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SPRAY PHENOMENA AND THEIR INFLUENCE ON THE IGNITION PERFORMANCE OF A MODERN AEROENGINE COMBUSTOR

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ABSTRACT

One way of reducing combustion emissions significantly 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 (engine idle and approach) and the pilot flame is anchored in an airflow recirculation zone. A save ignition of the fuel-air mixture at low pressure and low temperatures at the engine altitude conditions becomes more difficult, in particular in the case of a burner centred pilot injector, where the mixture formation takes place relatively far away from the ignitor. In this context the ignition characteristics of a lean burn injector system is examined within this project.

Most of the available CFD-codes allow for the computation of the combustor air flow, the fuel spray trajectories and the combustion process. One of the unsolved problems of CFD codes is the computation of the ignition process within a two-phase mixture.

In the following modelling approach the computed two-phase flow field inside the combustion chamber is the post-processing basis for a prediction of the ignition performance.

The present paper describes the validation of this subroutine in a model combustor under atmospheric conditions.

Two different spray shapes could be observed with one injector configuration at the same air and fuel mass flow conditions. This effect was observed at different combustor configurations.

Because the ignition performance strongly depends on the spray shape, any stochastic spray change during the ignition period will influence the ignition probability.

The investigation of the influencing factors, causing the spray forms mentioned is described in this paper including the airflow field, spray mass flow and atomization quality. For the investigation of the spray flip effect different laser measurements technique and simulations methods were used.

Tree different parameters influence the spray form: air-, fuel mass flow and atomization quality. The interaction between the airflow and spray has dominated influence on the mixture formation and combustion. Two possible spray and flame shapes determine different stability- and ignition characteristics of the combustor.

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.

1 INTRODUCTION

The further development of aviation requires new engines with an improved environmental compatibility. Along with the environmental aspect other requirements have to be fulfilled: the reduction of production and maintenance costs, the minimization of the specific fuel consumption and engine weight, and an increased reliability and a decrease of development costs.

One possible way of significantly reducing combustion emissions is a lean injection system in which the fuel is directly mixed with a large amount of the combustor air. A lean combustion system operates with an excess of air in the combustor primary zone in order to significantly lower the local flame temperatures and consequently reduce NOx formation. 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 the lower flame temperature.

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.

The pilot zone is active within the entire operating range of the engine. Only the fuel split between pilot and main stage is variable. The pilot only operation mode is followed by switching on all or part of the main injectors, i.e. a circumferential staging of the main modules. At full power conditions all mains and pilot burners are active. Fuel staging of the fuel injector modules requires thermal management of stagnant fuel regions within the injector.

Lean burn combustion technology has been developed within RR/RRD European and national research programs on the basis of a 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.

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). Lean burn premixing has to be accomplished within short distances between main fuel injection porting and main flame anchoring location within the combustor head. The main fuel injection can be arranged with a pre-filming air-blast concept.

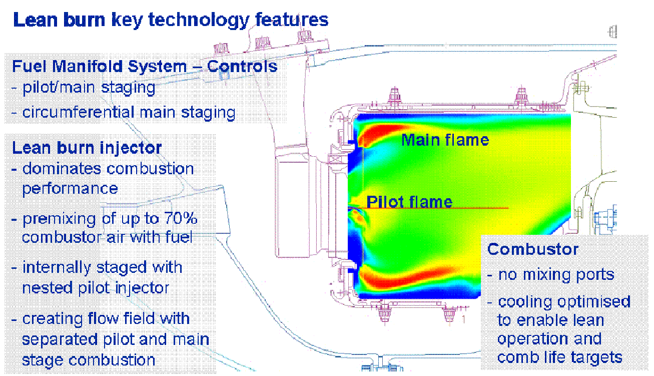

Figure 1: RR / RRD Lean burn single annular combustor architecture.

The injector design has to set up a recirculating flow pattern that produces a homogeneous mixture for low NOx emissions at full power conditions and high flame stability with low CO, UHC and smoke emissions at low power. The combustor consists of three air swirlers and two fuel circuits, and a flow splitter that divides the airflow into two airstreams (Figure 2). Two distinct flames (pilot flame and a main flame) are produced by two concentric fuel circuits that fuel the two airstreams (Figure 1). The set-up of a recirculating pattern depending on the amount of air-swirl in either a central or a decentral shape as shown in Figure 1 allows control of the flame 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 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. Knowledge about zonal interaction is a key issue towards the optimization of the overall combustor performance but due to the inherent coupling of heat release and aerodynamics an individual investigation of separated effects is rather difficult.

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

2 EXERIMENTAL METHOD

2.1 Atmospheric Combustor Test Rig

The measurements of combustion stability and ignitability were performed in a combustor chamber test bed at the BTU Cottbus Laboratory [4]. The construction of the test bed allows a relatively rapid change of tested configurations. To guarantee a good optical access a planar wall combustor was used as shown in Figure 4. 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 air supply and fuel supply systems. 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.

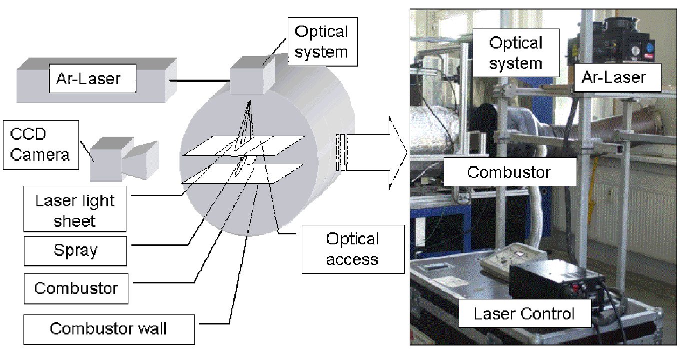

Figure 3: RR LDI fuel injector configurations; comparison with a conventional injector.

2.2 Ignition system

In combustors the combustion process is initiated by an energy supply from the spark plug to into a premixed air-fuel mixture.

The ignition process in a gas turbine combustor could be divided by Lefevbre into three distinct phases. During the first phase the ignition kernel appears. In the second phase, the flame propagation from this kernel in the combustor takes place. Finally, the flame spreads from the lighted liner to the unlighted liner during the third phase.

The ignition system of the test bed is based on the aircraft ignition system of Simmonds Precision. The ignition discharge energy of 0,98 Joules is guaranteed by an ignitor box, which is supplied with an input voltage of 12 Volts. The ignitor itself could be positioned in five possible ignitor positions along the upper combustor wall. This allows an investigation of the optimal ignitor position along the combustor wall.

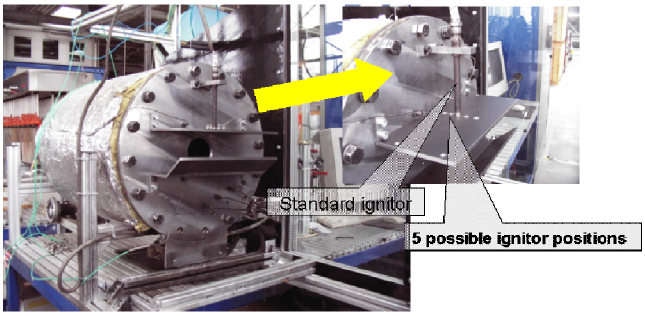

Figure 4: Ignitor application at the combustor test rig

2.3 Injector Configurations

The injector configurations A, B and C are developed for a de-central flow recirculation (Figure 5), which is realised by a low pilot swirl. The flame is stabilized in this case by the toriodal recirculation air flow zone around the combustor central axis. Configuration A differs from B by an atomizer with lower flow-number. Configuration D produces a central recirculation due to a high pilot swirl. The recirculating air flow zone is concentrated in the central area of combustor.

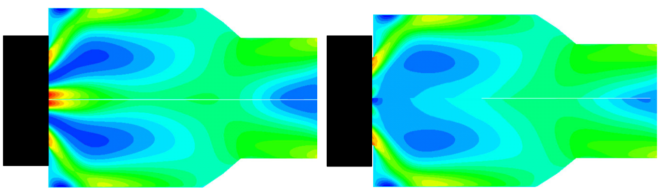

Figure 5: CFD de-central (left) vs central recirulation.

2.4 Spray and flame visualisation

One of most simple and informative ways to investigate the combustion phenomena of proposed injector configurations (hardware set of different swirlers and nozzle) is a visual evaluation of the flame and spray photos. Comparing the flame and spray pictures on the (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 a 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 determine the air flow structure. The nozzle design influences the atomization process. Therefore, acceptable flame parameters could be reached by choosing an optimal hardware configuration.

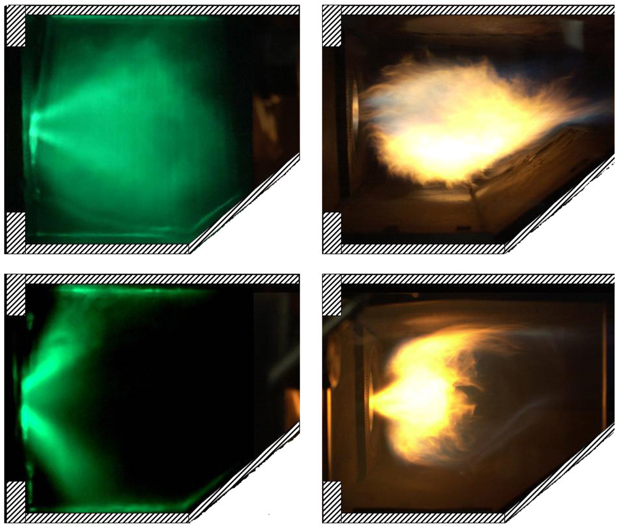

Figure 6: Spray (left) and flame (right) photos. The narrow cone shapes are represented in the upper row.

2.5 CFD Method

The spray-airflow interaction was investigated by applying the CFD code CFD-ACE+ from ESI. 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 using 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 droplets. 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 the 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 atmospheric test bed. The Rosin-Rammler SMD correlation gives the best correspondence with experimental results.

2.6 Ignition subroutine

The calculated CFD-ACE two-phase flow field inside of combustion chamber is the base for the following ignition modelling approach. The methodology for the ignition calculation was originally developed by Ouarty [4]. The first subroutine based on this methodology was suggested by Max Staufer [6] and finally adapted at BTU-VFA.

The ignition phase corresponding to the energy supply by the spark plug and the kernel creation is highly complicated to describe and the phenomena under which ionised species are formed are still not enough explored. During the sparks discharge when the kernel expands in the volume a pressure wave is created, which propagates with the local sound velocity. Therefore it is possible to assume the ignition process to be isobaric. Because of all the difficulties, the ignition model presented below only includes different phenomena that concern the flame kernel development after the sparks discharge.

Within the ignition kernel modelling it was assumed, that the outer pressure and temperature are fixed as boundary conditions; the mass and the composition of the mixture near the spark plug remains unchanged during the sparks discharge. Inside the ignition kernel is a perfect gas with constant properties assumed and the diameter of a sphere volume raised to the adiabatic flame temperature is written as

$$d_q = \left(\frac{E_{\min}}{\frac{\pi}{6} \rho \cdot c_p \left(T_f - T_0 \right)} \right)^{\frac{1}{3}} \qquad (1)$$

The equation for the minimum ignition energy could be solved by setting the heat loss and heat generation terms equal and combining them with the term for the sphere diameter.

$$E_{\min} = \rho \cdot c_p \frac{\pi}{6} (T_f - T_0) \left(\frac{6k\ (T_f - T_0)}{\Delta \bar{h}\ C_f^a C_o^b A e^{\frac{-E}{RT_f}}} \right)^{\frac{3}{2}} \qquad (2)$$

The solution of equation (1) can be found using an iterative method. After the calculation a function of minimum ignition energy along the combustor wall can be created. An example of calculation result of ignition subroutine is shown in Figure 10.

The equation (2) gives an explanation for the spray influence on the minimum ignition energy. The higher the fuel vapour concentration in the ignitor, area, the less energy is necessary to ignite the mixture.

3 RESULTS AND DISCUSSION

3.1 Ignition performance increase

Ignition tests were performed at the combustor test bed with different configurations. The main reason of these experiments was the determination of the air-fuel-ratio (AFR) at which a successful ignition of the air-fuel mixture is possible. A successful ignition process is counted when during the three consecutive ignition series 20 spark discharges (approximately 10 seconds) the mixture was ignited and the combustion process was stabilized after the flame propagation phase. The ignition test started at the rich mixture (AFR=25…30) and was repeated for the next leaner mixtures (step AFR=5) as long as three consecutive tests showed a light-up. In most of the tested cases the AFR of successful ignition was in the range from 15 up to 40…45 depending on the configuration design.

Config.	dp/p %	AFR 35			AFR 40			AFR 45			AFR 50			AFR 55		
A	2,5	+	+	+	+	+	+	+	-	-	-	-	-	-	-	+
B	2,5	+	+	+	+	+	+	+	-	+	-	-	-	-	-	-
A	3,5	+	+	+	+	+	+	+	-	+	+	+	+	-	-	-
B	3,5	+	+	+	+	+	+	+	+	+	-	-	-	-	-	-
A	4,5	+	+	+	-	-	+	+	+	-	-	+	+	-	-	-
B	4,5	+	+	+	-	-	-	-	-	-	-	-	-	-	-	-

Table 1: Ignition test results. (+) marking successful ignition; "-" marking unsuccessful ignition.

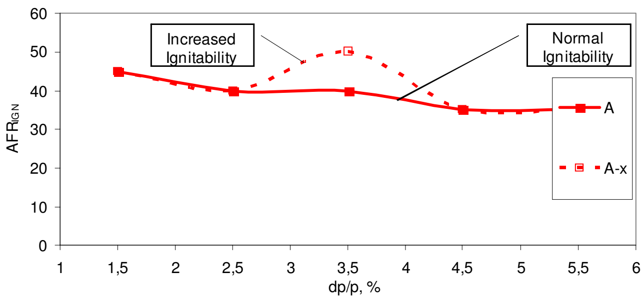

Figure 7: Ignition performance increase phenomena

Ignitability however was improved during one of performed ignition tests, even the mixture was very lean (AFR=50). Table 1 documents this fact for configuration A.

One of the tests showed a sure ignition at AFR=50, although at AFR=45 the mixture was not ignited. This ignition test was repeated for several times and a stochastic increase (test dependent) in the AFR-range of 50 was confirmed for this combustor configuration. During the ignition performance increase phase a spray-flip effect was observed [4]. Figure 7 illustrates the phenomena of ignition performance increase. The line A shows the ignition performance of configuration A. The line A-x represents the ignitability increase.

3.2 Factors influencing the ignition performance

The key-parameter, which causes this local ignitability increase, can be found considering all possible factors. Therefore, the first step is an analysis of all ignition-influencing factors. All possible factors influencing ignitability are shown in Figure 8.

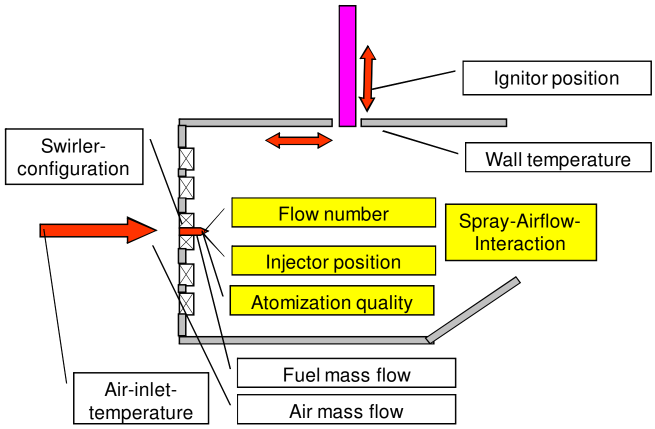

Figure 8: Parameters influencing ignition performance

The combination of different swirler geometries defines the airflow field inside of the combustors. Hence, the ignition performance changes when another geometry is used. The swirler geometry is defined for each combustor before the test and has not been changed during the ignitions procedure and following combustion process. The combustor inlet temperature T30 and wall temperature were steady during the ignition test and therefore they cannot improve ignitability. The air mass flow and fuel mass flow were not changed (the pressure loss was fixed at dp/p=3,5%). The spark plug was not moved during the test. The remaining possible effect influencing the ignition performance during the performed tests could be the interaction of fuel and air mass flow.

3.3 Spray flip influence on ignition performance

During the Mie-tests it was discovered that the spray shape is not stable [7]. Figure 9 shows two possible spray forms. The upper row represents the narrow cone spray and the wide cone spray is shown in the row below.

Considering the fuel distributions represented in Figure 9, it makes sense to assume the proposed positions (dashed line) to install the ignitor.

The spray fluctuates between the wide- and narrow cone. Figure 9 explains different ignition performance at a given ignitor position.

The droplets can not reach the ignitor area in the case of a de-central recirculation (narrow cone spray). When the spray changes its form to the wide cone, the droplets were transported to the ignitor area. By this way the mixture concentration at the ignitor increases.

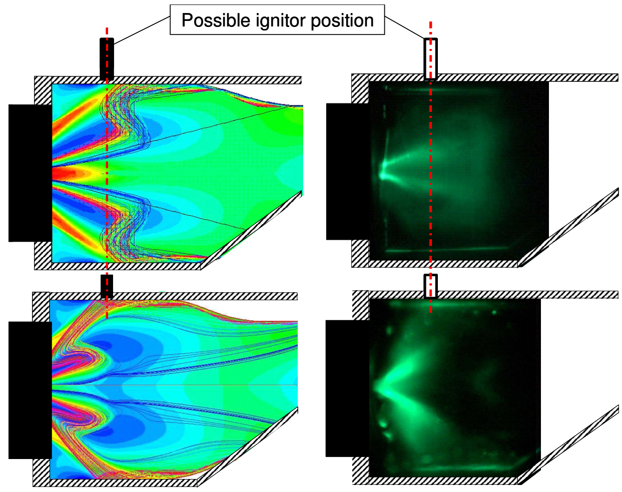

Figure 9: Narrow (top) and wide-cone (bottom) spray forms (left - CFD simulation, right – Mie photo)

For a better understanding of the combustor-ignitability under different mixture formation conditions a more detailed analysis using ignition modelling procedures was necessary. The functions for minimum ignition energy along the combustor wall were calculated by the above described ignition subroutine.

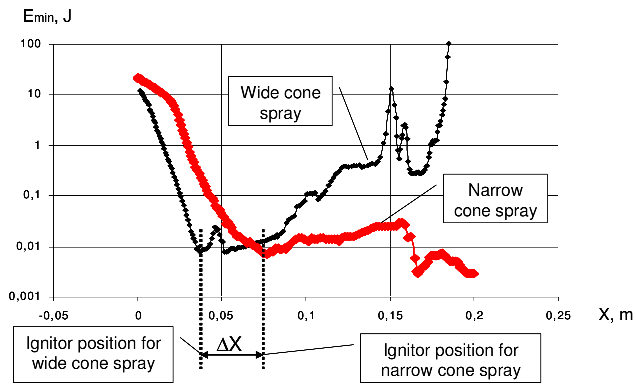

Figure 10: Calculated minimal ignition energy for central (narrow cone) and de-central (wide cone) recirculation case

Figure 10 explains the spray form influence on ignitability. Both curves were calculated by ignition subroutine on the base of CFD-results for central and de-central flow recirculation cases. The function describing minimum ignition energy for the wide-cone-case reaches the minimum at the injector outlet. The lower data set, which is represents the minimum ignition energy of the narrow cone spray, is displaced by dX in a downstream direction. Any fluctuations in the spray form results in a displacement of optimal ignitor position of dX. In other words, the optimal ignitor position depends on the spray form existing in the spark discharge moment. If the spray form is fluctuating (the fluctuating frequency is about 1 Hz), optimal ignitor position is fluctuating with the same frequency along the combustor wall in dX range. This fact explains a stochastic ignition performance. If the ignitor is situated in the range dX, the ignitability is not stable.

Achieved simulation results were confirmed by the analysis of the photographed data.

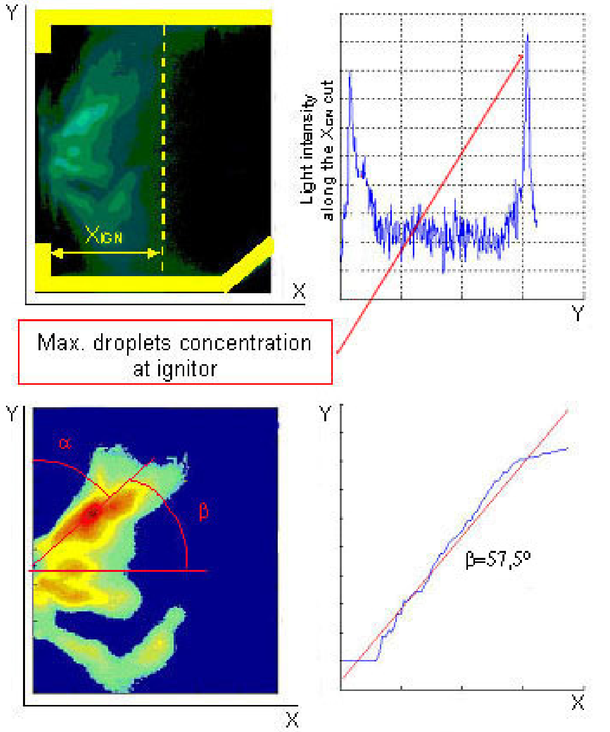

Figure 11: Wide cone spray investigation (fuel concentration and spray angle measurements)

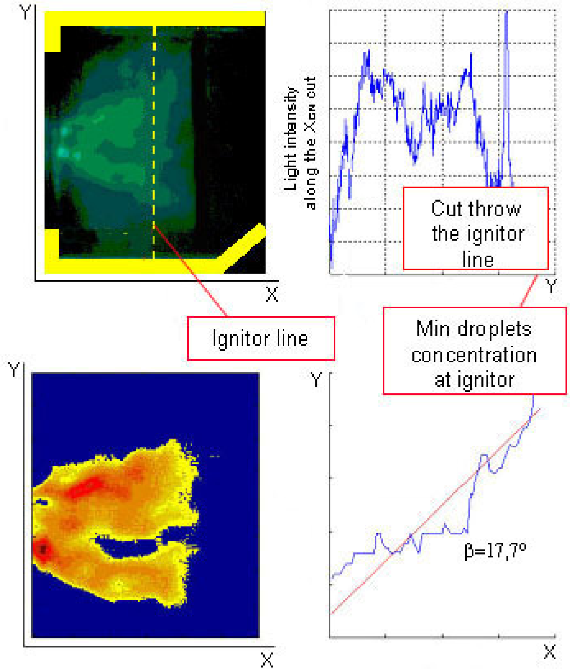

Figure 12: Narrow cone spray forms (fuel concentration and spray angle measurements)

Each spray photo was investigated by specially developed software. The above left spray photo in Figure 11 shows the ignitor position (ignitor line) during performed tests. The function below right on figure 11 gives the spray angle, which was determined using an adapted image recognising algorithm (image below left). The angle of 57,5° represents the wide-cone spray shape. Because the intensity of Mie-scattering correlates with the droplet concentration, the light intensity diagram created for the given ignitor cut (Figure 11 above right) explains the liquid phase distribution in ignitor area.

Although the wide cone spray brings a sufficient amount of droplets near the ignitor area (figure 11 right above), the de-central recirculation brings the droplets into the area behind (upstream) the given ignitor line. This fuel distribution case is characterised by a low amount of droplets near the spark plug (Figure 12 above right). From this way the simulation results are confirmed.

This fact causes ignitability deterioration. If the spray is fluctuating, each best ignitor position because of wide- or narrow cone case does not mean the optimal ignitor position of considered configuration.

4. SUMMARY

In the present study, ignition performance changes during the test were investigated.

In general, ignitability depends on many factors (combustor geometry, ignitor position air flow condition, fuel atomization quality).

- The ground level ignitability of a future low emission combustor at atmospheric conditions has been investigated experimentally and numerically. The main focus has been on the liquid fuel spray distribution and its effect on ignitability.
- Spray distribution depending on air-to-fuel ratio and stochastic air flow fluctuations has been identified as the main parameter determining the fuel droplet and vapour concentration near ignitor location.
- Two spray shape cases, narrow and wide cone spray investigated in detail.
- The experimental results were compared to spray distribution from CFD computations. The predicted spray angle and the post-processed minimum ignition energy show good agreement with the experiment.
- The current investigation can be seen as a basis for the improvement of the low power operability of low emission combustion systems for future aero engines.

5. NOMENCLATURE

$E_{\min}$	Minimal ignition energy
d_q	Ignition kern diameter
ρ	Density
c_p	Specific heat
T_f	Flame temperature
T_0	Ambient temperature
k	Thermal conductivity
C_f	Fuel concentration
C_o	Oxygen concentration
a,b	Reaction constants
A	Pre-exponential factor
$\Delta\bar{h}$	Heat of combustion
E	Activation energy
p	Pressure
R	Universal gas constant

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