TOWARD EMBEDDED OPTICAL MEASUREMENT TECHNIQUES FOR PRECISION COMBUSTION MONITORING IN AEROENGINES

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ABSTRACT

Certification policies on aeroengines are very demanding and technically challenging, since they combine an obligation of safety with technical specifications on performance and environmental issues. Over the last 15 years, fuel consumption was reduced by 30% per available seat per kilometer [1]. Drastic efforts were successfully made to reduce considerably NOx and noise emissions [2]. In the continuity of this effort, new regulations driven by the ICAO/CAEP11 are about to be decided concerning limitations on carbon monoxide and soot emissions.

In order to meet these future requirements, aeroengine manufacturers will have to make a better management of the current operation margins. More precision is requested in determining the operation status as well as refined controls. This paper is about the development of lightweight and small-size optical sensors that monitor the quality of combustion in real-time with high precision.

A broad panel of optical measurement techniques is available for advanced combustion diagnostics [3]. However, if a few applications exist for the monitoring of industrial burners, regarding gas turbine technology optical measurement techniques remain bounded to laboratories or test benches.

The miniaturization of optical elements combined to the improvement of high-temperature glass or transparent ceramics open a new path toward robust optical probes, able to perform well under aggressive flow conditions (high pressure and temperature air flow, erosion, strong radiative heat transfer, strong vibrations). The challenges are the design of the optical interface, the cooling and temperature stabilization of the sensitive parts of the sensor, and the compactness of the measurement chain.

The project "emotion" stands for **e**ngine health **mo**nitoring and refined combus**tion** control based on optical diagnostic techniques embedded in the combustor. It is financed by the Austrian Research Promotion Agency (FFG) within the frame of its programme on aeronautics called "Take-Off". Partners in this project are the company Combustion Bay One e.U. (CBOne), an engineering office specialized in advanced combustion management, and the Fachhochschule Joanneum/Aviation Institute from Graz (FH Joanneum). CBOne is project leader and focuses on strategies, feasibility study and testing, while FH Joanneum focuses on the integral aspect of the portable measurement chain for demonstration purpose.

A first consultation of the aeroengine manufacturers set the objectives of using embedded optical monitoring as follows. It should provide qualitative information of the operation, report on the flame stability and on the ignition success. Additionally, the inspection of the combustor's interior at rest using built-in cameras could replace in the future the inspection, using an endoscope.

Two strategies are investigated. These are image-based monitoring, using CCD chips situated in the vicinity of the flame, and fast-response photo-sensitive sensors. Imaging provides qualitative features on the flame such as shape, intensity and chromatic contents [13]. The photo-sensitive sensors report on the highly-resolved time signal of light intensity filtered at a given wavelength. For instance the UV component related to the OH^* emission is an indicator for the thermal power of the flame. At the time being, the second option is the most promising regarding rapid integration on a flying system.

The project emotion is introduced, and the early results using a combustion test rig are presented.

NOMENCLATURE

I_D	Dark current
U_D	External voltage
E_e	Radiation intensity
I_{PHOTO}	Photocurrent
dV	Differential voltage
V	Voltage
λ_{Rijke}	Characteristic length
C	Speed of sound
L	Length
f	Frequency
Φ	Equivalence ratio
w*l	Irradiated surface of the PD
q	Elementary charge
h	Planck´s constant
c	Speed of light
η_q	Quantum efficiency
λ	Wave length of light

ACRONYMS

CC	Combustion Chamber
CCD	Charged Coupled Device
FFT	Fast Fourier Transformation
PD	Photodiode
BNC	Bayonet Neill–Concelman Conector
A/D	Analog/Digital
SMD	Surface-mount device
TTL	Transistor to Transistor Logic
PLA	Polylactic acid
TLR	Technology Readiness Level
CBOne	Combustion Bay One
FH	Applied University of Science
SNR	Signal to Noise Ratio

INTRODUCTION

Health engine monitoring for the hot parts of an aeroengine is based on a regular maintenance programme, with regular inspections on the wing or during overhauls. There is at the moment none or very basic instrumentation built in the combustor. Optical measurement techniques for combustion diagnostic are widely used during the development of new aeroengines in a laboratory or on a test bench. Optical measurement techniques are non-intrusive, and deliver informations such as flame front position, emission products and combustion stability.

In the frame of the subsidised project EMOTION from the FFG in the scope of the so called Take-Off funding, a miniaturizing of optical sensors to gather real time information from the ongoing combustion process in the combustor of a gas turbine was executed.

Around a combustor annulus are about 20 injection nozzles situated where each nozzle should generate a flame during the ignition process. Real-time information about a successful ignition process for the whole combustor annulus is not in an industrial scale available jet. Today this information is provided by fast temperature sensors. An optical access to the combustor annulus can provide this information. By providing an optical access to the combustion chamber for fast response photo-sensitive sensors, the following real-time information will be provided:

- Flame – No Flame
- Ignition Success
- Quality of Load Conditions
- Combustion Stability (highly requested from the industry)

Furthermore CCD chips are going to be mounted outside of the CC. The cooling holes of the CC will give an optical access for the CCD modules to the flame. The image information from these CCD modules will generate information about the combustion quality and also operation monitoring (part, standard, full load) [13].

So with the integration of optical measurement techniques embedded in the CC a so called “traffic light” will be able to give real time information to the pilot or operator of the turbine about the ignition success, the stability of the combustion process, the load conditions and the combustion quality. The main focus in this article will be on the fast photo sensitive sensors. These measurement devices are quite small-sized and the information (light) can be captured directly in the CC or be transported to a non-aggressive location in the turbine.

EXPERIMENTAL SETUP

The tests with the fast response photo-sensitive sensors and the CCD module were carried out on the MethaNull test rig from CBOne in combination with the Siren from CBOne and with a so-called Rijke-tube [7], [11]. The combination of the MethaNull rig with the Siren allows it to simulate combustion instabilities at given frequencies, which are produced from the Siren. This is achieved by a certain air flow modulation at a wished frequency and amplitude, it also can be used for control purpose [8].

1. The MethaNull Test Rig

The test rig is a compact atmospheric combustion facility that includes a plenum, a staged burner, a combustor casing and an exhaust system. The burner itself is a premixed, lowly-swirled burner placed in a strongly-swirled secondary flow. In accordance with publication [7], the burner shall hereinafter be referred to as the “pilot burner” and the secondary flow as “main air”. Technical details on the burner and on the MethaNull technology are outlined in the same reference; here we consider a concentric stage burner, where the pilot burner is embedded in the main stage. This pilot burner is connected to a Siren that modulates the air flow. The complete test rig can be seen in Figure 1.

A flow control panel regulates the air and gas head pressure levels. The air supply system is connected to a pressurised air network (8 bar). A commercial propane bottle (type UN 1965 mixture C, 46,3 MJ/kg, 2 kg/m3) provides the gas supply. The ignition system is embedded. Redundant analogue and digital displays report on the air and gas flow conditions.

The plenum air supply is split into cooling air for the whole system and combustion air for the main air supply. The combustion chamber casing is protected from the flame by a heat-resistant glass tube that is fixed on the head plate, where the flame settles. The cooling air flows between the casing and the glass tube until it mixes with the burnt gases in the convergent section called the mixer. A further chimney section is added to condition the plume flow and to measure exhaust gas contents near the outlet.

Two optical access port-holes allow the flame tip and of the flame’s rear to be observed – i.e. to check whether there is a diffusion flame or not.

Although the combustor is atmospheric, a robust construction was chosen for safety reasons.

Some dimensions are only provided to give a sense of scale. The liner (glass tube) dimensions are 100 mm diameter * 410 mm length. The combustor casing has a 160 mm diameter (same for the plenum). The length from the front plate to the exhaust is 1240 mm.

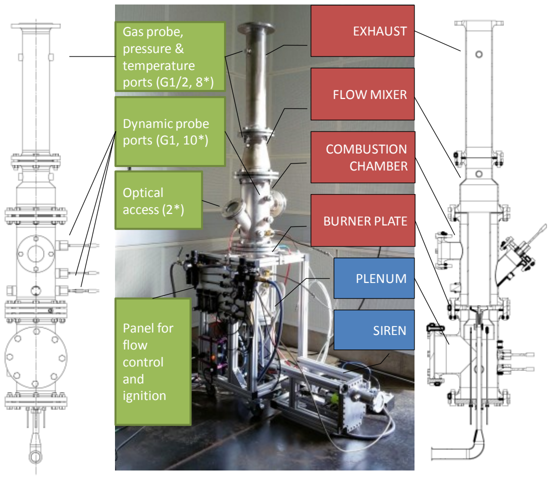

Figure 1: COMBUSTION TEST RIG

2. The SIREN

An actuator from CBOne is used to pulse the flow in a well – controlled manner. This simulates the presence of a combustion instability. Figure 2 shows the Siren with its components and detailed pulsation technique. A toothed wheel is rotating at a given frequency permanently. Further another mechanism is linked to the toothed wheel to control the position of this wheel. So the control mode of “NO PULSATION”, “MODERATE PULSATION” and “STRONG PULSATION” can be chosen from the operator. For all the here discussed pulsation with the Siren only STRONG PULSATION and NO PULSATION were investigated.

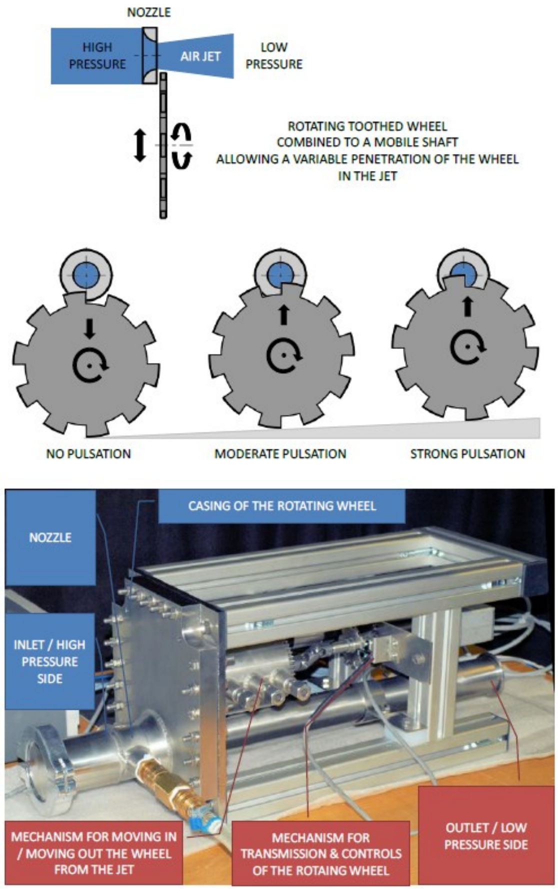

Figure 2: CBOne´s Siren with variable amplitude. Top: Principles. Bottom: Picture of the device. [10]

The discussed graphs in Figure 13 and in Figure 14 were showing the difference between stable and unstable combustion forced by the Siren.

3. Testing Configuration

A feasibility test was done using a real combustor liner for the comparison of the optical accesses of the test rig to the final accesses in a CC of a turbine. Especially for the CCD module the combustion liner of a Saab-Draken (Volvo RM 6C) was used on the burner plate of the MethaNull test rig, as can be seen in the Figure 3. The fast response photo-sensitive sensors are mounted on the optical access 2* and on the same access as the lower dynamic probe port (see Figure 1). As CCD module a camcorder is used for the data acquisition.

A second observation device is the Rijke-tube [11]. Here a Bunsen burner in combination with a glass tube, open on both sides, 0.5 m long and 40 mm in diameter, is used to detect thermo-acoustic instability's. The glass tube is positioned vertically over the Bunsen burner and by lightly entering with the glass tube over the burner the thermo-acoustic phenomena can be observed [11]. The exact length of 0.5 m is a really comfortable size. So the achieved frequency in the tube is the speed of sound and is only related to the temperature. Thus because of: $\lambda_{Rijke} = 2*L$ and $C=\lambda_{Rijke}*f$ where λ_{Rijke} is the characteristic length of the tube in m, f is the frequency in Hz, C the speed of sound m/s and L the length of the tube in m.

4. Circuits & Sensors

For the fast response photo-sensitive sensors two different circuits are observed. The first one is a so called Wheatstone-Bridge which is used for accurate measurement of resistors. So a known resistor is placed in series with an unknown resistor (the fast response photo-sensitive sensor) and parallel to those resisters two other known resisters are connected in series. If then a voltmeter is placed to measure the established voltage between the nodes shown in Figure 4, a varying voltage (signal) can be observed [4].

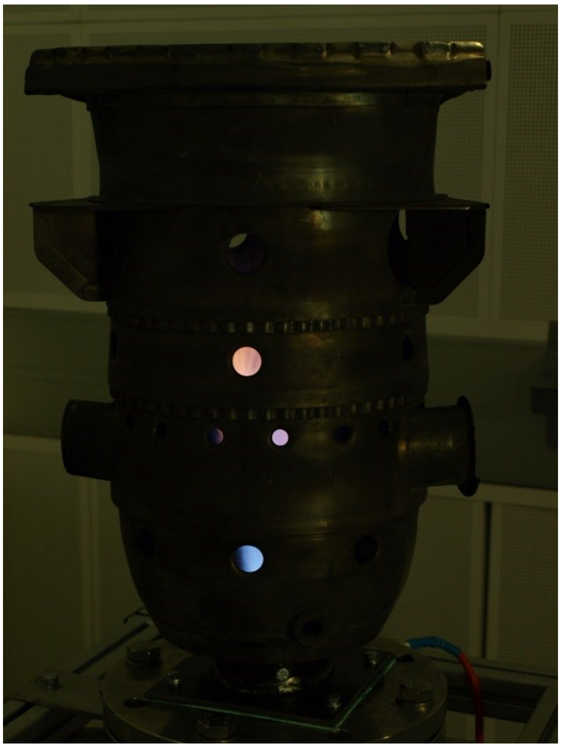

Figure 3: Combustion liner of a Volvo RM 6C

This signal is directly related to the intensity of the flame and includes the occurring frequencies. With a MATLAB routine the frequencies are then readout by use of the FFT [14].

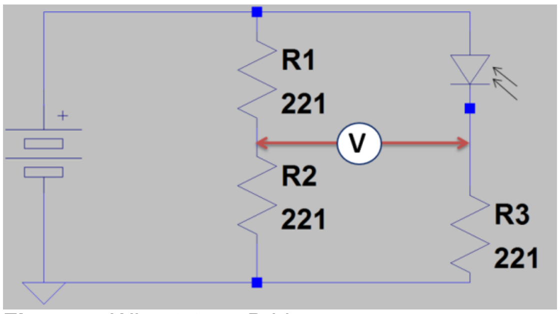

Figure 4: Wheatstone-Bridge

The second method used here for the application of the fast response photo-sensitive sensors, in means of a varying voltage depending on the intensity of the flame is to mount the sensor in reverse direction. Where S is the intensity of the PD, I_{PHOTO} the current going through the diode A, E_e the radiation power Wm^{-2}, w*l the irradiated surface m^2, q the elementary charge C, h the Planck´s constant m^2kg/s, c the speed of light [m/s], η_q the quantum efficiency and λ the wave length of light m. Figure 5 shows the field of operation for the sensor operated in reverse direction [6].

$$S = \frac{I_{PHOTO}}{E_e * w * l} = \frac{q}{h * c} * \eta_q * \lambda \quad [6]$$

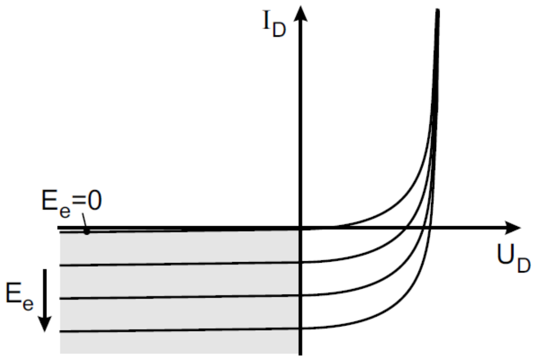

Figure 5: Characteristic diagram of the sensor at different radiation intensity [5]

The characteristic diagram in Figure 5 highlights that the sensor is covering several quadrants in the current-voltage diagram. For the case that the sensor is working in reverse direction and a reverse voltage is connected to the circuit (for this study a 9 V battery is supplying the reverse voltage) a so called “photocurrent I_{PHOTO}” is flowing throw the sensor depending on the radiation intensity [6].

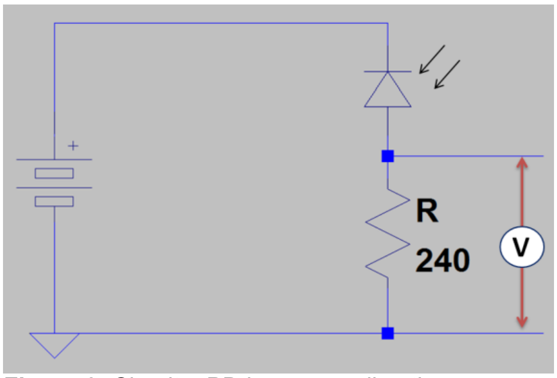

Figure 6: Circuit – PD in reverse direction

The great advantage of this circuit is that, for example for a SFH 229 Silicon PIN Photodiode from Osram, the radiation depending current is differing between I_{PHOTO}~28µA and I_D~50pA (indication from the manufacturer). And with the use of Ohms Law a resistor can be chosen depending on the scale of radiation. The voltage variation over the resister, generated by light fluctuations of the flame, is creating a signal which includes the real-time light information from the flame. Also here a MATLAB routine is then reading out of the signal the occurring frequencies from the flame with an FFT.

$$X(n) = \sum_{k=0}^{N-1} x_0(k) * e^{-\frac{j2\pi nk}{N}}$$

$$n = 0,1, \dots, N-1 \qquad [14]$$

Where $x_0(k)$ is the sample rate and N is the number of sample. FFT´s are used in a huge field of applications and are further discussed in [14]. A further task is the miniaturization of the sensor. So by using the technique of rapid prototyping, several probe carriers can be easily produced to fit the surrounding conditions close to the CC. For the use on the MethaNull rig and with the Rijke tube a stereolithography 3D printer, using PLA (glass transition temperature of 80°C and melting point of 150°C) as material and probe tubes with an inner located circuit were used. So, different methods are observed because of the miniaturization process and for cooling aspects. During this study the used coolant was fresh air.

DATA ACQUISATION

The optical sensors mounted on several positions (Figure 7, Figure 8 and Figure 11) on the MethaNull test rig, are producing analogue signals. All this sensors have a BNC interface from where the data is transmitted to an oscilloscope (type: LeCroy WaveAce 234) and an A/D converter (type: RedLab*1208FS). This data is real time analysed on the oscilloscope and recorded for further investigations with the A/D converter. The A/D converter is acquiring a signal with a 10 kHz sample rate. 90000 samples are rode out what gives than a 9 second signal from the ongoing combustion process. Alongside with the optical information from the flame also the generated frequency from the pulsation of the Siren is recorded. With that information's each optical signal can be compared with the forcing frequency from the Siren which is discussed under the point Measurements. Further some sensors are equipped with optical filters to compare the results with and without filtering out certain wavelengths. For the sensors with filter a BrightLine® Fluoresence Filter is used. The centre wavelength of the filter is 440 nm with a guaranteed minimum Bandwidth of 40 nm.

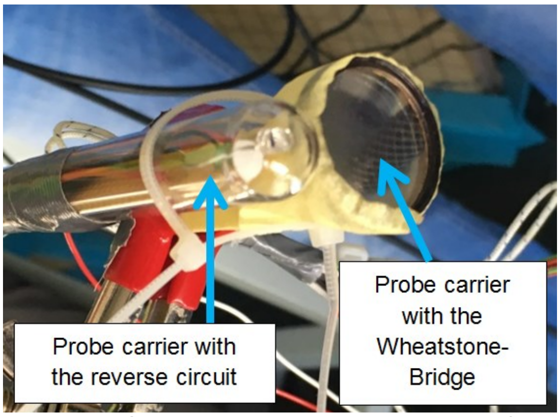

Figure 7: Sensors with and without optical filter. Right side: PLA probe carrier with optical filter. Left side: Optical sensor without filter in a probe tube.

The Figure 7 shows two optical sensors (right with filter) before they are brought to final acquisition position as shown in Figure 11. The measurement access in Figure 8 is positioned normal to the flame. The probe is cooled with air. For this cooling solution the circuit is placed in the middle of the test tube, so cool air can be blown in from one side of the tube and the hot air can exit the tube on the other side. A circuit board is dividing the test tube. On the top of the test tube is the PD, where fresh air can pass because of the circuit board inside. For getting information's about the sufficiency of the cooling also a temperature sensor is placed close to the PD (see Figure 9). The probe tube in Figure 8 has a diameter of 13 mm. For the use on the MethaNull test rig, this dimension was selected because of the optical interfaces and the first circuit (see Figure 9). For the ongoing project, the miniaturization target is a 6 mm diameter of the probe tube.

Figure 8: Optical access at the lower dynamic probe port on the MethaNull test rig

The temperature is a challenging task for the sensors in such a hot and aggressive environment (high pressure, high temperature, strong exposure to radiative heat transfer). For the PD, temperatures up to 125°C are allowed. So cooling is a challenging task for the sensor probe in the combustor layout. For information about the temperature on the top of the test tube a SMD temperature senor is placed close to the PD, see Figure 9.

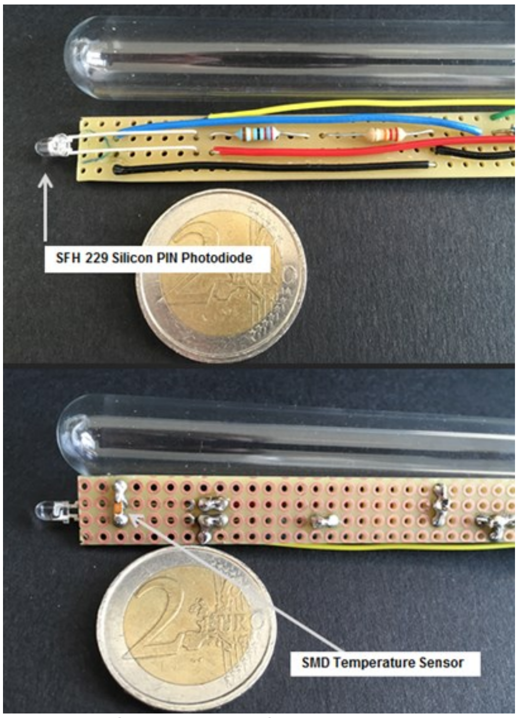

Figure 9: Sensor circuit for the probe tube

The experiments with the different probe carriers were executed with cooling, where the probe heads were in a stream of cooled air. This was efficient for the temperature sensitivity of the used components. For the future works an internal air-cooling will be added to the surrounding air, as discussed before. So, even a closer placing of the probe head to the flame will be possible.

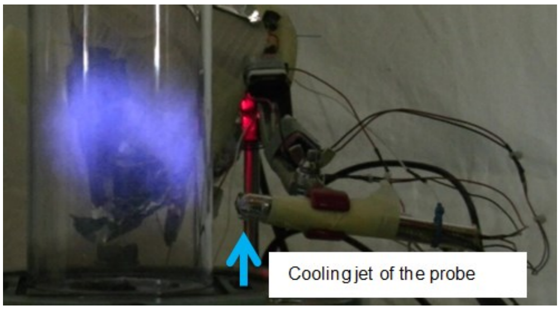

Figure 10: Probe cooling on the test rig

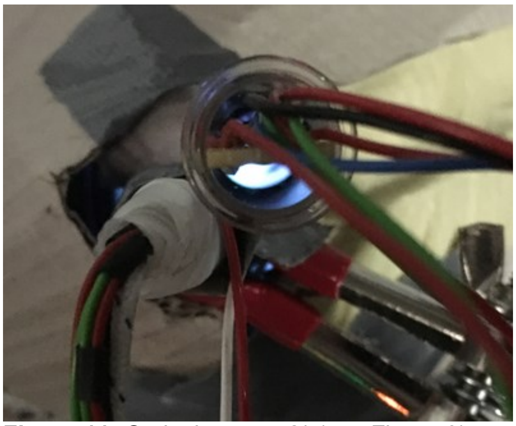
Figure 11: Optical access 2* (see Figure 3)

For the next steps, mounting sensors on the wall of the CC, cooling will be a challenging task here and so a second strategy will take place. Glass fiber is flexible and is able to resist the rough environment on the CC walls, so the optical information will be transferred to a location in the turbine housing where the conditions are more suitable for the measurement equipment. Also the fact for maintenance, sensors could be replaced more easily than if they are directly attached to the CC walls.

OPERATING POINTS

The sensors were undergoing the following tests on the MethaNull test rig and the Rijke tube.

- Ignition process
- Flame out / blow out
- Forced pulsation (instabilities at given frequencies)
- Thermo-acoustic waves

The ignition processes were executed on both facilities. Also the Flame out / Blow out were observed on both facilities. The forced pulsation, thus pulsating the pilot air with selected frequencies from the Siren was done on the MethaNull test rig. Thermo-acoustic flame behaviour was investigated on both installations. On the MethaNull test rig these phenomena can by studied by ~510 Hz and the Rijke tube is producing thermo-acoustic waves on a frequency related to the length L of the tube. In this study the tube length of 0.5 m was chosen, so the observed frequency is the speed of sound and the exact frequency is only correlated with the temperature.

MEASUREMENTS

For the ignition process the amplitudes of the voltage signals are compared, by means of flame (successful ignition) or no flame (no successful ignition or flame blow out) (see Figure 12). The differential voltage dV of the sensor on Figure 9 is about 0,029 Volt. For even a higher dynamic of the sensor signal further test´s with resistors up to 10 MΩ will be performed during the emotion project and should provide a higher dynamic between dark and light current. This dynamic is calculated by Ohms Law U = R*I.

The dark current is given by the manufacturer of the PD´s. The light current has to be measured. For this flame observations the light intensity of a lean flame are considered. On the MethaNull test rig (see Figure 1) the light current is about ~0.122 µA. This value comes from a testing circuit with the layout light current from the manufacturer.

The graph in Figure 12 is showing the structure of the signal before ignition, during the ongoing combustion process and further flame out / blows out.

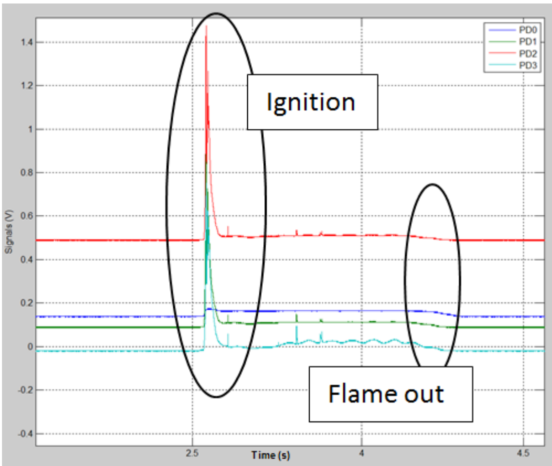

Figure 12: Successful ignition (left sight) and flame out (right sight)

Figure 12 shows the detected ignition process of four different probes, each equipped with a PD. The four PD´s are: PD0 – Sensor with a Wheatstone Bridge, PD1 and PD2 are Sensors with a reverse circuit and PD2 is placed in a test tube, PD3 is also a sensor in reverse circuit but with a higher amplitude because of its resistor with 1.8 MΩ instead of 240 kΩ as PD1 and PD2.

A further task of the sensor is the detection of unwanted combustion instabilities. This so called combustion instabilities can occur by the coupling of acoustics and combustion which then can lead to oscillating regimes [9]. These instabilities are unwanted in propulsion turbines and should be avoided to not endanger the combustor. To prove the optical detection of combustion instabilities the sensors were mounted on the MethaNull test rig (see Figure 1) and around a Rijke tube.

By forcing the combustion process with the Siren, several frequencies (instabilities) can be observed on the MethaNull test rig.

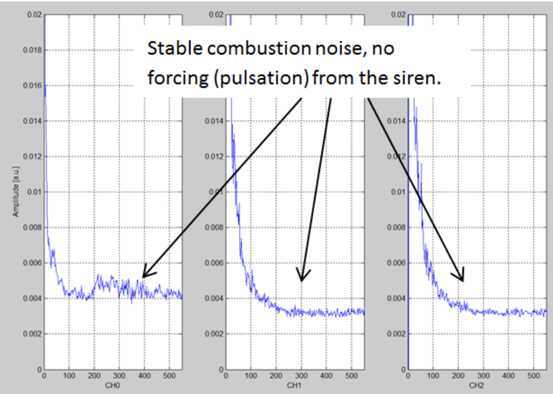

Figure 13: Stable combustion process

Figure 13 shows the FFT of the combustion noise in the MethaNull test rig by stable combustion conditions. The signals CH0 to CH2 are characterized as, CH0 - PD in a Wheatstone-Bridge circuit, CH1 – PD in a reverse direction circuit and CH2 – PD in a reverse direction circuit placed in a probe tube with 13 mm diameter (see Figure 9). The important information of this observation is that the burner is running normally. The only observed peak to see is by 50 Hz, which comes from the not perfectly shielded light sources in the laboratory. For this signal output an operator will get a green light signalized.
The next investigation is a forced pulsation (instability) by a selected frequency in the CC of the MethaNull test rig. This is shown in the Figure 14.

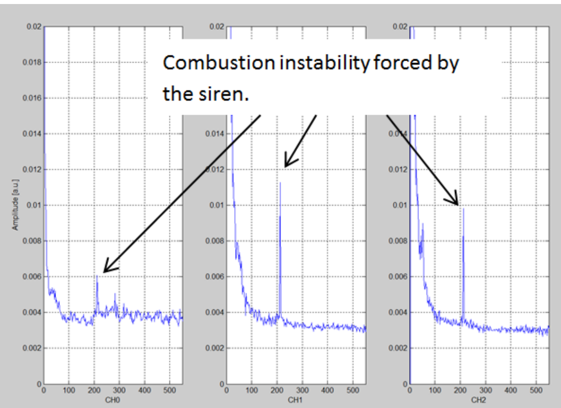

Figure 14: Combustion instability by 208 [Hz]

All here discussed signals are from the graphs in Figure 14. The difference in the dynamic between CH1 und CH2 must probably occur from light absorption by the probe tube. CH1 is a naked PD and CH2 is a PD in a probe tube (see Figure 11, the white and red wire between the probe tube und the left probe carrier). CH0 on the left is a PD operating in the Wheatstone-Bridge circuit (see Figure 4). Remarkable is the difference in the dynamic of the signals. This difference comes from the two different measurement methods used for this observation. A good method to compare those two measurement methods is the calculation of the SNR (Signal to Noise Ratio). So each method is validated by their signal performance by differing between signal and surrounding combustion noise [15]. By using the equation SNR = “peak amplitude” divided by “pedestal at the peak”, the performance between Wheatstone Bridge circuit and reverse circuit was doubled. As mentioned above, using optical filters and resistors up to 10 MΩ for the next probe generation with reverse circuits, the signal performance of the processes of interest, e.g. ignition, instabilities, blow out, will be further increased. The usual peak by 50 Hz from the grid in the laboratory is observed on the more sensitive circuits CH1 and CH2.

DISCUSSIONS

The miniaturization step from the first sensor with a Wheatstone-Bridge in a probe carrier made by rapid prototyping to the reverse circuit in a probe tube was successful. The goal was not only to miniaturize the circuit but also to get a higher dynamic in the signal. Figure 14 underlines this progress. The follow up of this work will be the optimization of the reverse circuit and to evaluate different cooling methods for a placed sensor in the CC. Further the signal transmission from the flame by glass fibre from the CC to less aggressive places in the turbine will be performed on the MethaNull test rig with the Volvo RM 6C combustion liner (see Figure 3).

The here used air cooling will be compared with other cooling methods. On the test rig air was a sufficient coolant also when the probe head was quit near to the flame, as can be seen in the Figure 10.

Special attention should be given to the data acquisition installation. To do not get back coupling from the grid, the used hardware should work in battery mode or a high shielded A/D converter has to be used to not overlay the light signal with false information from other sensors or the grid.

Another information from the ongoing combustion process in the CC for stoichiometric and lean natural gas flames is the equivalence ratio Φ. By measuring the intensity of the OH* and CH* radicals, the equivalence ratio can be derived from their intensity ratio [12]. To sort out the light information of these radicals, special optical filters from 305 to 325 nm for OH* and 420 to 440 nm for CH* radicals will be installed on the PD´s.

These investigations are going to be made also for not perfectly premixed flames.

CONCLUSIONS

Optical measurement techniques embedded in the combustor annulus will provide information which until know are not available during operation (only for laboratory use or for ground turbines). Refined combustion and real time monitoring from the combustion process will be more and more a highly requested demand from industrial aeroengine manufactures. The here presented work results are approximately situated at the level 3 to 4 in the TRL. In a further study in the next 3 to 4 years a prototype with an aeroengine manufacturer will be realized and tested in gas turbines.

The above mentioned technique of bringing the light information to a less aggressive place in the turbine seems to be a good solution for aeroengines to not need large design changes in the combustor design or around the CC annulus.

Also the filtering of the light signal of the flame will be more feasible by placing the sensor equipment not directly attached to the CC. After transmitting the light information to an analysing unit, the light will be divided for the required information parts (CH* radicals, OH* radicals, complete combustion noise…).

This technique will provide information which will help engineers to design less pollutant and more efficient aeroengines. Also the point in time for overhauls can be chosen on the base on this produced real time information for optimized maintenance.

Therefore the strategy is to develop both systems, the first with the sensor placed closed to the flame and the second with fiber glass to transport the light information to a less aggressive environment.

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