technical combustion system. Second, the scattering efficiency is extremely low, leading to the necessity of data averaging over several laser shots for each spectrum, especially in closed combustion environments with increased background noise which lead to a loss in temporal resolution of the measurements.

3. VERIFICATION OF SELF FLUORESCENCE APPLICATION BY RAMAN MEASUREMENTS

In a closed tube burner, lean premixed H_2-air flames were stabilized behind a perforated plate. The approaching flow was turbulent and the flames were stabilized in the recirculation zones behind the grid without a pilot flame. First 3-dimensional concentration and temperature distributions were obtained by Raman measurements, then the self fluorescence emissions were captured with the intensified CCD-camera system described above.

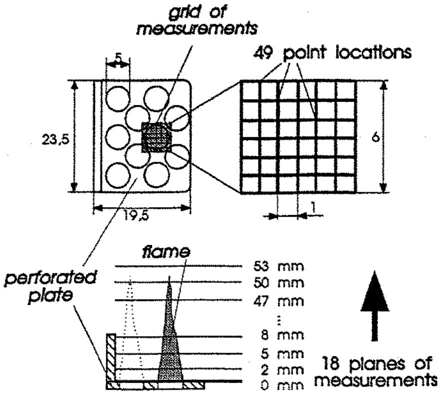


Figure 3.1. Schematic of scanning procedure of the investigated premixed flames by Raman scattering. 18 planes above the perforated plate, each containing a measuring grid of 7x7 points, yielding a total of 882 points, were examined for each burning condition. The center of the grid was identical to the location of the center of one opening behind which identical flames were stabilized. The planes were each 3 mm apart.

Behind each opening in the plate, separate but identical flames evolved. In order to characterize each of the flames, only one needed to be closely investigated. Fig. 3.1. schematically shows the scanning procedure employed for the Raman measurements. A 7x7 grid of measuring points was superimposed over the opening corresponding to the examined flame, each point of the measurement 1 mm from its neighboring points. The center of the grid was identical to the center location of the opening. The lowest plane captured was 2 mm above the grid, the highest plane at 53 mm, the planes were each 3 mm apart. With 49 measuring points in each plane, this yields a total of 882 points for the investigated flame.

The burner was mounted on a two-dimensional motor-driven sled. The Raman system and the positioning of the burner could be controlled from a single PC, allowing fully automatic data acquisition for all 49 points in each plane. The spectra were first stored on the computer hard disk, and subsequently evaluated. Since the number of spectra was too large for individual monitoring and selection during the evaluation, a code for fully automatic evaluation of the species concentrations of H_2 and N_2 was developed. From this the structure, i.e., the location of the reaction zone was obtained. The flames showed three characteristic zones (unburnt, partially burnt and fully burnt) which were separated by nearly conical contours. These are shown in Fig. 3.2. for a typical flame (left), as well as the superposition of the flames over each opening as seen from the wide side of the perforated plate (right). It can be seen that the contours of the reaction zones of the flames touch.

The self fluorescence images of the flames were taken viewing the wide side of the obstacle. The observed intensity distribution, resulting from integrated projections in the direction

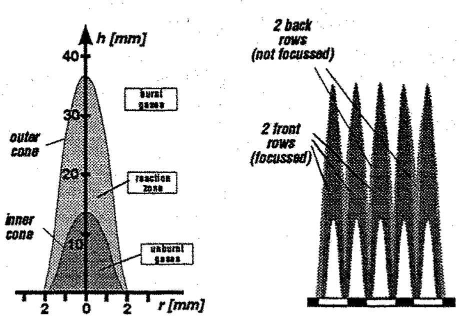


Figure 3.2. Left: Typical structure of the investigated premixed flames (equivalence ratio $\Phi = 0.29$;initial temperature $T_0 = 100°C$; approach velocity $\bar{u} = 10\ m/s$). The axes do not have the same scale.
Right: Front view of superimposed flames according to the structure displayed on the left. The reaction zones are marked dark. All distances are to scale.

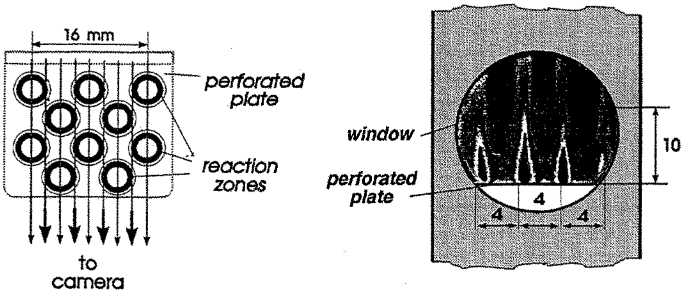


Figure 3.3. Left: Schematic of the intensity distribution observed due to the integration of the intensities along the path observed by the camera. The thickness of the arrows indicates the intensity of the integrated emission.
Right: Front view image of self fluorescence from the same flame shown in Fig. 3.2. The contours are slightly blurred from projection distortions due to the different distances of the individual flames from the lens.

of the lens, is schematically shown in Fig. 3.3 (left). Projection distortions limit the optical resolution of the flame images obtained from self fluorescence, yielding a slightly blurred image (right). It can be clearly seen that only the overlaid reaction zones yield strong emission intensities of self fluorescence, while the areas above the openings only show weak fluorescence due to a short integration path length. With increasing distance, the area of possible locations of the reaction zones increases leading to decreasing local emission intensity. Therefore, the integrated emissions observed by the camera also decrease rapidly and finally vanish above the height of the inner cone.

Since at the base of the flames, i.e., directly above the perforated plate, all investigated flames revealed the same structure, an analysis of the emission intensity could be performed in order to obtain information on the source of the fluorescence. While thermal fluorescence is extremely strongly dependent on the system temperature, chemiluminescence intensity is rather a function of the production rate of OH. In the images, an increase in intensity was recorded when the equivalence ratio of the combustible mixture was increased. When the initial temperature was increased, on the other hand, no change in emission intensity was obtained. Therefore it can be concluded that the self fluorescence in H_2-air flames originates from chemiluminescence rather than from thermal fluorescence. This conclusion is supported by a conservative estimation of the thermal fluorescence from the flames, which yielded maximum intensities well below the required minimum illuminance of the photocathode of the camera.

The pictures show that with self fluorescence, the reaction zones can be visualized very distinctly if the integrating character of the measurements is considered. Therefore the application of the method of self fluorescence yields very good global information on the shape and location of reaction fronts. Since the fluorescence seems to originate from chemiluminescence rather than from thermal fluorescence, the images mark the actual reaction zones even more distinctly since no emissions from the high temperature regions of the unburnt gases behind the reaction zones are captured. Self fluorescence is especially valuable in large scale systems providing poor access for laser techniques and requiring vast numbers of measurements due to the large volumes to be captured.

4. INVESTIGATION OF SUB– AND SUPERSONIC H_2–AIR–FLAMES BY MEANS OF NON–INTRUSIVE DIAGNOSTIC METHODS

Future fully reusable hypersonic air–lifting systems for orbital flight presume the application of supersonic combustion ramjet engines (SCRAM–jets). Due to environmental aspects and its high content of energy per unit mass, H_2 is the most promising type of fuel. To ensure the high performance and secure operation of H_2–fired SCRAM–jet engines, the mixing processes of H_2 and air as well as the stabilization and structure of the H_2–air flame in the combustion chamber must be understood very well. The investigations of those processes in sub– and supersonic flow combustion chambers by means of non–intrusive diagnostic methods are described in this chapter.

The structure and the behaviour of sub– and supersonic H_2–air–flames was investigated in a blow–down windtunnel with a two–dimensional combustion chamber as shown in Fig. 4.1.. The maximum Mach–number of the air was 1.3. The gaseous fuel was injected into the air flow under different angles with three different injection modes: single hole injection, twin hole injection and slot injection. The rearward facing step downstream of the injection block was used to create a recirculation zone with a free turbulent shear layer to enhance the mixing process of H_2 and air and to ensure stabilization of the flame. Quartz windows at the side walls made the combustion chamber accessible for the optical measurement techniques. Downstream of the exit of the closed channel a flame table with an additional rearward facing step was appended to the combustion chamber. The parameters for the investigations were the Mach–number of the air ($0.2 \leq Ma \leq 1.3$), the mass flow of the injected H_2 ($0.25g/s \leq \dot{m}_{H_2} \leq 3.0g/s$), the height of the rearward facing step in the combustion chamber ($0mm \leq h \leq 10mm$) and the injection angle ($\alpha = 90°$, $\alpha = 45°$, $\alpha = 0°$).

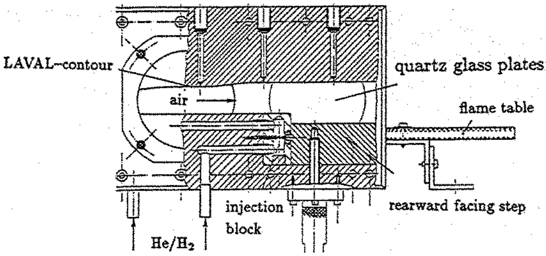


Figure 4.1. Combustion chamber for investigation of the structure and behaviour of sub– and supersonic H_2–air–flames. The H_2 was injected under different angles and geometries into the air flow, where the rearward facing step downstream to the injection block was used to enhance the mixing processes and stabilize the flames.

4.1. Mixing Processes of H_2 and Air in High–speed Flows

The influence of the turbulent recirculation zone on the mixing process of hydogen and air was determined by holographic interferometry with the finite–fringe technique. [1,3] As those investigations were done without combustion (so–called "cold mixing"), helium was used as a substitute for H_2 due to safety considerations. Apart from the general influence of the rearward facing step on the mixing process, the main matters of interest were the penetration of the mixing jet into the air and the mixing length. The finite–fringe technique was used because of its higher accuracy in determining the concentration profiles in the mixing jet.

When using a single injection hole to inject helium, the mixing jet will have a 3–dimensional structure. To take this into account, the mixing process was monitored from two perpendicular directions. Fig. 4.2. shows the interferograms received from the two directions and the evaluated concentration profiles of the mixing jet. The mass flow of the injected helium was 3.0 g/s and the Mach number of the air was 0.6.

The holographic interferograms show that the mixing jet contacts the side walls of the combustion chamber some 20 mm downstream of the injection hole, so that downstream from that contact point the mixing jet can be treated as 2–dimensional. It can be seen that the penetration is high because of the high specific momentum of the helium jet compared to the specific momentum of the air flow. The evaluated concentration profiles show large gradients in the shear layer of the recirculation zone, a fact which is very important for stabilization of the flame as discussed later in this chapter.

The influence of the air Mach number and the helium mass flow on the development of the mixing jet and on the structure of the outer flow field is shown in Fig. 4.3.. It can be seen that with an increasing Mach number, the mixing jet will be more and more compressed and deflected into the turbulent shear layer. Therefore the penetration is rapidly decreasing. In supersonic air flows an oblique shock wave, generated at the injection hole and deflected at the opposite combustion chamber wall, runs into the mixing jet and deflects it into the recirculation zone of the rearward facing step. Experiments showed that a rearward facing step leads to a normal shock wave upstream of the injection hole and therefore to the transition into subsonic flow. The increase of the helium mass flow, which is equivalent to an increase of the specific momentum of the helium jet, leads to an increase of the penetration

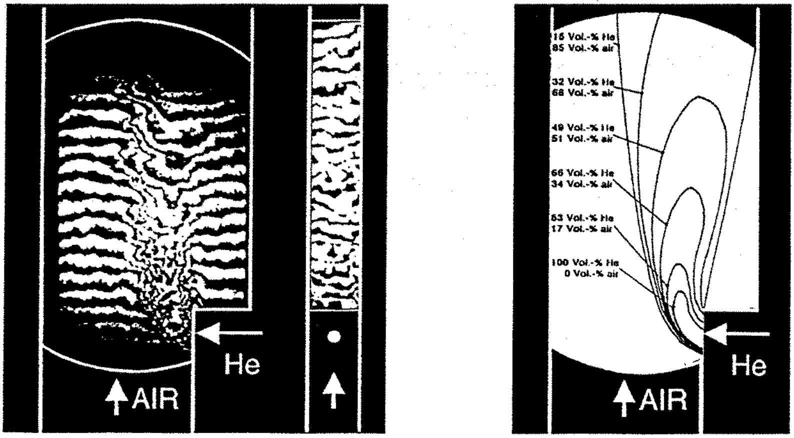


Figure 4.2. Holographic interferograms of a mixing jet monitored from two perpendicular directions and the evaluated concentration profiles of the mixing jet. The air Mach nunber was 0.6, the injected mass flow of the helium 3.0 g/s, and the injection angle 90°. The utilized exposure time of the CCD–camera was 100 ns. It can be seen that the mixing jet contacts the side walls of the combustion chamber some 20 mm downstream of the injection hole, so that from this point downstream the mixing jet can be treated as 2–dimensional. The evaluated concentration profiles show large gradients in the shear layer of the recirculation zone.

and mixing length. The thickness of the mixing jet is also increasing, which leads to a decrease of the concentration gradients in the jet.

The shapes of the mixing jets are very turbulent, with the size of the vortices on the surface increasing with increasing air Mach number and helium mass flow. These vortices lead to coherent, wavy structures on the surface of the flames which in some cases affect transversal flame oscillations. At air Mach numbers higher than 0.6 or 0.8, and depending on the helium mass flow, the mixing jet and turbulent shear layer overlap or are even identical.

Overall, the investigation of the mixing processes described above enabled prediction of the structure and behaviour of high–speed H_2–air flames, though helium was used as a substitute for H_2 and the experiment was performed without the influence of the combustion process.

4.2. Structure and Stabilization of High–speed H_2–Air Flames

The structure and the stabilization mechanisms of sub– and supersonic H_2–air flames was investigated by means of self fluorescence and shadowgraph imaging. Matters of interest were the temporal behavior and structure of the flames depending on the air Mach number and the H_2 mass flow as well as the influence of large–scale turbulent sturctures on flame stabilization. Though both applied techniques are integrating the optical information over

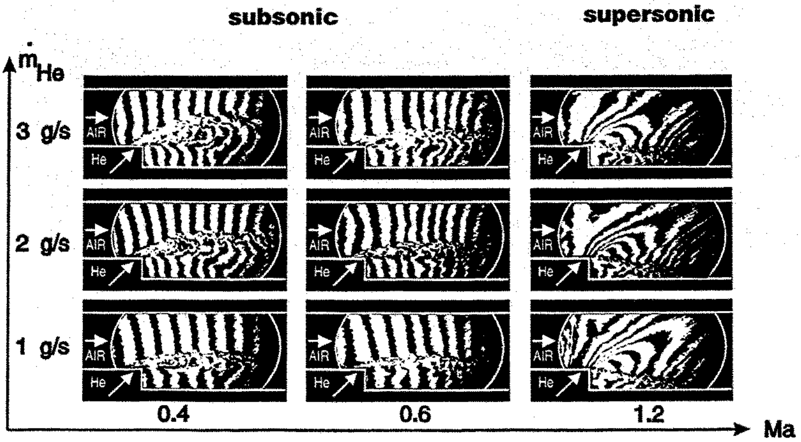


Figure 4.3. Influence of the air Mach number and the helium mass flow on the development and structure of the mixing jet. It can be seen that an increasing Mach number leads to a decrease of the thickness and penetration of the mixing jet. Oblique shock waves, generated at the injection hole and reflected at the opposite combustion chamber wall affect the deflection of the mixing jet into the recirculation zone of the rearward facing step. The increase of the helium mass flow leads to an increase of mixing length, penetration and thickness of the mixing jet. The shapes of the mixing jets are very turbulent, with the size of the vortices on the surface increasing with increasing air Mach number and helium mass flow.

the whole depth of the flame and thereby converting the 3–dimensional flame structure into a 2–dimensional picture, the 3–dimensionality of the flame can be resolved by using 2–directional synchronized imaging.

The high–speed H_2–air flames were stabilized in the vicinity of the recirculation zone inside the combustion chamber due to turbulent flame acceleration. Fig. 4.4. shows an example of how the stabilization spots of the flames behave in the vicinity of the rearward facing step, depending on the air Mach number and on the H_2 mass flow. The pictures were btained from flame self fluorescence with an exposure time of 1 ms. It can be seen that n increasing Mach number of the air, the stabilization spot moves downstream and the me shape becomes thinner; an increase of the H_2 mass flow causes an upstream movement he stabilization spot coupled with an increase of flame thickness. These observations are absolute agreement with the observations of the cold mixing experiment described in hapter 4.1. In general, it can be said that the position of the stabilization spot is in any ase inside the free turbulent shear layer between the main air flow and the recirculation one. This is caused by the high rate of burning velocity due to turbulent mixing effects in he shear layer on one side, and the moderate flow velocities inside the shear layer on the other side.

A very important parameter for the investigation of sub– and supersonic H_2–air–flames by means of self fluorescence is the exposure time of the intensified CCD–camera. When looking

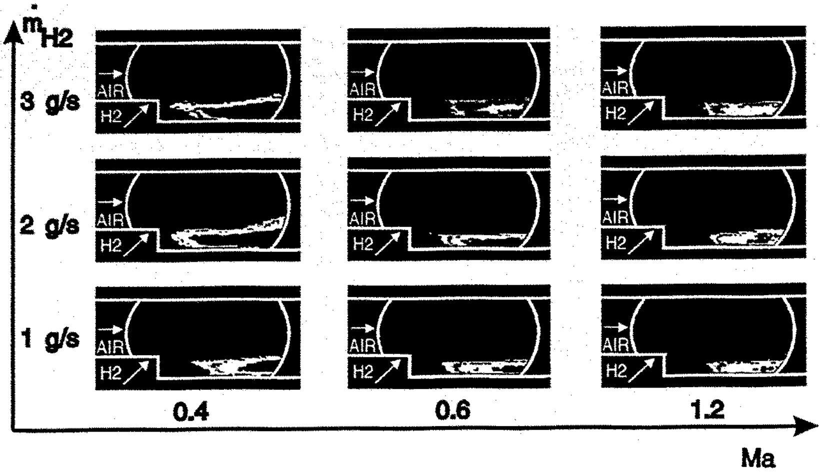
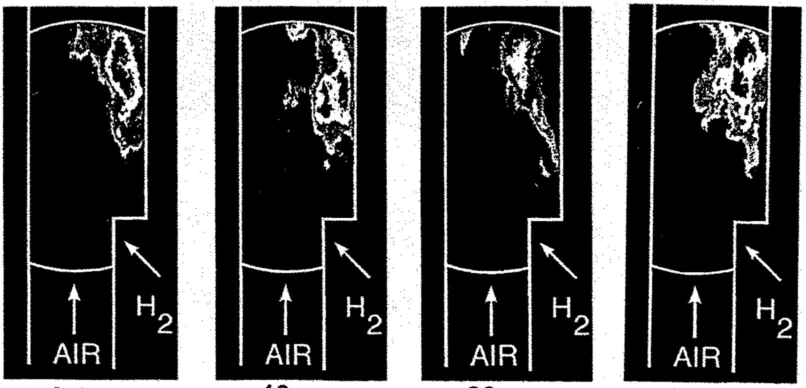


Figure 4.4. The stabilization of high speed H_2–air flames in the vicinity of the rearward facing step inside the combustion chamber as a function of the air Mach nunber and of the H_2 mass flow obtained from flame self fluorescence (originally in false colors). The exposure time was 1 ms. It can be seen, that the stabilization spot — the first visible reaction zone — moves downstream with increasing Mach number and the flame becomes more slender. Increasing H_2 mass flow causes the stabilization spot to move upstream and a broadening of the flame. In any case the stabilization spot is located inside the free turbulent shear layer which separates the main air flow from the recirculation zone.

at images taken with an exposure time of 1 ms (see Fig. 4.4.), the shapes of the flames are very smooth and time independent. Using an exposure time two orders of magnitude lower, the behavior of the flames is completely different. The flame shape is very irregular and oscillates up– and downstream periodically. Fig. 4.5. shows a temporal sequence of six images taken with an exposure time of 10 μs in time steps of 40 ms. The air Mach number was 0.2 and the injected H_2 mass flow 1.4 g/s. It can be seen that the stabilization spot is always inside the turbulent shear layer, but the flame shape moves up– and downstream periodically. It appears that these oscillations are due to large–scale eddies created in the shear layer. When increasing the Mach number of the air, the dynamic structure becomes more and more regular and the oscillations are suppressed as the large–scale irregular eddies vanish and are substituted by a coherent vortex structure.

This example shows impressively the influence of the exposure time on the evaluation of any kind of data collected from combustion processes by means of optical measurement techniques. The interpretation of those data is very much linked to the real dynamic behavior of the flames. Especially when using accumulative the Raman scattering technique, the dynamic behavior of the flame must be taken into account for evaluation of the received spectra.

As mentioned before, self fluorescence is an integrating technique which means that the light emitted by the excited OH radicals is accumulated over the entire depth of the flame. This



o ms 40 ms 80 ms 120 ms

Figure 4.5. Temporal behavior of the stabilized flames (originally in false colors) . A sequence of 6 images shown were obtained with an exposure time of 10 μs. The time interval between two succesive images is 40 ms. The air Mach number was 0.2, the H_2 mass flow 1.4 g/s. It can be seen that the structure of the flame shape is highly dynamic, but the stabilization spot is always within the turbulent shear layer separating the main air flow from the recirculation zone. This dynamic behaviour of the flame is due to a large scale irregular eddies structure generated in the turbulent shear layer. The sequence of images shown was taken at the lower stabilization limit of the flame. An increasing Mach number of the air affects a smoothing of this dynamic flame behaviour and the structure becomes more and more regular.

method ignores the 3-dimensionality of the flame structure. But the 3-dimensional structure of the flame can be determined when self fluorescence images are taken simultaneously from two directions perpendicular to each other. Fig. 4.6. shows the two perpendicular images of a H_2-air-flame with an air Mach number of 0.6 and a H_2 mass flow of 1.5 g/s taken downstream of the exit of the closed combustion chamber. The side view of the flame shows a region of high reaction rate in the center of the flame. Comparing this image with the top view of the flame, the region of high reaction intensity can be determined as a pair of steady vortices downstream of the exit. Experiments have shown that with increasing Mach number those two vortices unite in the center of the flame. Furthermore, it can be seen that directly at the exit the reaction rate in the middle of the flame is very poor. This example shows that the characterization of the flame structure may be very difficult without having at least two directions of view of the flame.

4.3. Comparison of the Mixing and Combustion Process
in High-speed H_2-Air Flows

Fig. 4.7. shows the comparison of the cold mixing experiments done with helium and monitored by means of holographic interferometry, and the corresponding experiments done with burning H_2 monitored by shadowgraph imaging and self fluorescence. It can be seen that the mixing jet of helium and H_2 is similar and the flow structure around the mixing jet and the flame comparable, especially with respect to the arising shock waves. The

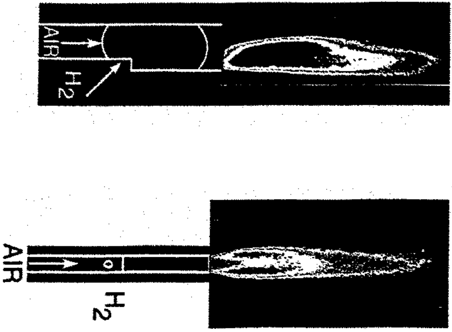


Figure 4.6. Side and top view of the flame downstream of the exit of the combustion chamber monitored by self fluorescence (originally in false colours). The air Mach number was 0.6, the H_2 mass flow was 1.5 g/s. It can be seen from the side view that there is a region of high reaction rate in the middle of the flame. Comparing this with the top view of the flame, this region can be determined as a pair of steady vortices downstream of the exit cross section. The top view image shows that in the vicinity of the exit cross section the reaction rate in the central stream line of the flame is very poor because of a high quantity of cold, unburnt H_2.

comparison area shows that the stabilization spot of the flame is located inside the shear layer which separates the main air flow from the recirculation zone. In general it can be said that the cold mixing experiments are in good agreement with the experiments done with combustion of H_2.

5. CONCLUSION

The experiments presented in this paper demonstrated that several non–intrusive diagnostic methods are suitable to reveal the behavior and structure of sub– and supersonic H_2–air–flames, not only in open but even in closed combustion chambers. Although shadowgraph and self fluorescence imaging are only qualitative measurement techniques, they give very good information about the dynamic structure of the investigated flames. It appears that the global information obtained from the more qualitative measurements is very useful in the selection and preparation of more precise laser diagnostic measurements, since the key locations for the combustion process in the chamber are revealed and the number of measurements required with the laser diagnostic techniques may be significantly reduced. This is especially useful if point or line Raman measurements are employed, since the 3-dimensional scan of an entire technical scale chamber would requirde lengthly measuring times and produce more data that can be handled. Therefore, a strategy for the approach of unknown combustion objects is proposed.

The first measurements should employ techniques capable of capturing the entire combustion volume to provide a general, rather qualitative understanding of the processes and events involved. From these measurements, the regions of main interest in the combustion chamber should be recognized and in a second set of measurements investigated quantitatively with non-integrating laser techniques like LIF or Raman methods.

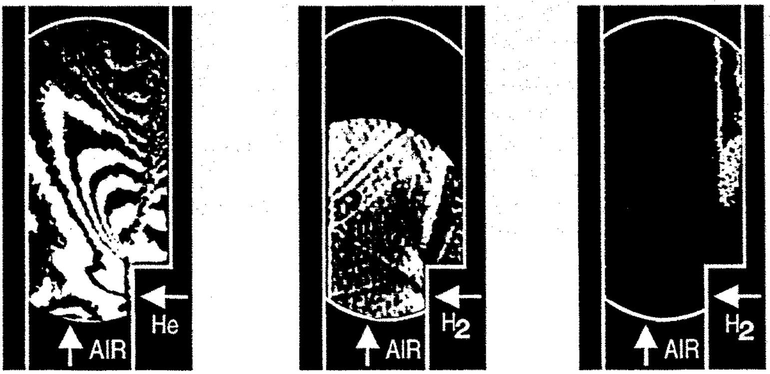


Figure 4.7. Comparison of the cold mixing experiments with the combustion experiments. The diagnostic techniques used were holographic interferometry for the mixing and shadowgraph imaging and self fluorescence for the combustion . The air Mach number was 1.2 and the H_2 masss flow 0.8 g/s. The mixing jet of helium and H_2, as well as the flow structure around the jet and the flame, are similar. Note that the stabilization spot of the flame is located inside the free turbulent shear layer between the main air flow and the recirculation zone.

6. REFERENCES

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COMMENTS

V.S. Abzukov, Chaboksary Study Center, Russia. I dont't agree with the speaker. I think that holographic interferometry may be used for investigations of the combustion in the chamber with the hot glass windows. Of course, there are many difficulties.

Authors' Reply. Holographic interferometry is very sensitive to changes of the refractive index over the entire depth of the optical path of the object beam. This includes the hot glass windows which cover the flame. The basic principle of holographic interferometry is that the whole optical setup i.e., lenses, mirrows, windows ect. has the identical temperture when recording the reference hologramm (preformed without the combustion process) and when recording the combustion process. So one has to make sure, that the glass windows of the combustion chamber have the same temperature under all operational conditions of the combustion chamber. This means that the windows have to be cooled actively with a responce time of a view milliseconds and a controll range of about 1000 K within a controll accuracy of less than 1 K. If these demands for the active cooling system of the windows can be fullfilled, holographic interferometry can be used to investigate combustion processes in a closed combustion chamber. But up to now no cooling system of this kind is available.

R.Pein, DLR Germany. Could you tell us something about the origin of the emission, e.g., is it thermal or is it chemiluminescence.

Authors' Reply. We could proof, that the emission we recorded by means of self fluorescence is based on chemiluminescence (see Chapter 3).