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Experimental Investigations and CFD-Modelling of a self-aspirating pulse combustor

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Abstract

The pulsation combustion process leads to increase the turbulence of the gas flow and to decrease the boundary layer between gas and solid resp. particles, which enhance the conditions for heat and mass transfer. These conditions are interesting for processes of thermal treatment of materials with high value creations. There is still a need of investigations for description of interactions between constructive and operational parameter to control pressure amplitude and oscillating frequency. The combustion process in a self-aspirating pulse combustor activates the resonance frequency from the combustor geometry. The produced pressure oscillations lead to periodical inflow of combustion air and hence to a pulsating combustion process. In the proposed paper the experimental results will be discussed and compared with the computational results. First of all experiments were carried out at a combustion chamber (about 40 kW) made of steel with the aim to investigate the mean influence parameters, such as geometry, fuel and air ratio and supply, etc.. Next to the investigations on the steel combustion chamber, experiments were carried out in a combustion chamber made of glass. The periodical flow and the combustion process were visualized with a high speed camera. In collaboration with the Institute of Photonic Technology Jena (IPHT Jena)[3], department laser diagnostics, two-dimensional pressure dependent laser induced fluorescence measurement of OH radicals (OH-LIF) were realized. These pressure dependent OH-LIF-pictures provide statements about the position and time of ignition, flame propagation and the phase shift between pressure and energy release. The phase shift between pressure and energy release is an important parameter influencing pressure amplitude and oscillation frequency. Furthermore the temperature distribution in the measurement layer can be computed from OH radical distribution. To compute this transient combustion process the CFD-software FLUENT was used. The computed contour plots of reaction rate and temperature distribution will be compared with the pictures of the high speed camera and the OH-LIF measurement.

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1. Introduction and Objectives

The combustion process in a pulsation reactor (PR) involves constant-volume combustion whereby energy release is superimposed with a self-actuated periodic oscillation of state variables (pressure, temperature, velocity). This combustion process is also known as pulsating combustion.

The combustion in a pulsation reactor is based on the combustion principle of the *Schmidt*-Tube. Under certain boundary conditions, the combustion process activates the acoustic resonance frequency of the combustion reactor. The resultant pressure oscillations generate a periodic air and respectively fuel / air inflow in the combustion chamber, which leads to the so-called self-actuating pulsating combustion.

The differences between pulsating combustion to stationary constant-pressure combustion process are mainly in the high combustion chamber loading, the intensification of the convective and diffusive heat and mass transfer and the progression of a self-aspirating combustion process (partly conversion of the fuel energy in work). Disadvantageous differences are in the high noise loading and increased wear through strong material loading. The increase in the convective heat and mass transfer is induced through an increased turbulence, also the diffusive heat and mass transfer through a reduced boundary layer thickness and respectively a periodic build up and size reduction of the boundary layer as a result of the pressure oscillations associated with the fluctuations from the gas velocity.

Complex relationships between acoustic, chemical reactions kinetics of the combustion process and transient fluid flow process have an influence on the operation manner (pressure amplitude and frequency) and also the stability of the pulsating combustion. A lot of knowledge is obtained through „trial and error"-experiments.

Until now there have been a number of investigations on self-actuating pulsating combustion whereby the background was predominantly in the application of heat transfer [1], [2] , [3], [4]. In relation to the mass transfer process in the reactor, in which there is a necessity for greater geometric apparatus dimensions, there are relative few investigations. Therefore a need in research still exists in order to explain the material conversion process in big pulsation reactors.

In addition to the measured data compilation of the pressure oscillation in the combustion chamber and the average temperature at different places in the combustion chamber, Laser Induced Fluorescence (LIF) of the produced OH radicals from combustion was carried out [5], [6], [7]. These technical measurement investigations provide in relation to the determination of relevant influencing factors of the main influential parameters (particularly pressure amplitude and oscillation frequency) to give more understanding to ignition mechanism, igni-

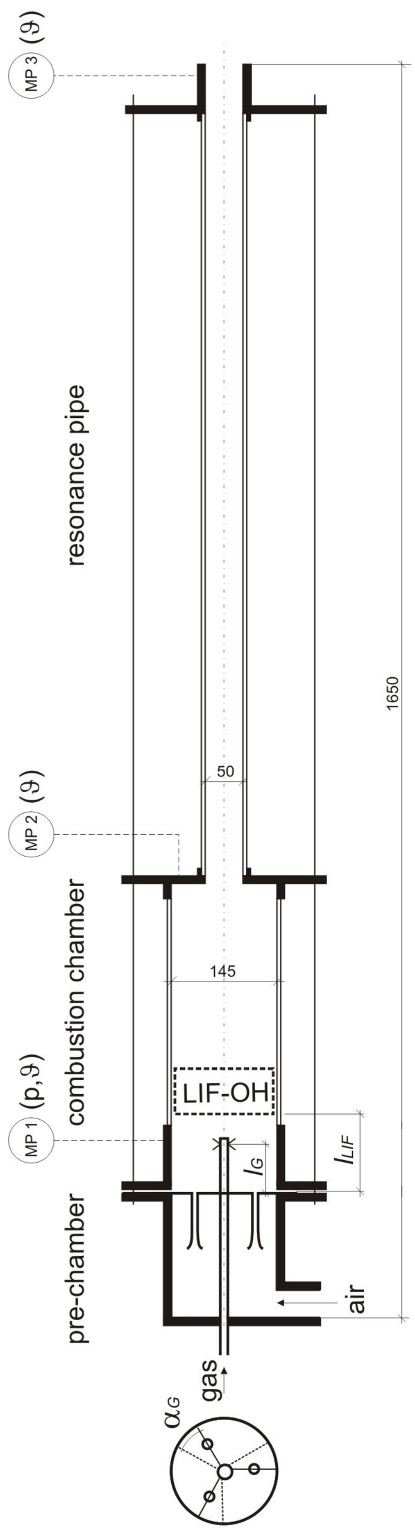

Fig. 1: Schematic diagram of the model of the Pulsations-reactor.

tion time point in relation to pressure oscillation, ignition position, flame propagation and temperature distribution in the combustion chamber.

2. Experimental Set-up

For the laser diagnostics investigations a pulsation reactor with *Helmholtz-Resonator*-form and vertical fluid flow direction was constructed. The cylindrical wall of the combustion chamber and the resonant pipe are made of quartz glass. For the LIF measurements in the combustion chamber a window of good optic quality was fitted to the glass cylinder.

The pulsation reactor (schematic in Fig. 1) composes of a pre-chamber, a valve plate, a combustion chamber and a resonance pipe. The resonance pipe is attached to the combustion chamber. The pre-chamber is separated from the combustion chamber through the valve plate with aerodynamic valves. In the valve plate there are three aerodynamic valves that are perpendicularly arranged, which rise in the pre-chamber. This construction results in an axial air entry in the combustion chamber.

The fuel gas (compressed methane 2.5) is centrally fed through a gas lance in the combustion chamber. At the end of the lance, there are three exit nozzles which are located on the cylinder mantel, that there is a radial fuel inlet in the combustion chamber. The experimental apparatus is equipped with the necessary measuring equipment (flow rate, pressure, temperature) for carrying out the experiments.

For the pressure measurements a piezo resistive pressure transmitter (water cooled) from the company Keller, Winterthur (Model PR25 with a front-flushed membrane and a sample rate of 5 kHz, calibrated for the range +/- 200 mbar) was used. The temperature measurements were carried out through NiCr-Ni thermocouples. For the

2D-LIF measurements a thin narrow band, variable KrF-laser (Compex 150T, Lambda Physic) was applied, and its laser beam is formed through a lenses combination with up to an approx. 40 mm high vertical light section.

This light section (see the rectangle with a dotted border in Fig. 1) is positioned above the gas lance so that it goes through the midplane of the reactor. It is done such that the light section cuts the pulsating free jet of the air supply above the aerodynamic valve (right side in the section plane, the left side of the section plane is resultantly positioned exactly between the two valves). The excited fluorescence of the OH radicals is registered perpendicularly with the help of an intensive CCD-camera. In the determination of the OH-distribution, the measured pressure in the reactor serves as a trigger signal for the activation of the LIF measurements, such that pressure dependent twodimensional concentration profile pictures of the OH radicals can be taken.

In the reactor of the experimental equipment, various operational (gas and air quantities) and constructive parameters (position of gas supply) can be varied. These have an influence on the fuel-air mixing process and that leads to a change in the characteristic parameters (pulsation frequency, pressure amplitude).

3. Parameter variation and carrying out of the tests

Into the investigations in section 1 of this paper mentioned objectives, the following constructive, operational and measurement parameters were varied.

Angle between the gas and air supply α_G	constructive
Distance between gas supplies from the valve plate l_G	constructive
Air-fuel ratio λ	operational
Gas flow rate (load) $\dot{V}_G$	operational
Measuring height of the Laser section l_{LIF}	measurement

The increased turbulence in pulsation combustion results in strong fluctuations in the OH-distribution and therefore the averaging of more repeated pictures is required. In the determination of pressure dependent OH-distribution through LIF measurements, ten different pressure measurements points of the pressure fluctuations were fixed (see Fig 2) and with these pressure measurements points in each case 100 single pictures of the excited OH radicals were taken through a CCD-camera and subsequently evaluated by averaging of the discrete pixels.

The single pictures were taken (Fig. 3) with an exposure frequency of approx. 10-15 Hz. The 2D-temperature distribution was calculated from the OH-concentration profile, in which two excitation wavelengths (OH-rotation states: $P_2(8)$, $Q_1(11)$) were generated.

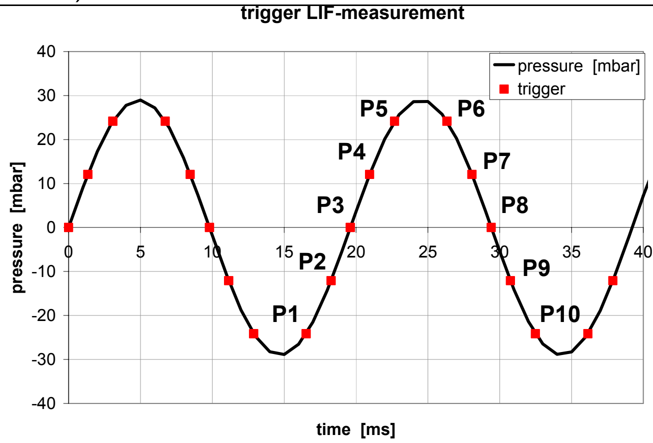

Fig. 2: Schematic illustration of pressure measurement points for LIF measurement.

4. Experimental results

The following shown measured results and diagrams are related to one certain experimental set-up. For the evaluation of this 2D-OH-distribution, the profile of the OH-concentration was given out for the first excited wavelength (P-transition) in the horizontal centre of the averaged laser section picture (white line in the top picture in Fig. 4) for all measuring points P1 to P10 (Fig. 4). From this profile, seven positions were chosen and these were plotted together with the pressure over the time. For the progression of the OH-concentration of these seven positions over time a simplified regression with a sine function was carried out, so that the phase shift between OH-concentration and the pressure oscillation could be determined (Fig. 5). This phase shift allows conclusions to be drawn about the ignition point within the measurement section.

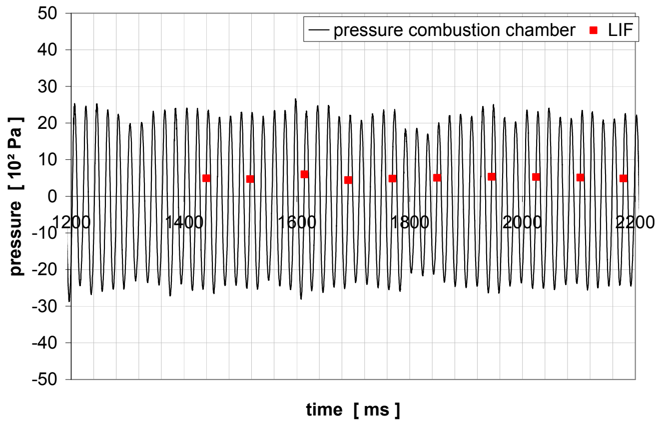

Fig. 3: Example measurement pressure oscillation with points of LIF photography at pressure measurement point P3.

Furthermore the position of the maximum OH-concentration of these profiles was plotted as well together with the pressure over time. For this evaluated graph for the pressure dependent OH-Concentration, a simplified regression with a sine function (Fig. 6) was used as well to determine the phase shift between the OH-concentration and the pressure change. In this case, a phase shift of φ = 34.9 exists, which is confirmed by the theory for the stable operation of a pulsation combustion.

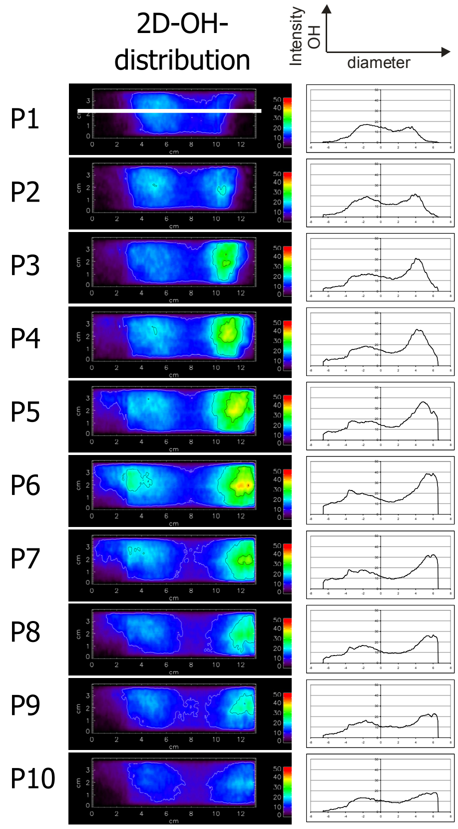

Fig. 4: Measured pressure dependent 2D-OH-distribution with profiles.

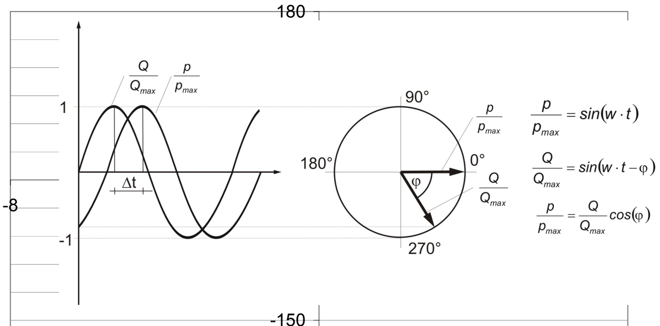

Fig. 7: Phase shift between pressure and energy release.

Fig. 5: Determined phase shift between pressure and OH oscillation.

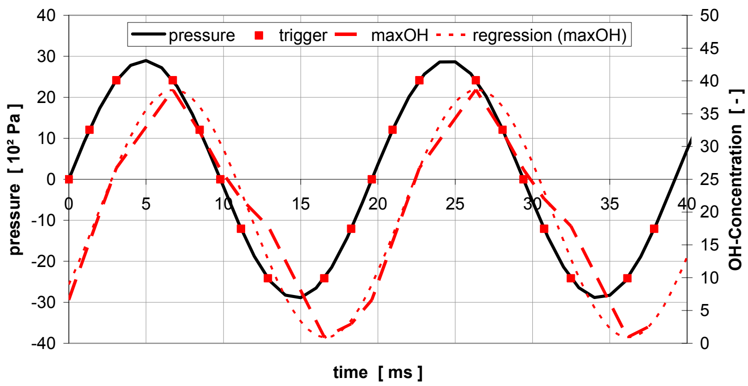

Fig. 6: Phase shift between pressure oscillation and maximal OH-concentration.

Principally for the erectness of the stable pulsation combustion the phase shift φ (see Fig. 7) between pressure oscillation and the energy release during combustion must lie in the range 270°<φ<90° (Rayleigh-Criteria) [8]. The highest pressure amplitude will be achieved when the pressure oscillation and the energy release move in a phase. The configuration of the phase shift is dependent on three characteristic times [9]:

1. Mixing time of the fuel and air
2. Mixing time of the fresh reactants with hot residual gas
3. Reaction time of the fresh reactants

To achieve a stable pulsating combustion the summation of these three characteristic times must be equal to the oscillation time of the acoustic resonance frequency of the reactor, which depends of the reactor geometry and the average temperature in the reactor.

Analogue to the evaluation routine of the averaged OH-LIF pictures the calculated temperature pictures are evaluated (Fig 8). By consideration of the temperature profiles, similarities in the form of the graphs can be noticed. The graphs of the temperature profile are strongly unclear (noisy), which is clearly visible in the stronger structuring of the 2D-temperature distribution. At the moment from the OH-LIF pictures a quality profile of temperature distribution can be obtained. For an exact determination of the temperature further work for calibration is necessary.

5. Results of the CFD-Simulation

For the CFD-simulation the software FLUENT was used. The configured parameters (air flow rates, gas flow rates, oscillation frequency) in the experimental investigations were used as the basis for the CFD-simulation. The pulsating operation was achieved here through an over the time sinus-shaped air supply. The fuel was stationary fed, which corresponds to reality, since the fuel gas is assigned with a significantly higher pressure as the resultant of pressure amplitude. For the flow simulation the standard-k-epsilon model was applied.

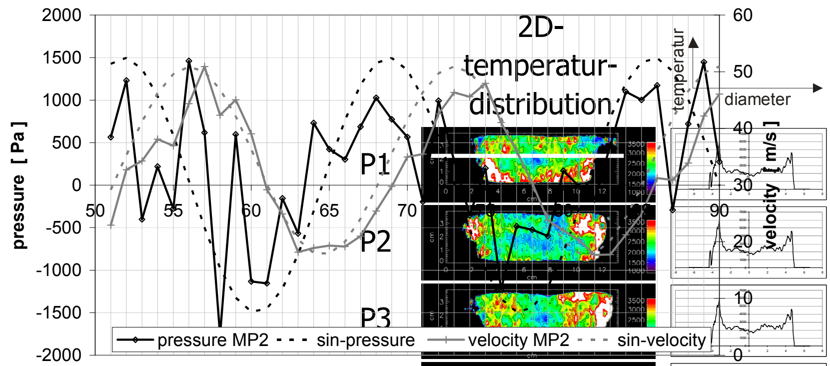

Fig. 9: CFD-computed pressure and velocity oscillation in the resonance pipe (MP2) ... fitted sinus function.

The integration of the combustion process occurs from the methane-air-1-step reaction equation with the combined model finite rate and eddy dissipation. In the mentioned calculation example the sinus-shaped air inflow is set with a frequency of 59Hz. The transient calculation is carried out with a time step of 1 ms. The walls are considered to be adiabatic, since in the foreground of the calculation was the computation of the pressure amplitude and not the heat transfer. As a resultant from the

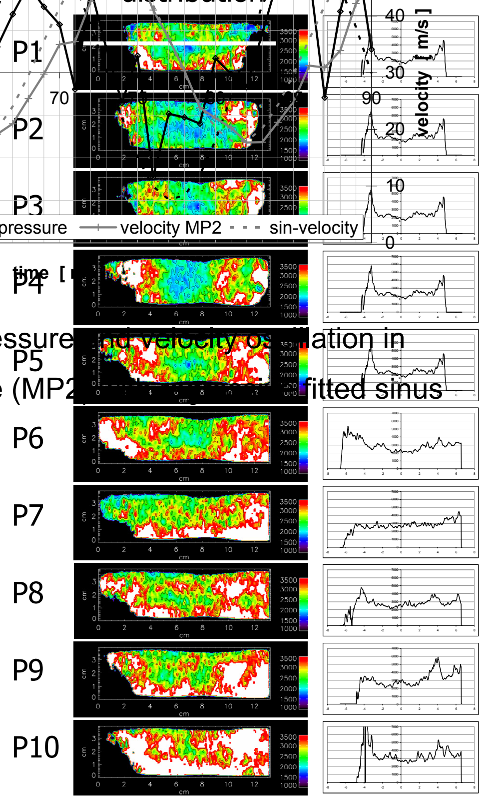

Fig. 8: Computed pressure dependent 2D-temperatur-distribution with profiles.

calculation in the resonance pipe (MP2), a pressure amplitude of 1392 Pa and a velocity amplitude of 16.5 m/s were determined. Experimentally pressure amplitude of 2905 Pa was measured. In this experiment the velocity amplitude was not ascertained.

Fig. 9 shows through CFD calculated pressure and velocity oscillations in the resonance pipe (MP2), a continuous line. The dotted lines show a related regressive fitted sinus function. Between pressure and velocity oscillation a phase shift of 90° can be noticed, which complies with the theory. The strong fluctuations in the pressure and velocity progression are probably attributed to the relative large time step in the calculation.

The subsequent pictures (Fig. 10) show the calculated contour plots of temperature and reaction rate at different pressures within an oscillation period. These are shown as a section through the middle plane of the reactor in comparison to the pictures from the high speed camera and the LIF measurements.

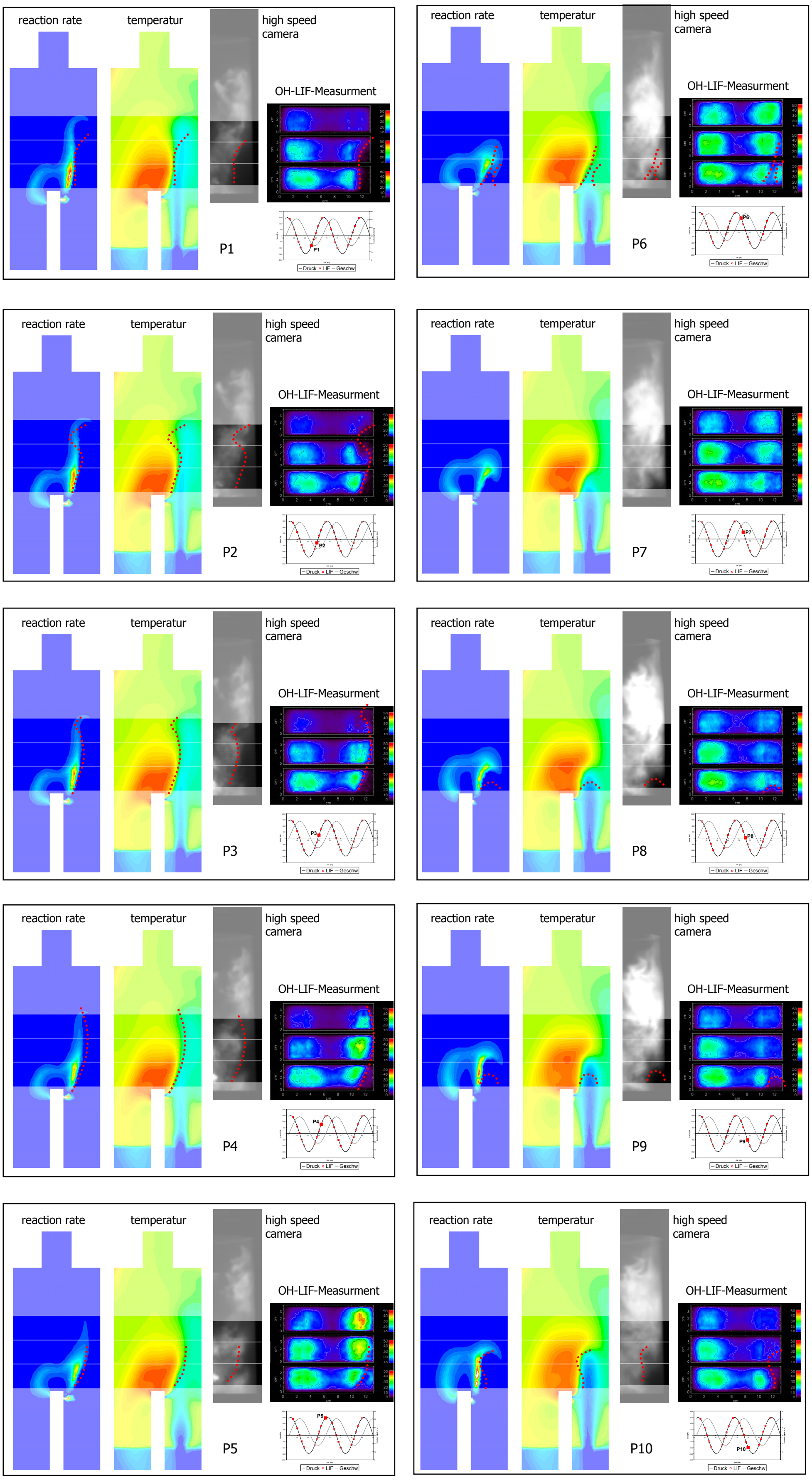

Fig. 10: CFD-computed contour plots of reaction rate and temperature in comparison with pictures of high speed camera and LIF measurement.

6. Summary

By the configuration of various constructive and operational parameters, the OH-concentration was measured in its relation to the prevailing pressure level within an oscillation period, in various heights above the combustion chamber bottom. In all experiments a correlation between the periodic changes of the OH-concentration in the considered light section and the change in the pressure were observed. The two dimensional pressure dependent plot of the OH-concentration provides here information about the ignition position, ignition time point; also the flame propagation and the calculation of the temperature distribution in the measurement section can be derived. From the experiment it is apparent, that the ignition position is determined from the position of the gas entry.

An important parameter for the evaluation of the combustion process is the phase shift between the OH-concentration and the pressure oscillation, which can be used for the determination of the ignition time point. Due to the periodic air supply from the aerodynamic valves in the combustion chamber, the ignition time point influences the flame propagation and also the reaction time of fuel and air. In comparison, the evaluated phase shift between OH-concentration and pressure oscillations with the deviation of the measured frequency from the calculated resonance frequency, it is clear that an increased deviation is associated with a larger phase shift i.e. with earlier ignition. The evaluation of the measured pressure curves of the individual experiments leads to the conclusion that with increasing deviation in the measured frequency from the calculated resonance frequency the size of the pressure amplitude decreases. An earlier ignition, which means the maximum of the OH-concentration is located timely before the maximum of the pressure oscillation, results in a reduction of the pressure amplitude.

The results of the carried out experiments confirm hence the theory, that the self configured pressure amplitude and the oscillation frequency can be determined significantly through the phase shift between pressure and energy release. For the up to now uncalibrated and evaluated 2D-temperature distributions through laser diagnostics, the underlying OH-LIF distribution for the P- and Q-transition are separately measured. For precise temperature determination the OH-LIF measurements of both rotation states must occur synchronously or with sufficient small delay. Qualitatively in view of the starting of flame and propagation, it results in comparable information about the concentration profile. The basic suitability of the adapted experimental configuration and the selected laser diagnostics method was demonstrated.

In the comparison, the CFD-simulation to the pictures from the high speed camera and the LIF-measurements, a good qualitative correlation of the periodic flow profile is recognisable. Likewise the phase shift between the pressure and the velocity oscillation is calculated correctly with 90°. The values of the calculated pressure amplitudes lie within the range of the measured pressure amplitudes. However for the CFD calculations, an incomplete mixing of the free jets of the air and fuel can be observed, which can be attributed to the inconsideration of the pressure wave in the calculation.

7. Literature

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