Experimental Investigation of the impact of imposed air inlet velocity oscillations on Soot Formation and Oxidation using an advanced 2-Colour-TIRE-LII

A. Aleksandrov*, H. Bockhorn

Engler-Bunte-Institute, Division of Combustion Technology
Karlsruhe Institute of Technology, Kaiserstrasse 12, 76131 Karlsruhe, Germany
e-mail: aleksandar.aleksandrov@kit.edu

Abstract
The impact of imposed air inlet velocity oscillation on the formation and oxidation of soot in non-premixed swirling turbulent flames due to acoustic perturbations at various frequencies (0-350Hz) is investigated. The investigation of such flames is of special interest for rich-quenched-lean -combustion concepts (RQL) applied in modern gas turbines. During RQL-combustion, the fuel is initially oxidized by air under fuel rich conditions followed by a fuel lean combustion.

For the investigation a model RQL-combustor was designed, were soot measurements in the highly turbulent, non-premixed swirling natural gas/ethylene flames at imposed air inlet velocity oscillations are performed. The main technique used is simultaneous 2-Colour-Time-Resolved-Laser-Induced Incandescence (2-Colour-TIRE-LII). This method is combined with line-of-sight averaged OH*-chemiluminescence imaging and measurements of the isothermal velocity field by high speed Particle Imaging Velocimetry (PIV). The goal of this work is also a detailed and well documented data basis for this standard configuration, which can be used from the combustion community for the development and validation of soot models.

1 Introduction

In modern combustion systems several concepts are developed aiming at reduction of the level of emissions of pollutants. In modern gas turbines the rich-quenched-lean (RQL) concept can be found. Here the combustion is taking place sequentially in partially premixed- or diffusion flames under fuel rich and fuel lean conditions to decrease the combustion temperature and, as a consequence, the NO_X-emission of the engines. Unfortunately, these combustion conditions are accompanied by the formation of soot [1, 2]. The particles originally formed during the fuel rich (diffusion controlled) step have to be completely oxidized in the fuel lean step in order to avoid the emission of soot particles into the ambient air with the exhaust gas of the engine.

Combustion oscillations due to flow instabilities may occur during non-stationary operating conditions of the gas turbine and are an additional challenge when trying to predict the soot emission from gas turbines. In spite of the significant progress being made with respect to the development and validation of soot models during the last decades, the understanding of the formation and oxidation of soot especially under highly turbulent – gas turbine like – conditions is still incomplete [1, 2]. This applies especially for combustion oscillations, the influence of which on the formation and oxidation of soot is more or less unknown.

The main goal of this work was to investigate experimentally the response of non-premixed swirling flames to acoustic perturbations at various frequencies (0 – 350 Hz) and to derive the impact of imposed air inlet velocity oscillations on the formation and oxidation of soot. For the imposed oscillations four loudspeakers at the air inlet of the model combustor were used. A natural gas/ethylene mixture is used as a fuel which is oxidized by air under fuel rich conditions in the first combustion chamber. An additional second combustion chamber enables the oxidation of the remaining HC, CO and soot, mimicing RQL-combustion.

Soot detection and soot particle sizing are performed using simultaneous 2-Colour-Time-Resolved-Laser-Induced Incandescence (TIRE-LII) [3]. This technique is a non-intrusive diagnostic method based on the simultaneous detection of the time resolved LII-signals at two different wavelengths. These measurements are combined with line-of-sight integrated OH* -chemiluminescence imaging and measurements of the isothermal velocity field by high speed Particle Imaging Velocimetry (PIV).

2 Experimental Setup und Methods

2.1 Model Combustor. For the present investigation, a model combustor for gaseous fuels with good optical access was designed and manufactured to apply advanced optical measurement techniques (figure 1). The air is supplied to both swirl generators individually. An additional burning chamber allows the implementation of RQL operating conditions

The measurements were performed in a plane through the nozzle axis. A natural gas/ethylene mixture is used as a fuel which is oxidized by air under rich conditions in the first combustion chamber (Φ = 1.56,

* Corresponding author: aleksandar.aleksandrov@kit.edu
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42 % C2H4, 58 % natural gas, P = 17.6 kW, atmospheric pressure). The air flow ratio (L = $V_{air, sec}$ / $V_{air, pri}$) between the outer and the inner swirl nozzle is L = 1.85, with a total air flow rate V_{air} = 171 l_N/min. In order to perform acoustic perturbations, four loudspeakers were mounted in both separated air inlets (two per air inlet). The response of the flame at several acoustic excitation frequencies between 0 Hz to 350 Hz was investigated.

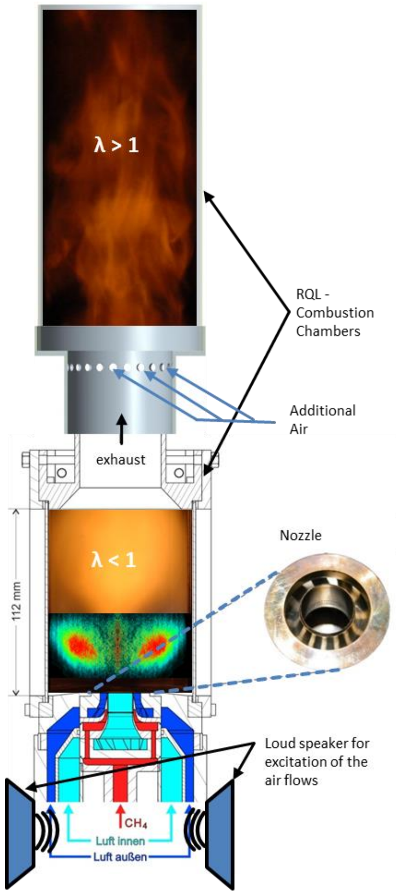
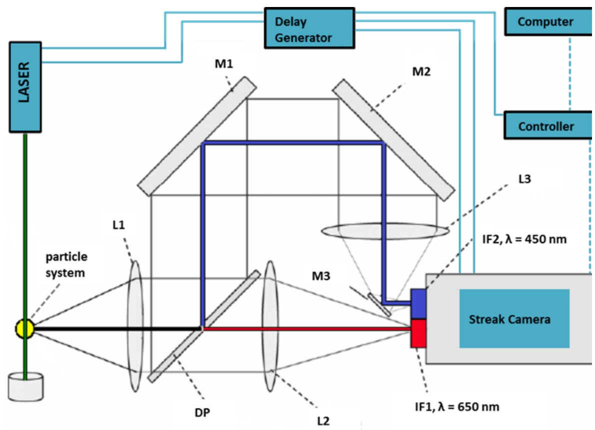


Figure 1 RQL – Model Combustor with excitation of the air flow

In order to quantify the intensity of the imposed flow oscillations, a sound pressure level was calculated (relative to the absolute threshold of hearing) from microphone measurements in the outer and the inner air supply. The comparison between acoustic unexcited and excited case shows an increase of the sound pressure level due to the air inlet perturbations with approximately 19 dB.

2.2 Simultaneous Two Colour-Time-Resolved-Laser-Induced Incandescence. The simultaneous 2-Colour-TIRE-LII is based on the simultaneous one-dimensional detection of the time resolved LII-signal at two different detection wavelengths along the propagation direction of the laser beam. A schematic drawing of the setup is shown in figure 2 [3]. A frequency doubled Nd:YAG - laser pulse (λ = 532 nm, t = 10 ns) induces the LII-signal in the measuring volume. The thermal radiation emitted from the particle ensemble is collected with a spherical lens L1 and afterwards the signal is separated by a dichroic plate DP into two wavelength regimes: λ1 > 500 nm and λ2 < 500 nm. The thermal radiation signals at both wavelengths are imaged onto the entrance slit of a streak-camera (Hamamatsu C7700) one aside each other with the help of the lenses L2 and L3, respectively. In front of the entrance slit of the streak-camera appropriate interference filters IF are positioned to further restrict both detection wavelength regimes. The center wavelength of the filter in the straight optical path is λ1 = 650 nm (Full Width at Half Maximum FWHM: 40nm) and λ2 = 450 nm (FWHM: 40 nm) in the folded beam path, respectively.

By applying Planck's law assuming grey properties of the soot particles the temporal evolution of the particle ensemble temperature can be calculated from the measured ratio of the time-resolved LII-signals obtained at two different wavelengths [3]



L1	D = 100 mm, f_1 = 220 mm	M3	30 x 20 x 2,5 mm
L2, L3	D = 100 mm, $f_{2,3}$ = 150 mm	DP	160 x 100 mm
IF1, IF2	FWHM: 40 nm	M1, M2	D = 100 mm

Figure 2 Experimental setup of the simultaneous 2-Colour-TIRE-LII technique [3]

One of the major advantages of the simultaneous 2-colour TIRE-LII experiments is that laser absorption is not to be modeled since the particle temperatures after the laser pulse are experimentally determined. These measured particle temperatures 10 ns after the laser pulse are the initial condition for the numerical simulation of the particle cooling independent of processes occurring during the laser pulse. Particle size distributions are obtained by fitting the simulated particle temperature decay onto the measured one by varying fit parameters. In the case of a particle system dominated by coagulation, the particle size distribution can be approximated by a log-normal distribution, where two fit parameters (medium size r_m and the width σ) are needed to describe the size distribution. A multi-dimensional non-linear regression method delivers these two parameters. A more detailed description of LII and the simultaneous 2-Colour-TIRE-LII method applied in this work can be found in the literature [3, 4, 5, 6].

2.3 High Speed Particle Image Velocimetry. The state-of-the-art non-intrusive flow velocity measurement technique is the Particle Image Velocimetry using small tracer particles. The particles follow the flow and, therefore, are used for the determination of the fluid velocity. In the present investigation µm sized MgO-particles were illuminated by a laser-light-sheet (INNOVA 70C-5) defining the measurement plane. A CMOS-camera (High Speed Star 5.1) captures the light scattered by the particles. Two pictures (double frame mode) are taken within an adjustable time gap of few microseconds at a repetition rate of 8000 Hz. The two images captured at time t and t' are stored on two frames of the CMOS- sensor. This allows to cross-correlate the two particle image distributions in small interrogation areas in order to determine their displacement at several positions of the observation field. A detailed description and the variety of PIV measurement techniques are given in [7].

3 Results and Discussion

In the following the isothermal flow field inside the combustion chamber at various air inlet perturbation frequencies is presented.

As expected, the averaged flow field for the non-excited case is not changed with the time and shows no variation in time of structure and value of the velocity. The typical inner and outer recirculation zone for a swirl stabilized flame is observed.

In figures 3, 4 and 5 the velocity fields at 50 Hz, 100 Hz and 350 Hz excitation are displayed. The flow field in the cases 50 Hz and 100 Hz is strongly influenced by the imposed air inlet oscillations. At 50 Hz, during one period the flow field is strongly changed and the inner recirculation (IRZ) zone disappears completely at some phase-angles for more than 6 ms. With air inlet oscillation of 100 Hz the velocity field is influenced to a lesser extent compared with the 50 Hz case. Here the IRZ exists in all phase-points over one complete 100 Hz oscillation cycle. The flow response to the air inlet perturbations is strongly frequency dependent. In contrast to 50 Hz and 100 Hz cases the velocity field remains unaffected by the acoustic oscillation at 350 Hz. The flow field remains unchanged in every single phase at 350 Hz excitation frequency and is similar to the unexcited case. The response of the flow to different oscillation frequencies affects crucially the mixing conditions between the fuel and the air, the radical distribution and the temperature field in the combustion zone of the primary combustion chamber and, hence, causes changes in the soot formation and oxidation conditions.

From figure 6 the strong impact of acoustic oscillations on the averaged soot volume fractions, averaged mean particle sizes and averaged particle number densities (avg_f_V, avg_r_m, avg_N_T) is obvious. It can be seen that, depending on the oscillation frequency, a reduction of the averaged soot volume fractions and soot particle sizes occurs. Between 0 and 200 Hz, the region with the highest soot volume fraction in the flame is stable and not shifted by the oscillations. This zone is located at 60 mm height above the burner (HAB) and 8 mm radial distance. At 350 Hz a different

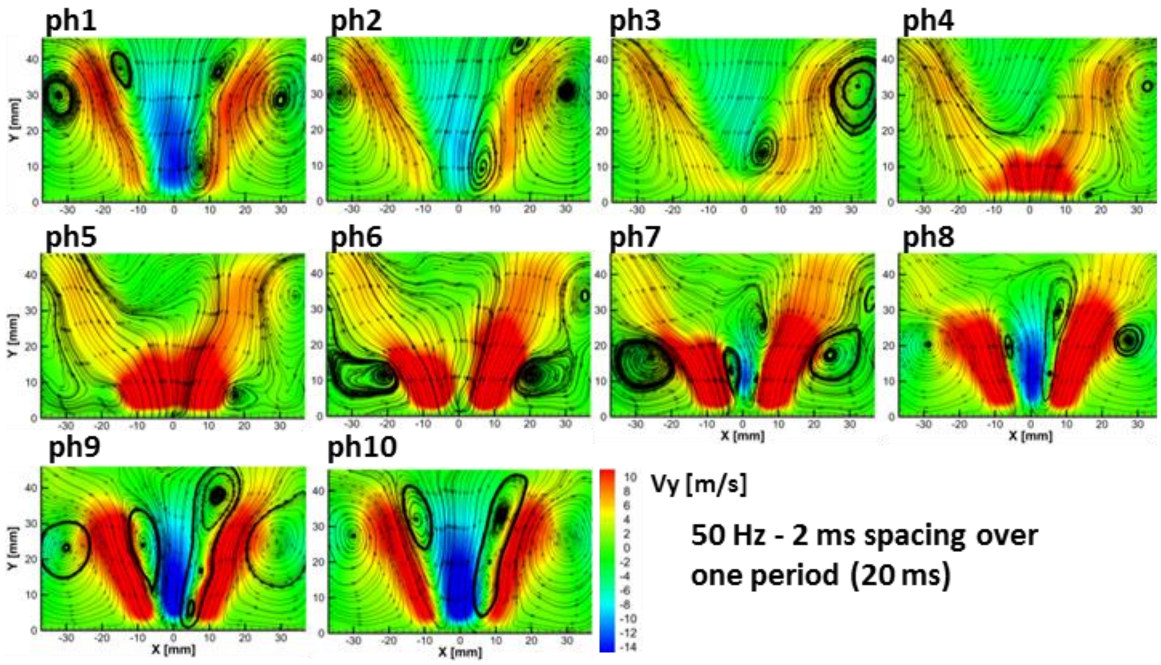


Figure 3 Phase-locked exposures of the isothermal velocity field with 2 ms spacing for a period duration of 20 ms at 50 Hz imposed acoustic oscillation averaged over 50 images

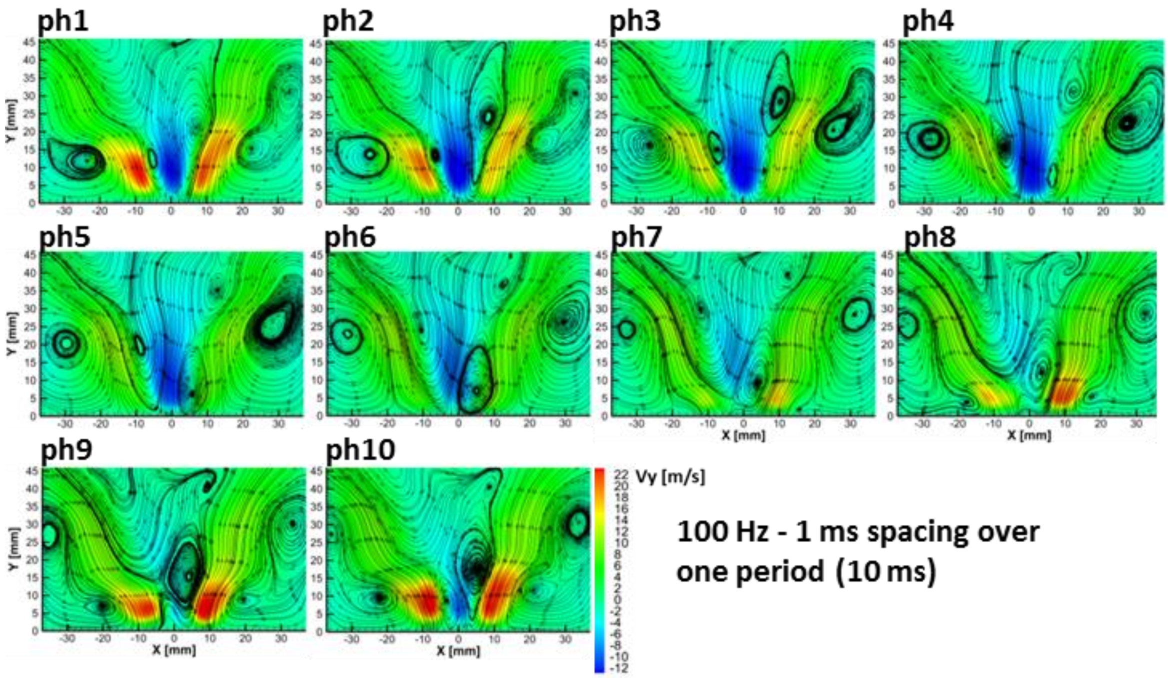


Figure 4 Phase-locked exposures of the isothermal velocity field with 1 ms spacing for a period duration of 10 ms at 100 Hz imposed acoustic oscillation averaged over 100 images

distribution is observed. In this case the highest soot volume fraction is detected at 46 mm HAB and 8 mm radial distance. From figure 10 it can further be seen, that the soot volume fraction decreases in all regions by approximately 50%, if the frequency is increased from 0 to 100 Hz. At higher frequencies (200 Hz), the response of the system is weaker, whereas at 350 Hz f_V is even higher than without acoustic excitation. This especially is obvious at HAB > 70 mm and in the outer regions of the combustion chamber. The averaged mean particle size is also reduced at 50 Hz, 100 Hz and 200 Hz whereas at 350 Hz no significant change in the size of the soot particles is observed. Further, a strong reduction of N_T occurs at 100 Hz, in the outer regions of the flame. At 350 Hz even an increase of the particle number density caused by applied oscillations is observed. The particle inception dominated zone (r = 5 to 13 mm at 70 mm < HAB < 90 mm) at 100 Hz is reduced in size, whereas it is enlarged at 50 Hz, 200 Hz and mainly at 350 Hz. From figure 6 is obvious for the unexcited case that the region near to the nozzle axis is the most important zone with respect to soot particle inception and coagulation (highest soot volume fractions, soot particle sizes and number densities). This

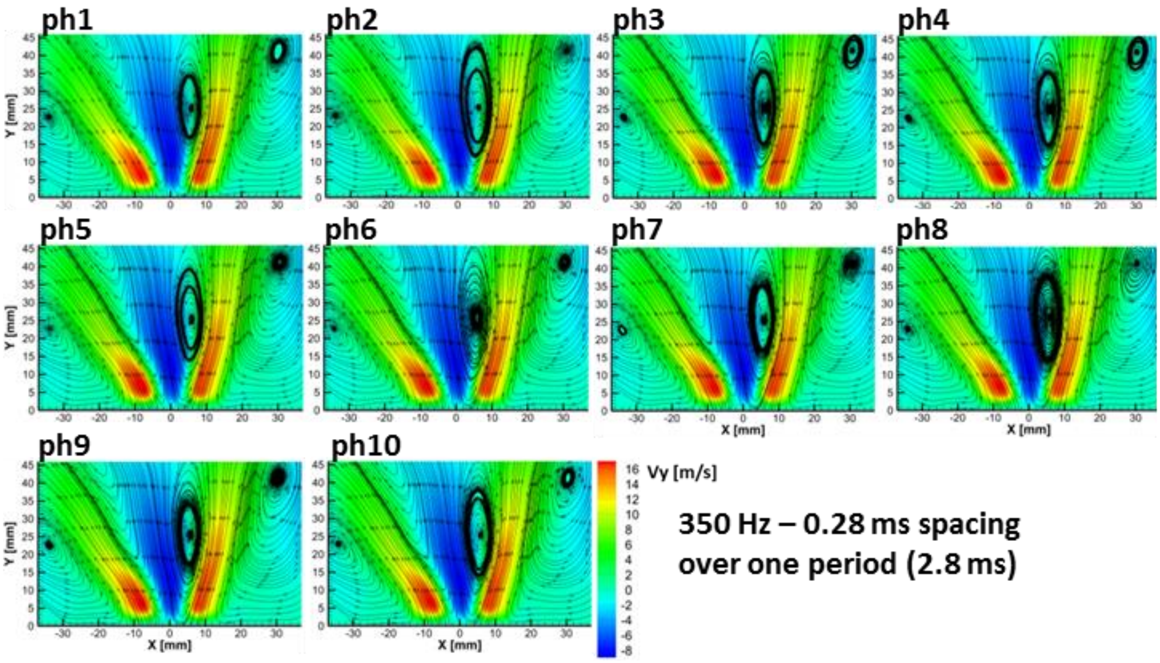


Figure 5 Phase-locked exposures of the isothermal velocity field with 0.28 ms spacing for a period duration of 2.8 ms at 350 Hz imposed acoustic oscillation averaged over 350 images

near nozzle axis region and the connected inner recirculation zone are strongly influenced by the imposed oscillations of the flow field, especially at 100 Hz.

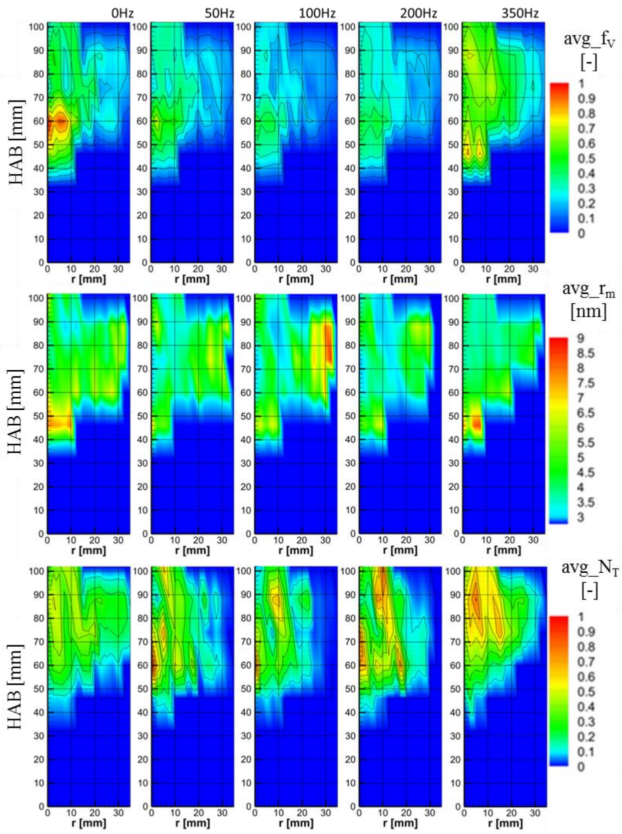


Figure 6 Averaged soot volume fraction, mean soot particle radius and normalized particle number density at various excitation frequencies

number density and at the same time larger mean soot particle sizes. The extent and location of the "oxidation regions" are strongly affected by the air inlet perturbations, especially at 100 Hz, where the zone dominated by oxidation reactions is the largest one for all cases (0 Hz to 350 Hz). This zone can be observed for all HABs at r > 24 mm.

Additional important information about the impact of the acoustic oscillations on the formation and oxidation of soot are obtained by OH*-chemiluminescence measurements. Without perturbations the flame is located at 10 – 15 mm above the nozzle and the region of high OH*-concentration is relatively compact. Especially at 100 Hz, the influence of perturbations on the flame becomes also evident by the enlargement of the zone possessing high OH*-concentration. Zones of high soot concentrations are reduced in the flame on account of the extension of zones with high OH-concentrations and thereby intensification of soot oxidation. From the OH*-measurements it can be seen, that the lift-off height of the flames 100 Hz is decreased by the acoustic oscillations. In figure 7 further can be seen that, the region of high OH* concentration is strongly affected by the oscillation at 100 Hz and changes its location at every single phase. Additional, fluctuations in the intensity caused by changes in the OH* concentration are observed. Hence a fluctuating heat release is the result of the imposed air inlet velocity oscillations. Especially at 100 Hz the increase of the OH* intensity at some phases is more than 100% compared to the non – excited case.

Figure 8 shows the response of the flame at 350 Hz oscillation frequency. In this case the OH* field is constant over the complete period and identical to the non – excited case (top of the figure 8).

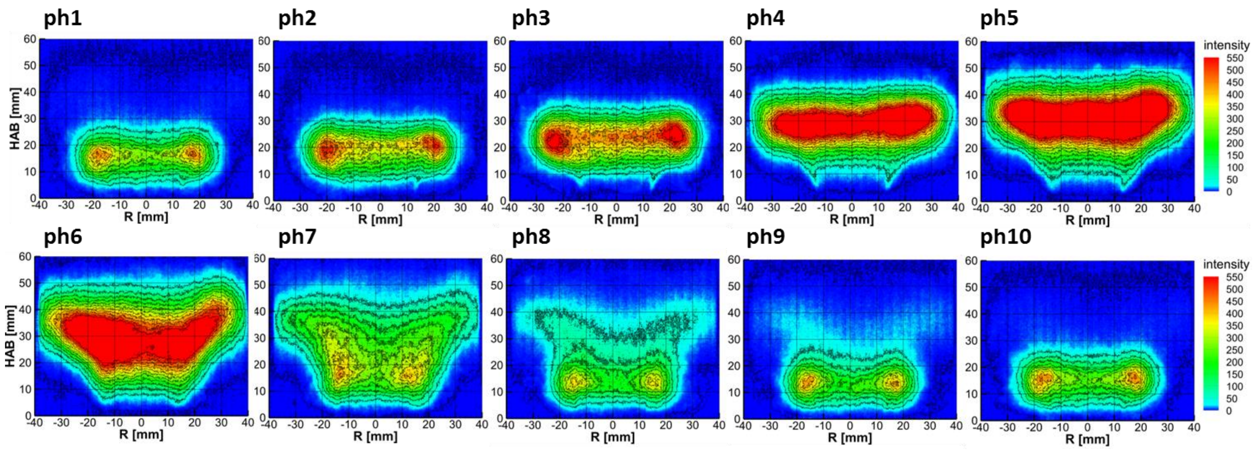


Figure 7 Phase-locked line-of-sight integral OH*-chemiluminescence exposures with 1 ms spacing for a period duration of 10 ms at 100 Hz imposed acoustic oscillation over 100 images

For the observed sooting tendencies of the investigated flames also the variations in the "oxidation regions" of the flame affecting soot oxidation are important. Soot oxidation is connected with reducing of the soot particle

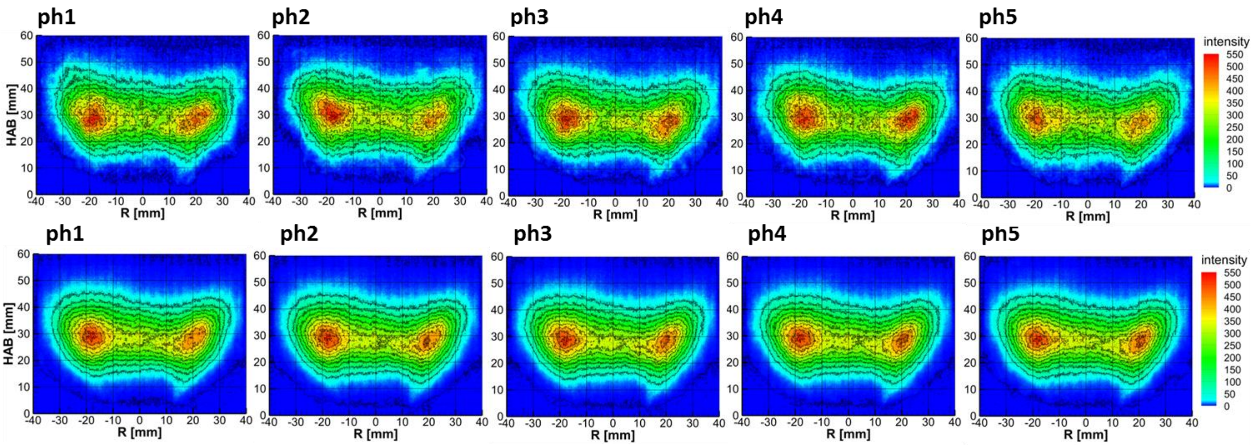


Figure 8 Phase-locked line-of-sight integral OH*-chemiluminescence exposures with 2 ms spacing for a period duration of 20 ms at 0 Hz (top) and 0.28 ms spacing for a period duration of 2.8 ms at 350 Hz imposed acoustic oscillation (bottom)

4 Conclusions

The response of non-premixed swirling flames to acoustic perturbations at various frequencies (0 – 350 Hz) and the impact of imposed air inlet velocity oscillations on the formation and oxidation of soot were investigated. Soot measurements at imposed air inlet velocity oscillations were performed using simultaneous 2-Colour-TIRE-LII. These measurements are combined with line-of-sight integral OH*- chemiluminescence imaging and isothermal velocity field measurements using high speed PIV.

The experimental results give insights in the formation and oxidation processes of soot and its interaction with acoustic oscillations in swirled non-premixed flames. A frequency and amplitude dependent decrease of the soot volume fraction, soot particle size and number density was observed. These variations were attributed to changes in the velocity field and the OH*-radical distribution. Variations in the mixing conditions between fuel and oxidizer, enlargement of the zone of high OH*-concentration (intensification of the soot oxidation) and smaller lift-off heights of the flame were observed. As a consequence, a significant impact of the air inlet velocity oscillations on the formation and oxidation of soot was found in our investigations.

The results of the high speed PIV measurements reveal a strong influence of the air inlet acoustic perturbations (at 50 Hz and 100 Hz) on the flow field in the combustion chamber. A shift of the maximal velocities (axial and radial) in radial direction was found. This observation leads to the conclusion, that especially in the case of 100 Hz the mixing conditions in the chamber are improved due to an increased radial exchange of the fluid. Consequently, the conditions in the combustion chamber are more homogenous and the flame behavior is more similar to premixed combustion with respect to the formation and burnout of the soot particles.

The velocity measurements show a significant enlargement of the inner recirculation zone and its temporal stability at 100 Hz excitation. At about 100 Hz the highest decrease in soot volume fraction (~ 50 %) and mean soot particle sizes (~ 30%) as well as on number density (outer region) was observed. Furthermore, the shift of the region of maximum particle number density was more pronounced at 100 Hz compared to other frequencies.

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References

[1] H. Bockhorn, A. D’Anna, A.F. Sarofim, H. Wang, Combustion Generated Fine Carbonaceous Particles, Proceedings of an International Workshop, Villa Orlandi, Anacapri (2007)
[2] H. Bockhorn, Soot Formation in Combustion: Mechanism and Models, Springer Verlag, Berlin, (1994)
[3] Th. Lehre, R. Suntz and H. Bockhorn: „Time-Resolved Two-color LII: Size Distributions of Nano-Particles from Gas–to–Particle Synthesis”, 30th Symposium (International) on Combustion, The Combustion Institute, Pittsburgh, 2585 (2004)
[4] T. Lehre, B. Jungfleisch, R. Suntz, H. Bockhorn, Appl. Opt. 42, 2021 (2003)
[5] T. Lehre, H. Bockhorn, B. Jungfleisch, R. Suntz, Chemosphere 51, 1055 (2003)
[6] M. Charwath, Experimentelle Untersuchung und numerische Simulation der Rußbildung in laminaren Methan/Luft Diffusionsflammen, Dissertation, Karlsruhe Institute of Technology (KIT), (2011)
[7] M. Raffael, Chris E. Willert, Steve T. Wereley, J. Kompenhans, Particle Image Velocimetry: A Practical Guide, Springer Berlin (1998 1st ed./ 2007 2nd ed.)