INVESTIGATION OF THE TRANSIENT FLAME DEVELOPMENT USING A COMBINATION OF ADVANCED OPTICAL MEASUREMENT TECHNIQUES

A. Eder, B. Edlinger, M. Jordan, F. Mayinger

Keywords: *Premixed Combustion, Laser-Doppler-Velocimetry, Length-Scales, Schlieren-Cinematography, Laser-Induced Predissociation-Fluorescence*

Abstract

The present paper deals with the investigation of various combustion processes by means of highly sophisticated optical measurement methods. Many optical techniques are capable of describing phenomena in thermo-fluid-dynamics, but only a limited number of process variables are obtained by each of these techniques. In order to develop and to validate computer codes simulating combustion phenomena, only the combination of several measurement techniques on comparable experiments leads to a satisfactory data base containing the most important process variables. The application of the high-speed Schlieren-technique, the Laser-Induced Predissociation Fluorescence, and the Laser-Doppler-Velocimetry on comparable transient combustion processes in several test-facilities is shown within this paper. Emphasis is put on the determination of length-scales due to their importance regarding turbulent combustion.

1 Introduction

Optical methods are used in combustion research since many years because of their outstanding characteristics. Since they work non-intrusive and inertialess they do not influence the combustion-process that has to be investigated and can be used for highly transient processes.

Author(s): A. Eder[1], B. Edlinger, M. Jordan, F. Mayinger
[1]Lehrstuhl A für Thermodynamik, Technische Universität München, 85747 Garching, Germany

The concerned combustion-phenomenon is the acceleration of an initially slow flame by single obstacles of different blockage ratios for lean hydrogen-in-air or methane-in-air mixtures.
In case of a ignition after a possible failure of any gas infrastructure at industrial or civil cites, the pressure load due to fast propagating flames can endanger the integrity of the building. Although the global characteristics of the preceding flame-acceleration has been investigated by various authors, the data basis obtained by locally highly resolved measurement-methods determining process variables like density, temperature, velocity, and species concentration is still very poor. This must be attributed to the fact that the required resolution in time and space can not easily be achieved. Nevertheless, this data-basis is very important for the validation of computer codes, simulating these accidents.
To understand the influence of the local geometry, the experiments for this study are performed in three explosion tubes of different scale and geometry:

1. A closed tube with a length of 6m, round cross section, Ø 66mm,
2. an annular combustion chamber, length 6m, round cross section, Ø 80mm.

Both test-facilities are equipped with at least one optical accessible window section to investigate the combustion process.

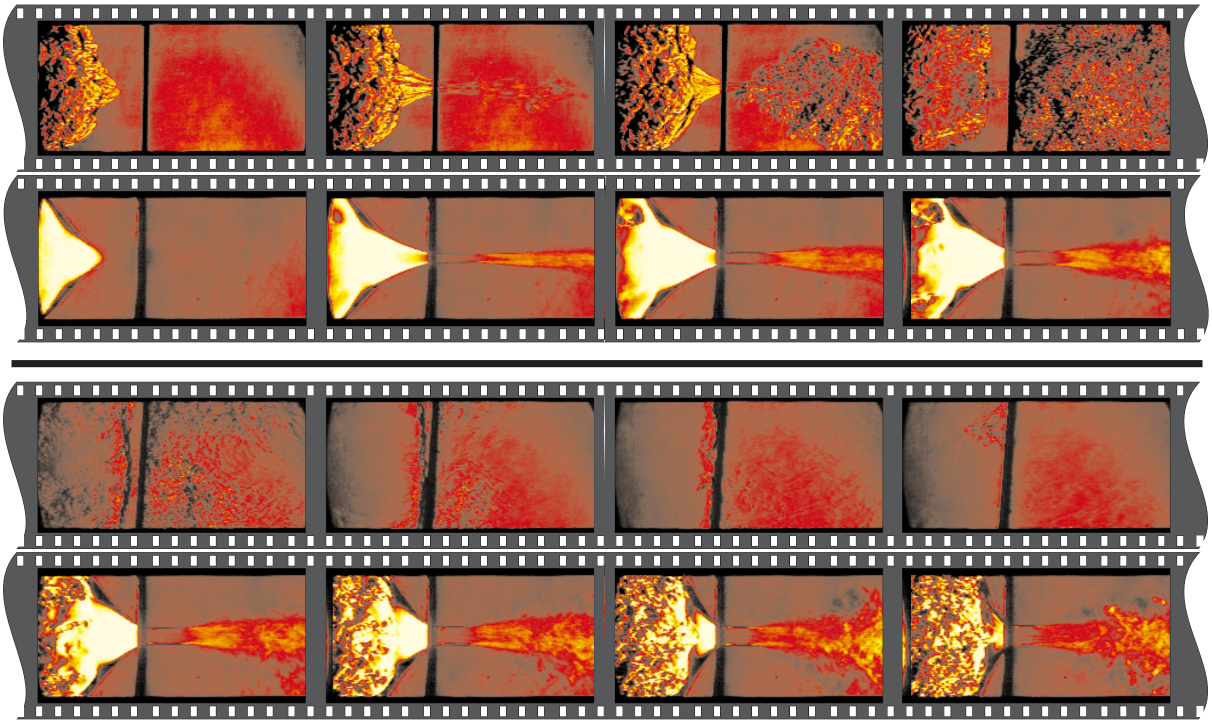


Fig. 1 High-Speed Schlieren-Cinematography, showing the flame acceleration by a central orifice during a combustion-process of a hydrogen-in-air flame (1st and 3rd row) and a methane-in-air flame (2nd and 4th row) in a closed tube, time between two pictures: 1*ms* [7]

2 Applied Measurement Methods

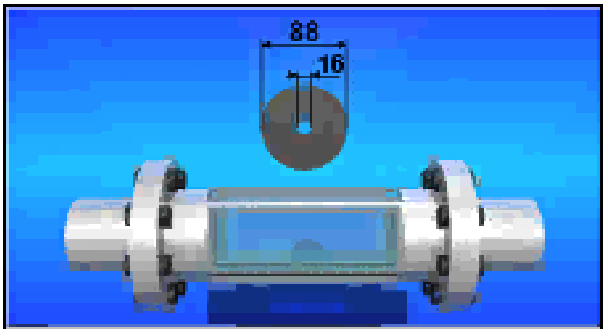
In the present study, the *Schlieren-technique* is used to get a global understanding of the combustion-phenomenon to be investigated. By means of *Laser-Induced Predissociation-Fluorescence* it is possible, to visualise the flame-position with a very high spatial resolution. *LDV-measurements* make it possible to determine the momentary stage of flow quantitatively as well as statistical turbulence quantities to get a total understanding of the entire combustion process.

2.1 Schlieren-cinematography

The classical Schlieren-cinematography, which was first described by Toepler in 1864, is used to record the global flame propagation process by means of visualising density gradients. Until now, drum cameras - using photographic film material - were used to produce high speed photographs. One of the main disadvantages of this method was the handling of the photographic material. Due to the film developing process, the results of an experiment could be seen at the earliest half an hour after the experiment had been performed.

Using modern high speed video-cameras, it is possible to record sequences with repetition rates of some 10.000 images/sec and to store several thousand images into the internal memory of the system. The result of an experiment can be seen in form of a video film immediately after its recording. 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 video technique is the fact that the internal image memory of the system can be overwritten continuously. By setting a trigger signal, the camera stops recording and, e.g. the last thousand images, recorded before the trigger signal (in our case provided by a light-barrier) occured, are kept in the memory. This is a very helpful tool to investigate e.g. self igniting combustion processes, since the ignition time can not always be predicted precisely.

By doing this, the combination of a well old but sophisticated optical measurement-technique with latest recording devices allows a very good insight into the dynamic processes of flame acceleration. The image-sequences shown in Fig.1 give a good impression of the capability of the applied set-up. For the combustion process through a central orifice with a blockage ratio BR of 95%, a flame propagation with an initial mixture of 12 Vol.% hydrogen in air is compared to a 9.5 Vol.% methane in air-mixture. An example of a video-film made of these images can be seen in video 1. The optical setup of the Schlieren measurement-technique is explained in the header of this video [9].



Due to the high resolution in time, the entire ignition process behind the obstacle can be examined. Only with this device it is possible to measure e.g. the time-difference between the obstacle is reached by the flame in the "first" chamber and the occurrence of the ignition in the "second" chamber. This period of time is one of the central parameters for the intensity of the combustion behind the obstacle.
The disadvantages of these systems is the resolution of the video system, which is very small compared to the resolution of a classical photography. Disadvantages of the Schlieren-technique itself are the fact that only integral images through the whole depth of the combustion-chamber can be recorded and due to the visualisation of density-gradients, the flame itself can not be distinguished from the hot exhaust gas.
In order to avoid this, a further optical measurement-technique, the Laser-Induced Predissociation-Fluorescence is applied to the same combustion processes.

2.2 Laser Induced Predissociation-Fluorescence, LIPF

The Laser-Induced Predissociation-Fluorescence is a very accurate measurement method in order to visualise the flame location with a very high spatial resolution.

Combustion-radicals are an intermediate

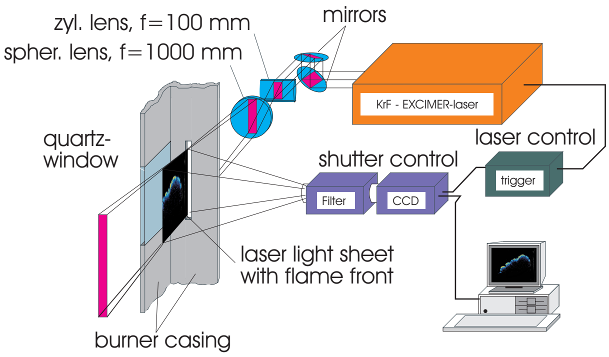


Fig. 2 Optical setup for laser induced fluorescence

product of the fuel-air reaction. In the case of hydrogen-combustion, OH-radicals, and for methane combustion C_xH_y-radicals in combination with OH-radicals indicate the exact position of the flame-front. By choosing an appropriate laser-wavelength, these radicals are excited to a higher electronic energy state. The fluorescence can be observed by the transition from an excited electronic state to a lower state. An optical setup for LIPF-measurements is shown in Fig.2. The radicals are excited within a lightsheet with a thickness of less than $1mm$ in order to visualise thin layers of the flame. By using an excimer laser running with KrF as laser medium and emitting light with a wavelength of $248nm$, the excitation of the OH-radicals by $A^2\Sigma^+, V = 3 \leftarrow X^2\Pi, V = 0$ appears. A wavelength selecting optics allows to tune the laser for the P1(8) excitation of the OH-radical. The pulse duration of the laser is $17ns$, the lifetime of the OH-radicals in the excited state ranges between 10^{-10} and 10^{-5} sec [5]. The fluorescence appears frequency-shifted $(A^2\Sigma^+, V = 3 \rightarrow X^2\Pi, V = 2)$ at a wavelength of $295 - 304nm$. Both, additional fluorescence signals and Rayleigh scattering are tuned out by means of appropriate filters. Due to the performance of the excimer laser,

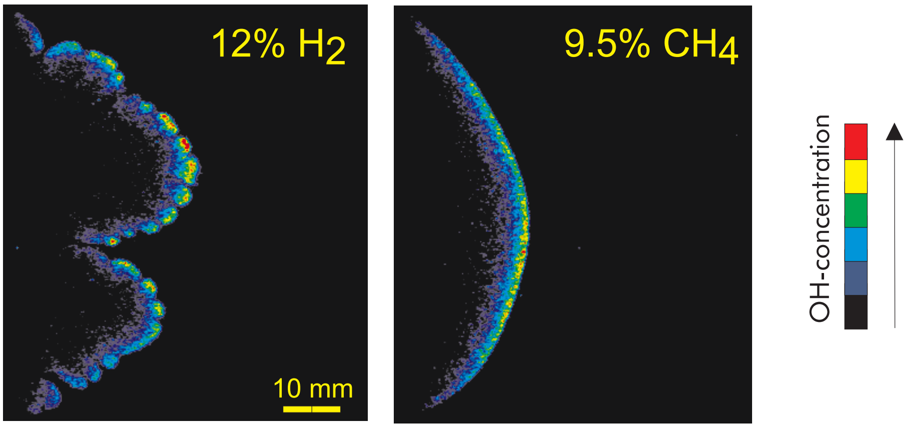


Fig. 3 Comparison of the OH-distribution of a 12 Vol.% H_2-in air and 9.5 Vol.% CH_4-in air, taken with LIPF

allowing a repetition rate of the LIPF system of only up to 80Hz, the whole combustion process can not be recorded. Nevertheless, the flame propagation can be reconstructed by evaluating several single shots taken at different flame positions.
The emitted fluorescence signal of the excited radicals can be observed by an intensified CCD camera. The obtained images contain information about the shape of the flame and the local radical concentration.
For practical use, the experiment has to be as clean as possible due to the relative low fluorescence signals. As with all light scattering processes, the test chamber should be free of reflection. Due to the fact that ordinary glass is not transparent for UV-light, the windows of the test-facilities have to be made out of quartz glass.
A comparison of different flame-shapes in an explosion tube is shown exemplary in Fig.3. Although both flames have approximately the same laminar burning velocity of about 0.4 m/s, the shape of the flames differ significantly due to the various diffusivities of the initial gas-mixture. The information about the local distribution of the reaction zone in case of a hydrogen or methane flame is a very useful information, needed for the numerical modelling of the combustion process.

In Fig.4, an example of a hydrogen flame penetrating through a central orifice is shown.

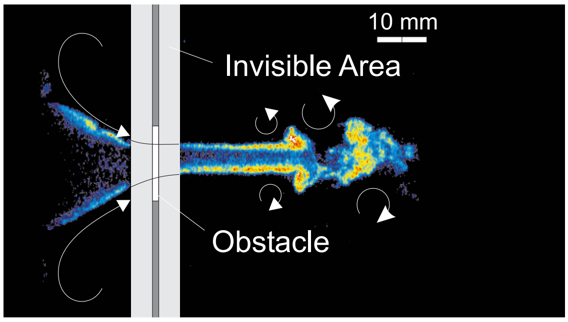


Fig. 4 OH-radical distribution through an orifice (blockage-ratio 97%) of a 12 Vol.% hydrogen-in-air flame (red highest OH-concentration)

The areas of enhanced chemical reaction can be clearly determined and located about three to four orifice diameters behind the dividing wall. The example shown in Fig.4 leads to the assumption that the macro-scale eddies of the expansion flow of the flame -outlined by arrows- have an important influence on the surface of the flame. For a detailed understanding of the combustion-process it is necessary, to additionally investigate the turbulence-structure of the expansion flow and to determine characteristic length scales. This is performed by means of Laser-Doppler-Velocimetry measurements.

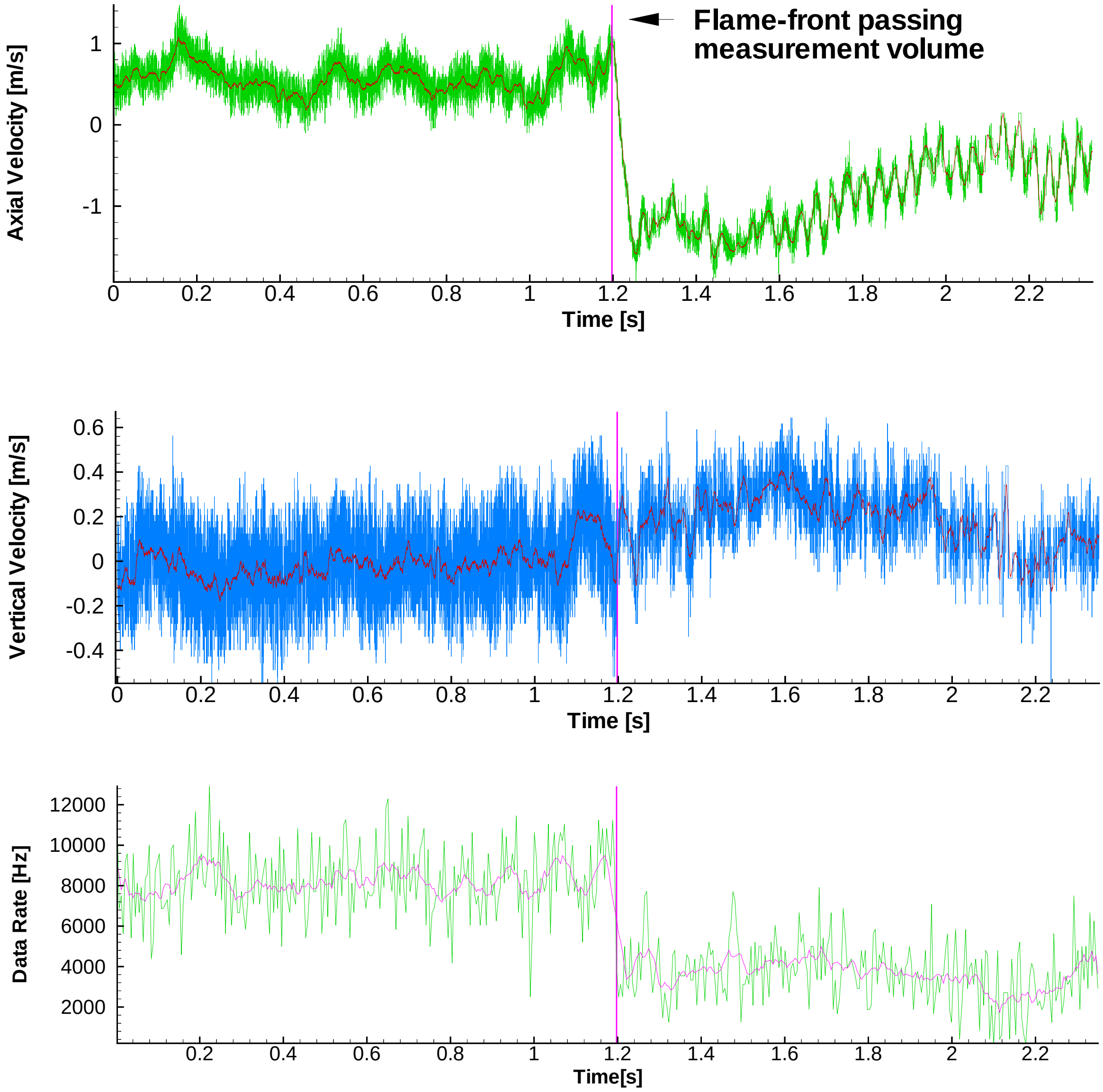


Fig. 5 Laser-Doppler-Velocimetry records and resulting data-rates of the LDV-system of a 10 Vol.% hydrogen-in-air flame penetrating through an obstacle with BR=60%, location of the measurement volume: 50 mm behind the obstacle, middle of a round explosion-tube

2.3 Laser-Doppler-Velocimetry, LDV

To get a detailed understanding of turbulent flame propagation, it is indispensable to examine both, the expansion flow induced by the flame itself and the turbulence in front of the flame front. Since it is not yet possible to calculate turbulent flows in large scales due to a lack on sufficient computer-memory and computer-performance by Direct Numerical Simulation (DNS), statistical methods have to be applied. Besides the mean flow velocities, statistical quantities such as the turbulent kinetic energy k or the turbulence intensities of the flow are of special interest. But the classification of turbulent flows with the quantities mentioned above is not sufficient referring to the interaction of turbulence and flame propagation. The distribution of characteristic length scales of the turbulent flow has an important influence on the flame propagation.

These quantities are to be obtained by means of a Laser-Doppler-Velocimeter system (for a detailed description of the LDV measurement principle refer to the specialised literature

([4],[12]). The LDV arrangement used for the present studies consists of a two-colour, three-beam system based on a 5 W Argon-Ion Laser and a DANTEC X-Optics detecting the axial and transverse velocity components simultaneously. The optics is operated in backscatter mode in order to facilitate traversing between various measurement points. To determine both, positive and negative flow velocities, one beam of each pair is frequency shifted by 40MHz using a Bragg-cell.
The detection of the scattered light is done by two photomultipliers. The photomultipliers are connected via a frequency shifter to a DANTEC counter system (type 55L90A). The frequency shifter is used to shift the detected Doppler-signal ("burst") to a lower frequency domain in which the counters have their maximum resolution as well as to remove the Doppler pedestal. The counter-system determines the flow-velocity of a particle by measuring the time for a fixed number of passings of the zero line of the Doppler-burst. The Doppler-signals are band-width-filtered before being processed to ensure a high signal-to-noise ratio. The velocity data of the counter-system are processed by a two-channel DOSTEC LDV-Interface, which can be operated either in a fixed sampling mode up to 100kHz for each channel or in coincidence-mode. The head of the LDV-Optics consists of a lens with a focal distance of 310mm. In this case, the resulting diameter of the measurement volume is 90μm, the length is about 1.4mm and the fringe-spacing 4μm.
The light scattering is provided by titanium-dioxide particles intermixed with silicium-dioxide particles (Aerosil) in order to avoid agglomeration of the particles due to humidity of the process air. Additionally, the mean seeding diameter is reduced by means of the shear stresses in the free jet of a small nozzle through which the particles are blown into the test-facility. The mean diameter of the particles was determined to be about 1μm [3].
Shortly before the flame passes the measurement volume, the turbulence parameters are of special interest. In that period of time, the LDV-records describe the turbulence within a finite volume of the unburnt mixture that will be caught by the flame front within the next time step and is therefore responsible for the local burning rate. One beam of the LDV-system is used as part of a laser light barrier, to detect this very moment. Additionally, this incident can be determined by analysing the data rate of the LDV-record. The data-rate decreases rapidly due to refraction of the laser-beam by the density-gradients of the flame, see Fig.5.
The raw LDV-Data are postprocessed in order to eliminate spurious data which were caused by noise introduced by the photomultipliers and processing electronics. Therefore, velocity-data above and below a certain clipping-level and outside a data-bandwidth defined by a running mean and a running standard deviation are eliminated. Only experiments with an amount of eliminated data less than 3% of all data-points are used for further evaluations.
As mentioned above, the turbulence in front of a flame front is a central parameter for investigating the connection between burning-velocities and turbulence-quantities. The period of time in which the flow-parameters are to be evaluated, has a considerable influence on the resulting turbulence quantities when investigating transient flows. A fixed number of data-points or a fixed time interval is often used independently of the momentary stage of flow as well as the local geometry. To compare various experiments in different test-facilities, it is indispensable to take both, the momentary main-velocity, the degree of turbulent fluctuations and the local geometry into account for the determination of the time-interval.
An adequate time-scale is the *Integral Time Scale* T_E. It represents a characteristic measurement for the longest correlated structures of a turbulent flow [11] and is determined by

$$T_E = \int_0^{\tau_0} R_E(\tau) d\tau, \qquad (1)$$

where $R_E(\tau)$ is the normalised *Eulerian time-correlation coefficient* or *autocorrelation* function of the axial fluctuating velocity component u'; τ_0 is the value of of the time lag for which

$R_E(\tau)$=0.

$$R_E(\tau) = \frac{\overline{u'(t)u'(t+\tau)}}{\sqrt{\overline{u'^2(t)}}\sqrt{\overline{u'^2(t+\tau)}}} \tag{2}$$

This quantity depends directly on the turbulence fluctuations and indirectly on the mean flow-velocity due to the turbulence-frequency of the flow.

In Fig.6, an autocorrelation function of the LDV-record in Fig.5 is shown. The integral-time scale is determined to be $T_E = 4ms$ according to Eq. 1 in this example. For this period of time, statistical turbulence quantities, such as the turbulence intensity for every measured velocity-component (e.g. u_{rms}), or the turbulent kinetic energy

$$k = \frac{1}{2}(u_{rms}^2 + v_{rms}^2 + w_{rms}^2) \tag{3}$$

are determined. The intensities are taken as the rms-values of the deviation from the moving average:

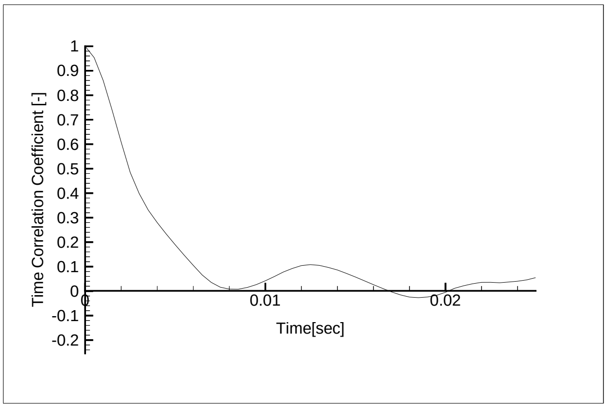


Fig. 6 Time correlation coefficient of the LDV-record shown in Fig.5

$$u_{rms} = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(U_i - \overline{u}_i)^2}, \tag{4}$$

with n as the number of data-points within the time-interval T_E before the flame passes the measurement volume.

The classification of turbulent flows with mean-quantities of fluctuations is not sufficient to investigate the turbulence-flame interaction.

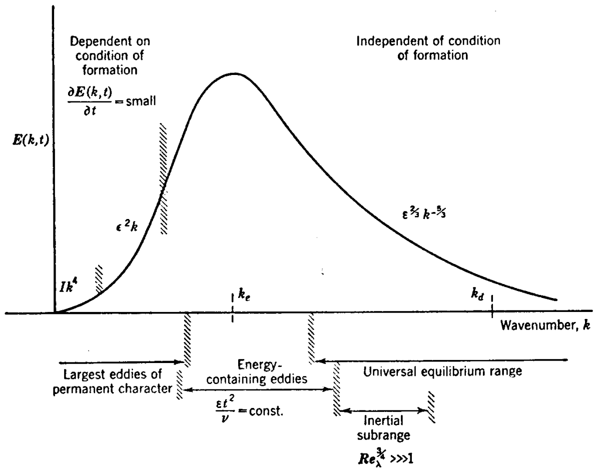


Fig. 7 Three-dimensional wave number spectrum [6]

Rather the distribution of eddy length-scales has an important influence on the turbulent flame propagation. Fig.7 shows an energy spectrum of the turbulent flow over the entire range of possible length-scales. The area containing the highest energy -referred to as the energy containing eddies- is characterised by the integral length scale Λ. It is obtained by

$$\Lambda = \frac{1}{2}\int_{-\infty}^{\infty} R_{ij}(r)dr \tag{5}$$

with the *Eulerian spatial-correlation* coefficient

$$R_{ij}(\vec{x},\vec{r}) = \frac{\overline{u_i'(\vec{x})u_j'(\vec{x}+\vec{r})}}{\sqrt{\overline{u_i'^2(\vec{x})}}\sqrt{\overline{u_j'^2(\vec{x}+\vec{r})}}}. \tag{6}$$

R_{ij} describes the relation of the velocities of two measurement points with $\vec{x}$ as the vector to the first point, where the velocity u_i is measured, and $\vec{r}$ as the distance to the second point, where the velocity u_j is measured. Thus, for the measurement, one measurement point is fixed and the other one will be displaced. In non-isotropic flow fields, both, negative and positive values of the correlation coefficient have to be measured, since the correlation function is not symmetric. Therefore, two LDV-systems are needed for measuring length-scales in non-isotropic flow-fields.

Fig.8 shows the turbulence intensities of the axial and vertical velocity component of an expansion flow of a flame front around a central orifice with a blockage ratio *BR* of 60% of the whole cross-section of the duct. For lean mixtures like in this example (the initial condition is 10 *Vol*.% hydrogen in air), the turbulence field can be regarded as isotropic (see Fig.8).

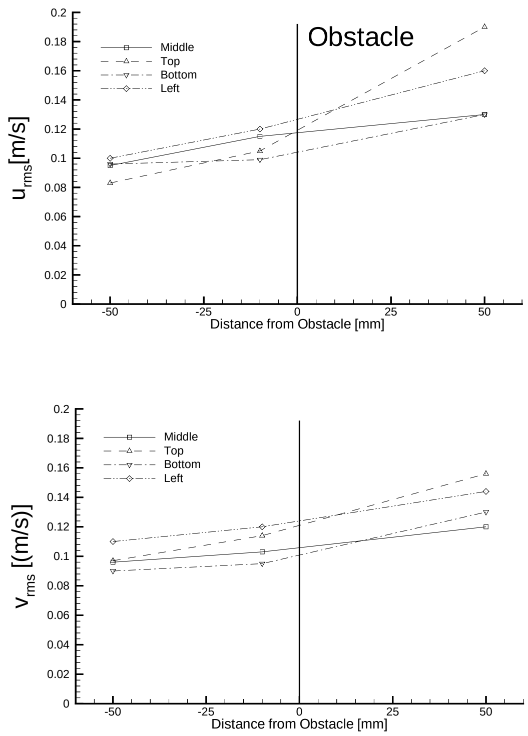


Fig. 8 Turbulence intensities in front of and behind an obstacle with a blockage ratio of 60%. Round explosion-tube (Ø 66*mm*), expansion flow of a 10 Vol.% hydrogen-in-air flame.

For isotropic flow fields, the spatial correlation function is symmetric. Therefore, Eq. 5 can be written as

$$\Lambda = \int_0^\infty R_{ij}(r)dr. \quad (7)$$

When applying the Taylor Hypothesis, it is possible to determine the integral length-scale by means of measuring the fluctuations at one single point. According to Frost [6], the Taylor Hypothesis states that, if $\bar{u} \gg \sqrt{\overline{u'^2}}$, the fluctuations at a fixed point of a homogeneous turbulent flow with a constant mean velocity $\bar{u}$ in x-direction behaves as a turbulent field passing that point with a constant velocity $\bar{u}$. In this case, the fluctuations over the time are nearly identical to the momentary velocity-distribution along the mean velocity-axis at this point (”frozen turbulence”). Taylors Hypothesis implies:

$$\overline{\left(\frac{\partial u'}{\partial x}\right)^2} = \frac{1}{\bar{u}^2}\overline{\left(\frac{\partial u'}{\partial t}\right)^2} \quad (8)$$

Due to $x = \bar{u}t$, the integral length scale can now be calculated by

$$\Lambda = \bar{u}T_E \quad (9)$$

Therefore, the integral length-scale can be determined by only one velocity measurement device, taking into consideration the above mentioned assumptions regarding the turbulence field. According to this procedure, the integral-length-scale in the example of Fig.5 is determined to be $4mm$, since the mean flow-velocity is $1m/s$ and the integral-time-scale was already determined to be $4ms$ (see above).

The integral length-scale is a very important quantity when describing a turbulent flame-propagation. It is one of the central parameters in characterising turbulent flames by means of a phase diagram proposed by Borghi [2] (see Fig.9) and Peters [10]. This appears to be a valuable tool for the general assessment of combustion processes in any turbulence regime. The integral length scale appears directly in the definition of the *Damköhler number Da*, which is defined by the quotient of a characteristic time-scale of the flow and the chemical time-scale of the reaction,

$$Da = \frac{\tau_\Lambda}{\tau_c} = \frac{s_l \Lambda}{\sqrt{u_{rms}}\delta_l} \quad (10)$$

with the laminar flame thickness $\delta_l = a/s_l$ and the laminar burning velocity s_l (see e.g. [8]). The Damköhler number implies, to what extent the gas mixture enclosed by a large eddy of the dimension Λ is burnt until this eddy loses its identity due to the viscosity of the flow. It describes the influence of the large eddies on the reaction zone.

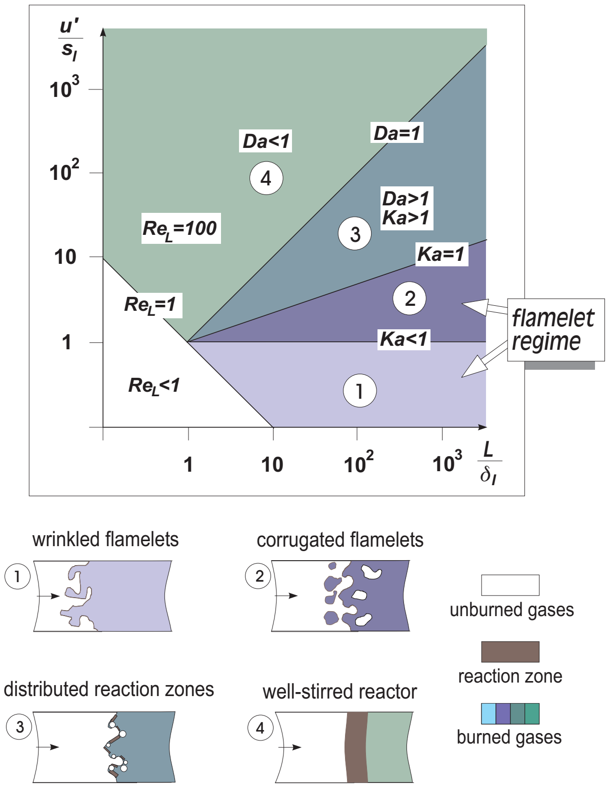


Fig. 9 Phase diagram for turbulent premixed combustion according to Borghi [2]

The second important parameter mentioned in the phase diagram of Borghi is the *Karlovitz number Ka* which describes the influence of the smallest eddies of the flow (*Kolmogorov micro scale eddies*) on the structure of the flame-surface:

$$Ka = \frac{\tau_c}{\tau_s} = \frac{\delta_l}{s_l}\sqrt{\frac{\varepsilon}{\nu}} \tag{11}$$

with the time scale of the smallest eddies τ_s, the viscosity of the gas-mixture ν, and the dissipation rate ε of the flow. The term $\sqrt{\varepsilon/\nu}$ as well as the size of the Kolmogorov micro-eddies $l_s = (\nu^3/\varepsilon)^{\frac{1}{4}}$ can not be determined directly by means of LDV-measurements. Abdel-Gayed et al. [1] developed the following relation between the integral-length scale and the Kolmogorov microscale:

$$\frac{l_s^4}{\Lambda} = \frac{40.4}{15}\frac{\nu^3}{u_{rms}^3} \tag{12}$$

When knowing the integral length scale as well as the root-mean-square value of the fluctuations, it is possible to classify turbulent flames regarding their combustion regimes. Both, the integral length scale and the turbulence intensities are therefore the most important quantities when investigating turbulent flow regarding the local burning velocity of a flame.

3 Concluding Remarks

Advanced optical measurement methods open new perspectives for the measurement of transport phenomena during transient combustion processes. For a better understanding of these phenomena as many as possible important parameters have to be determined with a very high resolution in time and space. Therefore, only a combination of several sophisticated optical measurement techniques applied to the same class of experiment (regarding geometry, initial conditions of the test-facility, ...) lead to satisfactory results.
The determination of the size of the flame surface from Schlieren- and LIPF-data leads, together with the turbulence-intensity and length-scales obtained by evaluating LDV-records, to an important data-basis for the improvement of turbulent numerical combustion models.

Acknowledgements

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Nomenclature

Da	Damköhler-Number
s_l	Laminar Burning Velocity
ρ	Density
p	Pressure
Λ	Integral length scale
λ_s	Kolmogorov micro scale
Ka	Karlovitz number
τ_c	Chemical reaction time
τ_s	Lifetime of the Kolmogorov micro vortices
τ_Λ	Lifetime of the macro-eddies
BR	Blockage Ratio, ratio between blocked and unblocked area
U	Flow velocity, $U = \overline{u} + u'$
$\mathrm{R}_E(\tau)$	Eulerian Time Correlation Coefficient

$R_{ij}(\vec{x},\vec{r})$	Spatial Correlation Coefficient
T_E	Eulerian Time Correlation Coefficient
ε	Dissipation Rate
ν	Viscosity of the gas-mixture
δ_l	Laminar flame thickness
u_{rms}	Root-mean-square-value of u', $u_{rms} = \sqrt{\overline{u'^2}}$

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