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ACOUSTICAL DIAGNOSTIC OF SPRAY-AIRFLOW INTERACTION IN A MODERN AERO ENGINE COMBUSTOR CHAMBER*

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Abstract

One possible way of significantly reducing combustion emissions of an aero engine is a lean injection system in which the fuel is directly mixed with a large amount of the combustor air. The operability of an aero engine requires a high flame stability, which leads to a staged fuel injection arrangement for a lean burn combustion system. The pilot injector is fuelled at low power operations (engine idle and approach) and the pilot flame is anchored in an airflow recirculation zone.

This paper describes the acoustical diagnostic of spray-airflow interaction phenomena, which is identified as the main factor for combustion stability and ignition performance.

The time depending sound pressure level spectrum of the flame was measured during the tests. From the spectrogram it was possible to deduct the period, where each spray form exists. Compared to the laser diagnostics it is the most effective way to investigate the spray flip.

The proposed methodology could be used for monitoring the flame form inside of an aero engine.

1 INTRODUCTION

The environmental requirements to the civil aviation becomes in the next time stronger. The future aircraft demands new environmental friendly aero engines. Therefore, the following goals have to be reached during the aero engine development: the reduction of production and maintenance costs, the minimization of the specific fuel consumption and engine weight, an increased reliability and a decrease of development cost and time. The second important point of environmental improvements is the aero engine noise. During the last 55 Years the noise emissions were reduced from 110-120 dB to 90-100 dB. The research work was concentrated on fan noise and jet noise minimization during these years. However, the combustion chamber has a dominated influence on the noise formation in all components of the aero engine. This is the main reason to pay attention to the combustors noise in the next years.

Lean burn combustion technology has been developed within RR/RRD European and national research programs based on the single-annular combustor architecture [1] [2] [3] as shown in Figure 1. Due to cost, weight and complexity reasons these staged lean combustion systems were implemented into relatively simple combustor architecture of a single annular combustor to ease the application to an aero engine. Moreover, a single annular combustor offers a favourable surface to volume ratio.

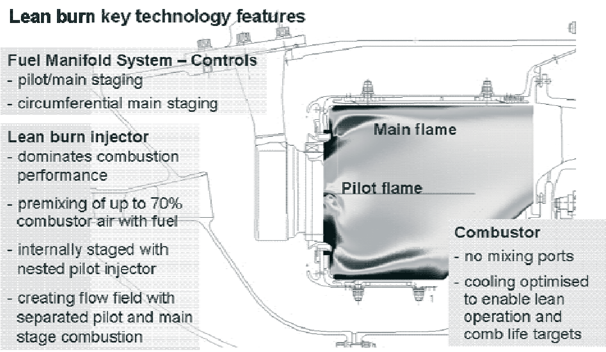

Figure 1: RR / RRD Lean burn single annular combustor architecture.

By using the lean injection system in which the fuel is directly mixed with a large amount of the combustor air it is possible to significantly reduce the combustion emissions. A lean combustion system operates with an excess of air in the combustors primary zone in order to significantly lower the local flame temperatures and consequently reduce the formation of NOx. Up to 70% of the total combustor air flow may be premixed with the fuel before entering the reaction zone. In this zone an optimal homogeneous fuel-air mixture is the key factor to actually achieve lower flame temperatures.

On the other hand, the operability of an aero engine requires a high flame stability, which leads to a staged fuel injection arrangement for a lean burn combustion system. The pilot injector is fuelled at low power (engine idle and approach) and the pilot flame is anchored in an airflow recirculation zone. The pilot zone is operating on the rich side of stoichiometry and has to therefore be optimized for low carbon monoxides (CO), unburned hydrocarbons (UHC) and soot.

Fuel staging is accomplished by an internally staged lean-burn fuel injector, which generates a homogeneous fuel-air mixture in a given combustor volume enabling combustion with reduced peak temperatures at medium to high power operating conditions. The fuel injector configuration features a concentric arrangement of a main fuel stage embedded into large swirling air streams carrying the biggest portion of the combustor air and a nested pilot fuel injector located in the centre (Figure 2). The combustor consists of three air swirlers and two fuel circuits, and a flow splitter that divides the airflow into two airstreams. Two distinct flames (a pilot and a main flame) are produced by two concentric fuel circuits that fuel the two airstreams (Figure 1). Setting up a recirculating pattern depends on the amount of air-swirl in either a central or a de-central shape as shown in Figure 4, which allows control of the flames structure and the zonal interaction.

As the pilot zone is operating fuel rich, the main air flow is quenching the reaction compromising its ignition, LBO and efficiency performance. In addition, pilot smoke production and fuel consumption may be affected. As the main is operating fuel lean, fuel preparation and hence combustion efficiency at medium power conditions could be adversely affected. Therefore, the pilot flame needs to sustain the main combustion process.

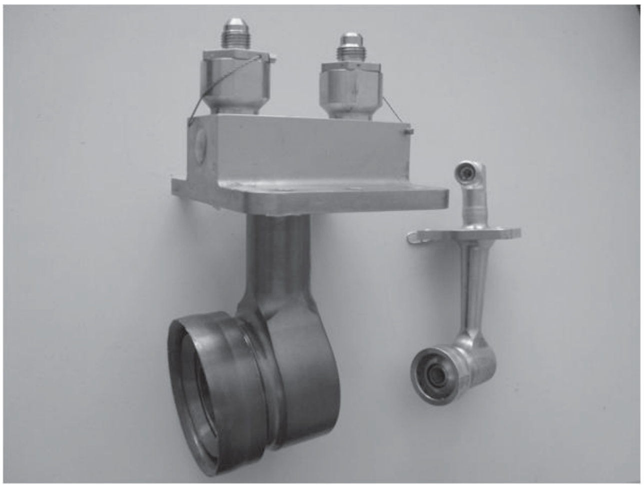

Figure 2: RR LDI fuel injector configuration comparison with a conventional injector.

To optimize the combustion characteristics of predefined configurations many test were necessary. Unfortunately, some tested injector configurations showed different stability performance during the tests. The flame changes its form stochastically. The spray-flip effect, which was a reason for the flame form changes, was observed at different combustor configurations. For example, a rapid spray deflection causing the flame shape change from a narrow to a wide cone form means a sudden decrease of the combustion stability. Eventually, the flame extincts if its weakest stability limit is reached. The narrow cone spray changes into a wide-cone spray upon slight changes of intake/air feed conditions. The wide-cone spray is favorably directed to ignition source, increasing the ignition capability. On the other hand the stability of this wide-cone flame form is very low. In contrast to this the narrow cone spray shape does not show a wide range ignition capability, but increased flame stability. Because the flame shape depends on the spray parameters, any spray changes will define the flame characteristics. For example, a rapid spray deflection means the flame form changes from narrow to wide cone. By this way the combustion stability decreases and the flame extinguishes, when the stability limit is reached. It is mandatory to design a simple diagnostic system in order to recognize and prevent an undesired change of spray and flame shape, while all operability requirements in terms of flame stability and ignitability are fulfilled.

2. EXERIMENTAL METHOD

2.1 Atmospheric Combustor Test Rig and Injector Configurations

The measurements of combustion stability and ignitability were performed in a combustor chamber test rig at the BTU Cottbus Laboratory [4]. The construction of the test rig allows a relatively rapid change of tested configurations. To guarantee a good optical access a planar wall combustor was used as shown in Figure 3. Due to the planar quartz glass on the combustor side, the view on the flame and spray from the operator place is improved. The test bed has an air supply and fuel supply systems.

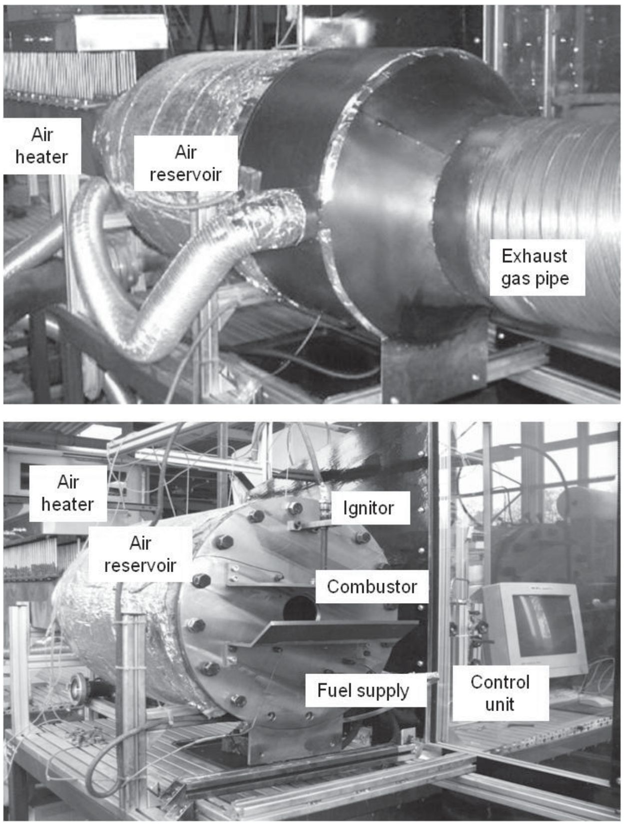

Figure 3: Atmospheric combustor test rig at the VFA, BTU Cottbus.

The air flow fields inside the combustor can be created by assembling swirler kits in the injector unit (Figure 4 below). The injector configuration A is developed for a de-central flow recirculation (Figure 4 above), which is realised by a low pilot swirl. In this case the flame is stabilized by the toroidal recirculation air flow zone around the combustors central axis. Configuration B produces a central recirculation due to a high pilot swirl. The recirculating air flow zone is concentrated in the combustors central area.

This method allows a flexible exchange of different testing configurations with predefined flame properties.

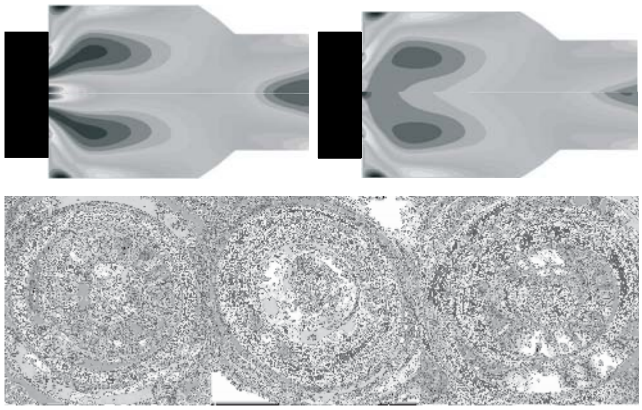

Figure 4: CFD de-central (above left) vs. central recirculation (above right) and test configurations (below).

2.2. CFD Method

The spray-airflow interaction was investigated by applying the CFD code CFD-ACE. The fluid flows are simulated in the CFD-ACE code by numerically solved partial differential Navier-Stokes equations, which govern the transport of flow quantities. The code solves the governing equations of mass, momentum and energy by using an approximation by a finite volume approach. Auxiliary, the code solves equations for the particles movement and droplet evaporation.

Various turbulence models are implemented in CFD-ACE, however a standard k-ε model was used for the calculations presented in this paper. This two equation model employs partial differential equations to control the transport of the turbulent kinetic energy k and dissipation energy ε. The used model is based on Launder and Spalding.

The droplet movement is modelled by solving the Lagrangian conversation equations for discrete particle parcels tracked through computational domain. The number of different droplet sizes injected into this domain defines the number of parcels. Each parcel consists of a fixed quantity of identical droplet. A parcel is tracked during its lifetime until leaving domain or full evaporation. This calculation procedure is repeated during iteration process for each parcel.

By applying this simulation methodology the droplet trajectories at different airflow field conditions and atomization parameters were computed.

To accelerate the simulation process a 2D axis-symmetric approach with reduced number of cells was used. Atmospheric inflow conditions were applied to reach a good agreement with experimental results from the atmospheric test bed. A Rosin-Rammler Sauter-Mean-Diameter (SMD) droplet size correlation gave the best agreement with experimental results.

2.3. Spray and flame visualisation

One of known simple and informative ways to investigate the combustion phenomena of proposed injector configurations is a visual evaluation of the flame and spray photos. For the spray visualization in the combustor test bed an optical access for the laser light sheet on the upper combustor wall was organized. The air-cooled argon ion laser used for this purpose produces a continuous light with a wavelength of 488-514 nm.

An optical head with a lens system is mounted directly at the combustor and allows translation of the laser ray from the argon laser into the spray research area inside of combustor. At the end of the optical head the light cut is expanded into a divergent two-dimensional layer with a thickness of 1 mm. The line-cutting plane represents the exposure level for the camera photographs. The mounting system of the laser head makes a free positioning possible of the laser cut at the spray cone. A standard digital camera photographed the scattered light at every spray droplets.

Comparing the flame and spray pictures in Figure 5 it was found that the shapes of fuel distribution and flame structure are similar at the same test conditions (swirler configuration, air- and fuel mass flow). In other words, the spray form highly correlates with the flame structure (Figure 5). During the current spray tests it could be confirmed, that the air flow field significantly influences the spray cone shape. The de-central recirculation supports a narrow cone shape spray and the central recirculation creates a wide cone spray. A comparison between the Mie-scatter picture of the spray and the flame form allows the documenting of a very clear dependence between the flow-, spray- and flame form. In the case of de-central recirculating flow field, the narrow cone spray results in a very stable narrow cone flame form. In contrast, the combustion process is not very stable in the case of a wide cone flame and extincts at approximately 50% of the air-to-fuel ratio reached in the case of the narrow cone flame.

In general, the correlation between the airflow and spray define all main combustion parameters. The combustor geometry and swirler configurations define the air flow structure. The nozzle design influences the atomization process. Therefore, acceptable flame parameters could be reached by choosing an optimal hardware configuration.

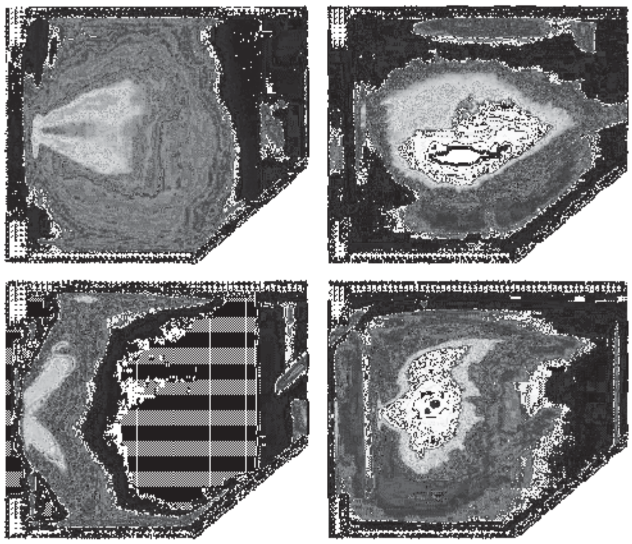

Figure 5: Spray (left) and flame (right) photos. The narrow cone shapes are represented in the upper row.

2.4. Acoustic measurements

A handheld sound level meter and frequency analyzer type AL1 (NTi Audio) was used for the acoustic measurements and was fitted with a ½" MiniSPL microphone with an omnidirectional directivity. This instrument allows measurements in a frequency range from 20 Hz up to 20 kHz. It was set up for third-octave band measurements with an flat input filter, an input range of 60 to 140 dB re 20 µPa and fast time weighting (t=125 ms). Besides the measurement of the instantaneous sound pressure level (SPL) the equivalent sound pressure level was logged as a linear time average over periods of 10 s duration.

Figure 6 explains the acoustic measurement arrangement. Three measuring locations for the microphone were defined around combustor rig. All three locations were placed circularly around the combustor axis with a distance of 1,3 m. Locations 1 and 2 were situated on the horizontal plane, fixed on the combustor axis level, which is 1 m above the ground level. The measurement location 3 was fixed at the

angle of 30° below the horizontal plane to have a direct line of sight to the flame without disturbing mountings.
During the measurements, several combinations of altered pressure drops, air fuel ratios (AFR) and flame forms were analyzed. Afterwards the stored values for each set of these parameters were averaged over the three locations.

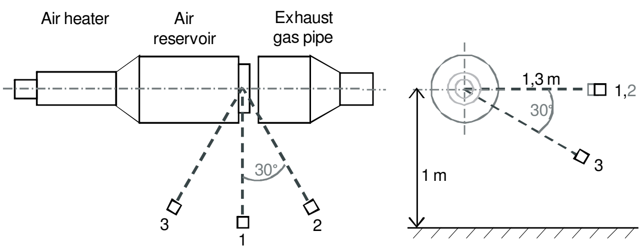

Figure 6: Microphone test arrangement.

In addition to the SPL measurements recordings of the sound pressure time histories were made for a subset of parameter sets using a digital recorder with a sampling rate of 44.1 kHz and 16 bit resolution. These recordings were then used to calculate spectrograms (time histories of the spectrum) using the freeware signal analyzing tool 'Sonogram 2.80'.

All measurements were carried out at normal atmospheric conditions in the laboratory hall at an ambient temperature of 20°C and static air pressure of 1010.35 Pa.

2 RESULTS AND DISCUSSION

3.1. Spray-Airflow Interaction

During a stationary combustion test of configuration A at the BTU Cottbus a flame-deflection effect (so-called flip) was discovered. Although the air- and fuel flow were constant, the flame suddenly changed its form from narrow to wide cone. By this rapid flame-flip all important combustion parameters were changed. It has to be mentioned at this point, that the narrow cone flame is more stabile and shows higher weak extinctions values, than the wide cone flame. The influence of the flip-effect on the ignition performance was discussed in details in [4] and [6].

The same form change occurrence was observed during the spray experiments. Because the flame properties are strong depending on the spray characteristic, the investigation is concentrated in the following on the spray behaviour only. The spray instability causes the flame fluctuations. That means the spray-airflow interaction is one of important factors influencing lean blow-out (LBO) and ignition performance.

It has been observed that two different spray shapes may exist at the same air- and fuel flow condition. This effect was investigated with different air swirler configurations.

Therefore, it was necessary to investigate the influencing factors that cause all observed spray forms. To characterize the spray at this point, two main spray parameters – droplets concentration and the spray angle - have been analysed. The method of the Mie-scatter picture acquisition has been described above. During the tests it was found out that the spray form is not stable in the area at higher fuel mass flow and medium airflows only. For the ignition and combustion process this behaviour means that the combustion mixture ignites accidentally and the flame stability is time dependent.

In the area of a low fuel mass flow the wide spray cone dominates. The area of the medium fuel mass flow is unstable and inside of this area the spray shape is changing from wide cone to narrow cone. The narrow cone spray dominates at high fuel flows. In case B the narrow cone is only possible at low air mass flows.

The curve shown in Figure 7 represents the border between both possible spray forms of the tested configuration. In the area above the curve only the wide cone spray exists. In the area below the curve the narrow cone spray is present. The curve itself characterizes an unstable regime, where the wide- and narrow spray cone shape may alternate stochastically.

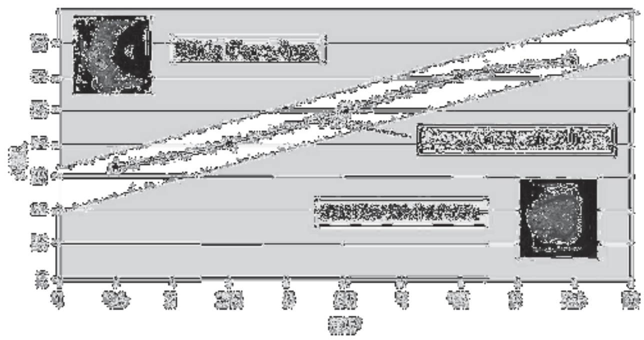

Figure 7: Spray deflection line of configuration A.

In general, the following factors influence the spray shape: airflow field, spray mass flow and atomization quality. To define the influence of each factor, a separate variation of the investigated parameter has been done [5].

The air- and the spray swirl in combustion chamber have their own momentum and as a result, the droplets are deflected from their ballistic initial trajectory by the centrifugal and turbulent flow field forces. The mechanics of the droplets movement in rotating airflow is different in comparison to the movement in steady air. The droplets deflection in a steady medium depends on the centrifugal forces, which are defined by the initial swirl of the fuel atomizer. The centrifugal forces acting on each droplet will significantly be changed in a swirling airflow. In fact, each spray or flame shape is dominated as a reason of strong interaction of the air- and fuel flow parameters, which are defined by given injector hardware.

3.2. Investigation methods of the flip effect

The simplest way to research the flame and spray flip effects is the CFD simulation. By choosing of different air flow and spray parameters is possible to create different particle distributions inside of combustor. Some data cases will correspond with the wide cone form. By using of the parameter sets the narrow cone spray form will be reached. By this way, the flip-effect can be predicted using CFD-simulation. This forecast is only for some predefined steady cases possible. The modelling of stochastic and transient effects is difficult.

As an example, the influence of two parameters, namely the fuel mass flow and atomization quality on the spray shape will be shown. Figure 8 (left part) illustrates the simulation results for the configuration A at constant fuel- and mass flow. The atomization quality (droplet size Sauter-Mean-Diameter SMD or d_{32}) was varied. Figure 8 represents simulation results for SMD = 50 µm (lower row) and the results for SMD = 20 µm (upper row). In both cases a Rosin-Rammler distribution of droplets diameter was used. In fact, two spray shapes are possible at the same fuel and air mass flows only due to different droplet size spectra and the resulting dispersion characteristics.

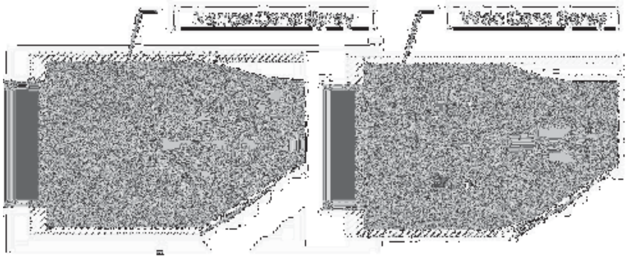

Figure 8: CFD steady-case modeling of the spray-flip

Visual comparison of represented results highlights the result, that the atomization with SMD = 50 µm correlates with the narrow cone spray and the SMD = 20 µm corresponds to a wide cone spray. Smaller particles are caught in the de-central recirculation air flow and transported to the combustor wall. The bigger particles with higher momentum are centrifuged into a larger spray cone angle. With this in mind, similar rig tests were done for the configuration A (de-central recirculation, low flow-number atomizer) and B (central recirculation, high flow-number atomizer). In this case completely different spray behaviour was achieved, because the high flow-number atomizer produces mostly wide cone spray (Figure 8 right)

The simulation results were confirmed by the spray measurements at combustor rig.

CFD gives the opportunity to discover all possible reasons, causing these effects. For example, the spray behaviour can be investigated by variation of droplet velocities, SMD, air mass flow and air swirl angle in CFD-model of combustion chamber. Unfortunately, the used simulation methods cannot explain how fast the spray and the flame are fluctuating. Although these methods give exact information about the spray and flame forms, it is difficult to create a time-depended characteristic of all flame-change occurrences. This time characteristic is indispensable for the investigation of the flame fluctuation effects.

3.3. Acoustical measurements at the rig

The basic idea to control the combustor performance by sound measurements was proposed by GE [4]. The system developed by GE controls the fuel flow of a gas turbine combustor using a dynamic pressure sensor in the combustor. This method allows predicting the blow-out and improves the pressure conditions within the combustor.

The system informs about the general combustion performance based on the dynamic pressure inside the combustors. Using this technique, a number of influence factors can be monitored that can change combustion performance like ignition, flame propagation and flame fluctuations. However, it is not possible to make a direct conclusion about the quality of the combustion process. The method gives no a priori information about the flame form and corresponding flame parameters.

To get more information about the combustion inside of combustion chamber, a number of measurements of sound pressure level and the respective frequency spectra are necessary. For this purpose the sound emissions during the tests with configuration A were measured. Figure 9 and 10 show the results of the analysis of these measurements. All results shown in these figures were done for an air mass flow of 0.13 kg/h at atmospheric conditions.

The spectra shown in both diagrams can roughly be divided into three frequency bands. The band from 20 up to 200 Hz is showing a strong dependence of the SPL from the air fuel ratio (AFR). Thus the SPL depends on the fuel amount in the combustor air. Comparing the medium frequency range, a distinctive difference between the wide-cone flame and hollow-cone flame can be observed. The measured SPL of the wide-cone flame form is much higher in this band than the SPL of the narrow cone flame.

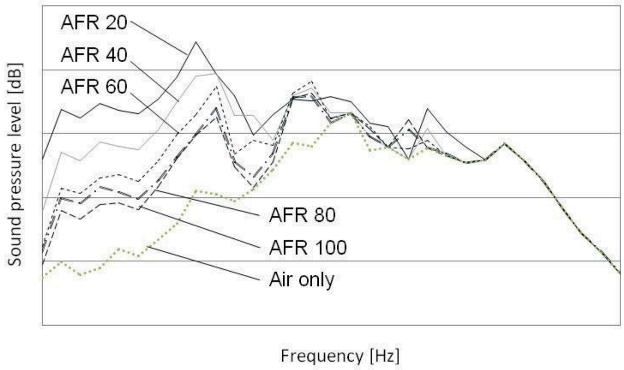

Figure 9: Third-octave band sound pressure level spectra (configuration A, narrow cone phase).

The higher frequency range is not interesting for the following evaluation study because no notable distinction between the individual AFR is visible. From these results it becomes obvious that the sound pressure level spectrum carries enough information to be used for the analysis of the combustion process.

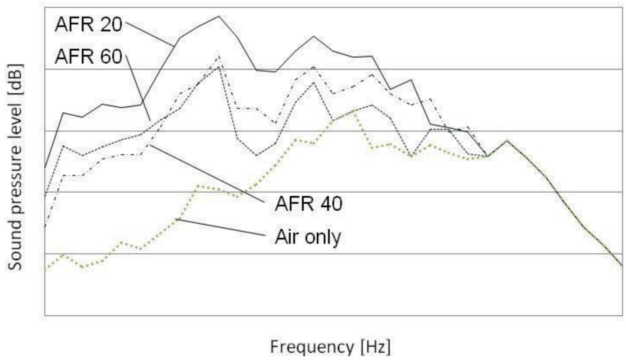

Figure 10: Third-octave band sound pressure level spectra (configuration A, wide cone phase).

Figure 11 explains the main trends in the future sound pressure diagnostic of combustion process in an aero engine. The evaluation procedure of the data shown in Figure 11 allows a speed mixture formation analysis inside of combustor chamber. The fuel air ration can be estimated by measuring of sound pressure levels at defined frequencies, frequency ranges and air mass flow conditions.

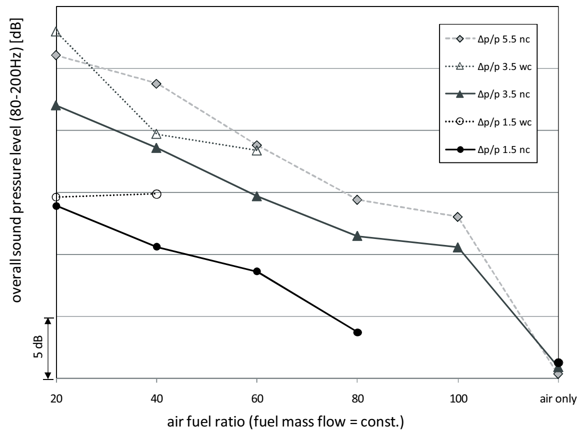

Figure 11: Overall sound pressure level between 80 and 200Hz as function of AFR and air mass flow (configuration A, wide cone).

Two sound pressure recordings were made during ignition and combustion on the test rig, at a pressure drop of ΔP/P=3.5 % and an AFR of 20. The spectrograms of these recordings give a first overview of the possibilities of acoustic monitoring of the processes in the combustion rig. The spectrograms were calculated using a hanning window function, a time window length of 4096 samples, an overlapping of 10 steps per frame, logarithmic frequency and amplitude scale. The dynamic range is 50 dB, from white (0%) to black (100%).

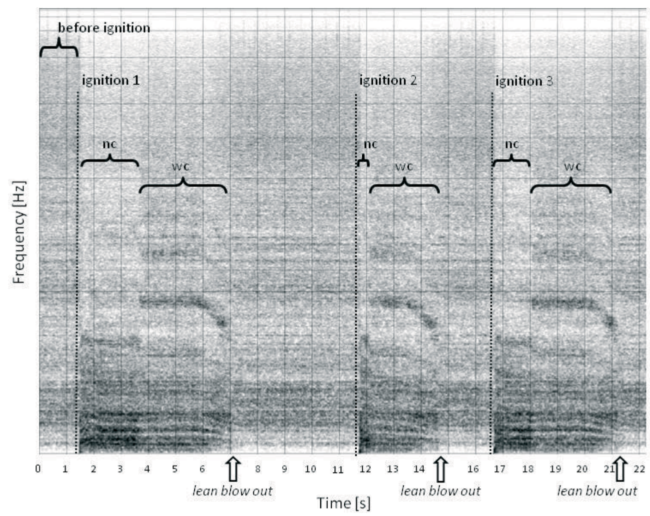

Figure 12: Spectrogram from sound pressure recording

In Figure 12 three slightly different ignition trials are shown (with marked ignition points at 1.5 s, 11.5 s and 16.5 s). After each ignition the flame shape was altered from narrow cone to wide cone (~3.5 s, ~12.5 s and ~18 s). Then a lean blow out condition was set, where the flame extinguished.

Before and between the individual ignition passes the noise was almost stationary broadband, caused by ancillary units like the air compressor, the fuel pump and the mean airflow within the combustor when no combustion was taking place as well as the air flow through the bypass vent.

In a spectrogram, (thin) vertical lines indicating short time broadband impulses, like the noise of the igniters spark every 0.4 seconds. Horizontal lines are an indicator of very narrow band or tonal noise.

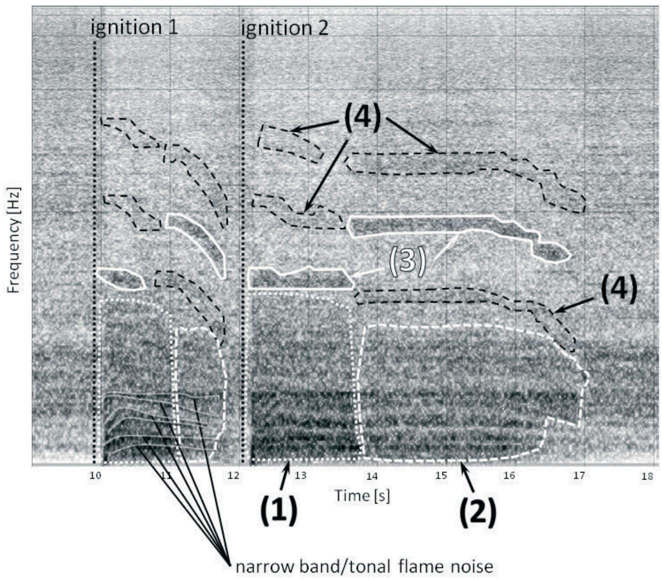

Figure 13: Detailed Spectrogram from sound pressure recording 1

In Figure 13 there is a more detailed graph of the first recording. The major regions of interest are marked. They also show up in the spectrogram in Figure 12. The regions are mainly the tonal and broadband noise of the flames itself between 100Hz and 2 kHz as well as environmental and static noise up to 5 kHz. According to Lefebvre [8] the flame noise covers the spectrum of frequencies as per description.

The white dotted area (1) marks the main region of narrow cone flame noise, which has a high overall SPL and contains broadband noise between 100 and 1500 Hz, with some blunt peaks at specific frequencies, resulting in visible horizontal lines.

The white dashed area (2) marks the mean region of ‘wide cone’ flame noise, which has a lower SPL compared to the narrow cone flame and contains broadband noise up to 1200 Hz.

The solid white outlined area (3) seems to be a strong acoustic resonance of the exhaust funnel. For narrow cone flames it can be found at about 1400 Hz and for wide cone flames at about 2100 Hz.

The black dashed areas (4) are minor acoustic resonances of the exhaust. Further noticeable areas are visible in the spectrograms shortly after ignition, where the flame noise rises in frequency for about a half second until a near steady state is reached. This appears to be the result of a flame stabilizing process after the ignition.

Another noticeable aspect is the early disappearing of low frequencies when the flame gets in lean blow out condition and ceases, this could be considered as faster extinguishing of large high-velocity flamelets at the flames outside boundaries.

4. CONCLUSION

The thesis formulated above allows concluding that the three main parameters influence the spray form: air-, fuel mass flow and atomisation quality. The spray characteristic defines the flame parameters. The combustion performance is caused by the flame characteristic.

The spray shape and the flame form are defined by the air flow field. In the case of a central recirculation a wide cone spray appears and at de-central recirculation the narrow- and wide cone spray can exist. The fuel mass flow and atomization quality have influence on the flame shape formation.

The combustion performance resulting from a specific spray shape will be changed by a possible spray-flip. Therefore, it is mandatory to design a lean burn combustion system in order to prevent an undesired change of spray and flame shape, while all operability requirements in terms of flame stability and ignitability are fulfilled.

The optical methods give enough information about the spray and flame parameters for defined time point. The investigation of the flame-flip-effect demands a transient parameter evaluation. Acoustic measurements represent the base method for the monitoring of all necessary parameters describing the unsteady combustion phenomena.

The new method was developed on the base of performed acoustic measurements. This method can be used to predict an unexpected flame form change. The analysis of proposed acoustic measurements gives the possibility to detect the main flow parameter inside of each combustors of an aero engine. Furthermore, this method allows monitoring of the combustion parameter in each combustor during a diagnostic procedure by connection of visual and audio information. Compared to the method described in reference [7] the proposed acoustical measurement procedure yields information about the injector air mass flow and fuel mass flow. The irregularity of combustion performance is easy to analyse by comparison of the flow information from neighbour combustors. A large difference of estimated fuel mass flows demonstrates possible troubles of the fuel preparation of an injector with the smallest fuel mass flow.

Proposed sound measurements with relevant evaluation give support at investigations of the combustion instability and allow providing a speed diagnostic of aero engine combustion chambers. This methodology opens new research possibilities in the combustor chamber design.

5. NOMENCLATURE

AFR	Air to fuel ratio
SMD	Sauter Mean Diameter
ΔP/P	Pressure loss over the combustor chamber
SPL	Sound Pressure Level
wc	Wide Cone Spray
nc	Narrow Cone Spray

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