DEVELOPMENT OF A PILOTED LEAN BURNER FOR AN AERO-ENGINE COMBUSTOR: INFLUENCE OF LIQUID FUEL PLACEMENT ON POLLUTANT EMISSIONS

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ABSTRACT

Within the German Energy Research Programme "500MW on a single shaft", Rolls-Royce Deutschland Ltd & Co KG and the German Aerospace Center DLR have carried out detailed investigations of different liquid fuel injectors for the main stage of a lean burner. The main injection principle follows a jet in cross-flow arrangement. Two other concepts with a prefilmer and a trailing edge injection were additionally derived. Planar non-intrusive measurement techniques e.g. Mie-scattering, chemiluminescence of the OH* radical, LIF and PDA were applied up to P_{air}=6bar and T_{air}=822K in a single sector combustor. Emission measurements were carried out up to P_{air}=20bar and T_{air}=822K in a high-pressure test facility.

It was found that the fuel split between pilot and main injector has a significant effect on flame structure, the location of the reaction zone, and the evaporation behaviour of the "mixed" pilot and main flame. Low NO_x emissions are observed with main burners with a low fuel penetration into the central recirculation zone. The use of trailing edge injection at the atomizer lip and a combination of fuel swirling and increased fuel flow number has shown significant NO_x reduction of ca. 68% compared to central fuel injection.

1. INTRODUCTION

In recent years, a notable decrease of pollutant emissions for aero-engine combustors was achieved due to the reduction of specific fuel consumption and a continual optimisation of diffusion flame combustors. As a consequence, today's aero-engine gas turbines meet the emission limits established by the International Civil Aviation Organization (ICAO) with some margin. However, new legislation for nitrogen oxides NO_x for new engines became effective at the beginning of January of 2004 (CAEP IV) and a further tightening of NO_x emissions will be introduced in 2008 (CAEP VI). To further improve the thermodynamic efficiency and the specific power, future aero-engines and stationary gas turbines will consequently operate at a much higher pressure-ratios and increased combustor inlet temperatures leading to a higher production of thermal NO_x.

A main challenge in the development of modern aero-engine gas turbine combustors is therefore the continuous reduction of pollutant emissions. Significant reduction of NO_x emissions is offered by the application of lean premixed and prevaporised (LPP) combustion. The limited operating range and inherent technical problems of LPP combustion, e.g. self-ignition and combustion instability, implies a significant restriction for aero-engine combustors. To overcome the shortcoming of the classical LPP design a promising concept is a lean combustion with either a partial premixing of the fuel and oxidizer prior to combustion or direct injection of the fuel into the primary zone of the combustor. One of the most important tasks is an optimisation of the liquid fuel placing.

Within the German Energy Research Programme "500MW on a single shaft", Rolls-Royce Deutschland Ltd&Co KG and the German Aerospace Center have carried out detailed investigations of different liquid fuel injections for the main stage of a lean burner. Through a comprehensive sensitivity analysis of the main injection the aim of the work was to achieve further NO_x reductions compared to conventional diffusion burners. In the following section, the burner concept and further variants will be described. To improve the understanding of the underlying fuel placement mechanisms and their influence on global combustion parameters, non-intrusive measurements in a single-sector rig and emission measurements within a high-pressure sector rig were carried out and some of the main results are presented below.

2. LEAN BURNER CONCEPT

The burner design is based on the so-called "swirl cup" concept. Former investigations regarding burner sizing and injection optimization are reported by Rackwitz et al. [1], other issues e.g. flame stability and cooling requirements are described by Bake et al. [2]. Fuel is mixed with an excessive proportion of air i.e. the resulting burner air-to-fuel-ratio (AFR) is very lean. Two co-rotating radial air swirlers provide a high swirling until the burner exit leading to a centralized flame stabilization. The fuel injection device consists of two parts: a main fuel injector optimized for low emissions and a pilot fuel injector to enable high combustion efficiency and to improve the stabilization of the flame. Fig. 1 shows a schematic of the lean burner from RRD and a photograph of an observed flame. The image was taken at a combustor pressure of P_{air}=6bar, an air inlet temperature of T_{air}=700K, a fuel split of 20%, i.e. only 20% of the total fuel is feed though the pilot injector, and a burner AFR according to 92% of the design point air-to-fuel ratio (AFR_d).

The main fuel is injected in liquid phase with discrete jets at the atomizer lip. A jet in crossflow arrangement offers the possibility of a rapid break-up of the liquid columns. The fuel is injected into regions with highly turbulent shear stresses leading to an intensified mixing of fuel and air. Detailed experimental results of the breakup and penetration of plain liquid jets in crossflows can be found in the literature e.g. for non-inclined liquid jets by Hussein et al. [3], Wu et al. [4], Becker and Hassa [5] and for inclined liquid jets by Fuller et al. [6]. In the present study 13 variants of multiple liquid jet injections for the main burner were investigated. Here, the number and diameter of fuel ports as well as the circumferential injection angle of the fuel jets were varied.

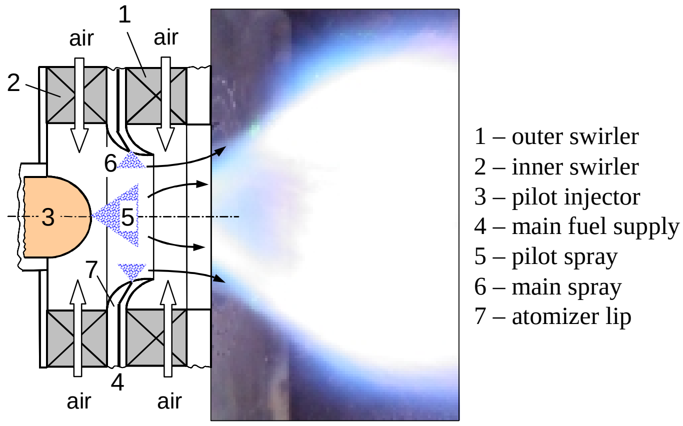

Figure 1: Lean burner from RRD with pilot and main fuel injection, exemplary photograph of the “mixed” flame.

In addition to the jet in crossflow injections mentioned above, two other concepts were derived with a trailing edge injection at the end of the atomizer lip and a prefilmer configuration (see Fig. 2). A trailing edge injection of discrete swirled fuel jets, as realised in concept (b), follows a lean direct injection approach with nearly no residence time of the liquid fuel inside the burner. The main fuel will not penetrate into the central recirculation zone. High turbulent shear stresses between the two swirled air streams will improve the air fuel mixing.

A developing liquid wall film on the inner surface of the atomizer lip via discrete fuel jets is realised in concept (c). Here, nearly no radial penetration of the main fuel towards the central recirculation zone will occur. All three main fuel injection concepts (a) to (c) were integrated into a common burner design with identical aerodynamic swirl generation and pilot injection.

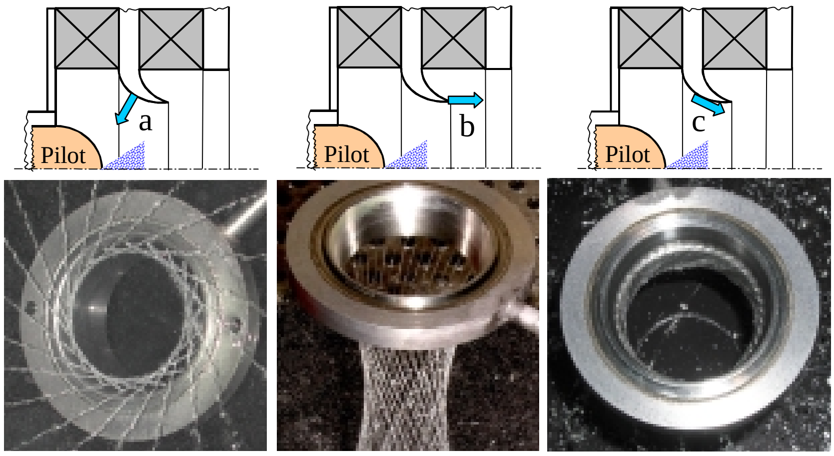

Figure 2: Schematic of investigated main injections: (a) swirled jet in cross flow[1], (b) trailing edge injection[2], (c) prefilmer[3] (top), images of fuel injection into stagnant environment (bottom) ([1,2,3] patents pending).

Additionally, Fig. 2 shows images fuel flow tests of the main injectors prior to the combustion test. The calibrating fluid MIL-C-7024 was used as a fuel substitute for aviation kerosene. At ambient conditions the fuel flow to the burners was successively increased and injected into stagnant environment. With this simplified flow check of the injectors, qualitative information about the initial fuel distribution generated by the discrete jets can be derived. Especially for very small fuel ports the identification of blockage or disproportional port sizes against specification is essential to ensure adequate initial fuel homogeneity.

3. NON-INTRUSIVE MEASUREMENTS

3.1. Single Burner Rig With Optical Access

The single sector combustor (SSC) test rig of the DLR Institute of Propulsion Technology was chosen for the experimental investigation using non-intrusive optical measurement techniques. The SSC test rig offers three-way optical access to the primary zone for application of laser light sheet techniques and is capable of operation at up to 20bar of combustor inlet pressure, 850K of air inlet temperature and air mass flow rates of 1.3kg/s.

A schematic of the test rig is shown in Fig. 3 outlining the different flow paths for the primary air, cooling air, secondary air and the fuel supply. Electrically preheated air enters the combustor plenum through a choked nozzle. It is then fed to the flame tube through the burner and the heat shield of the combustor dome plate from where it enters as a cooling and purging film along the quartz windows of the primary zone. The primary zone length is limited by addition of secondary air by means of mixing jets. The flame tube is cooled on the outside by non-preheated cooling air. All airflows exit the combustor through a single choked exit nozzle. In addition to the non-intrusive optical measurements, emission measurements in the exit of the combustor were carried out in parallel using a water cooled exhaust probe from RRD. Details about the SSC test rig can be found in Behrendt et al. [7].

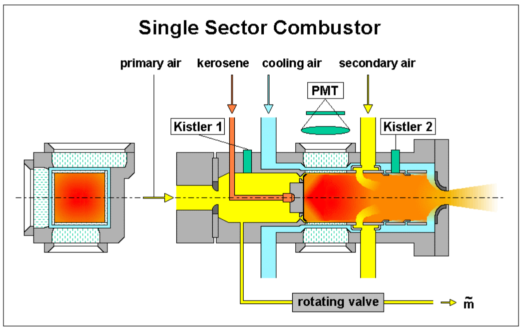

Figure 3: Schematic of SSC test rig.

3.2. Results – Fuel Placement and Flame Location

Planar non-intrusive optical measurement techniques were used to characterize the fuel placement, the reaction zone and the flame temperature in the primary zone of the SSC test rig. Simultaneously, conventional emission measurements were applied for the lean burner concepts (a) – (c) to investigate the effect of fuel flow split μ (0% - 100%) and of the air inlet temperature (T_{air}=700K, 822K) on burner performance. Here, fuel flow split μ is defined as the ratio of pilot fuel flow to the total fuel flow through the pilot and main injector.

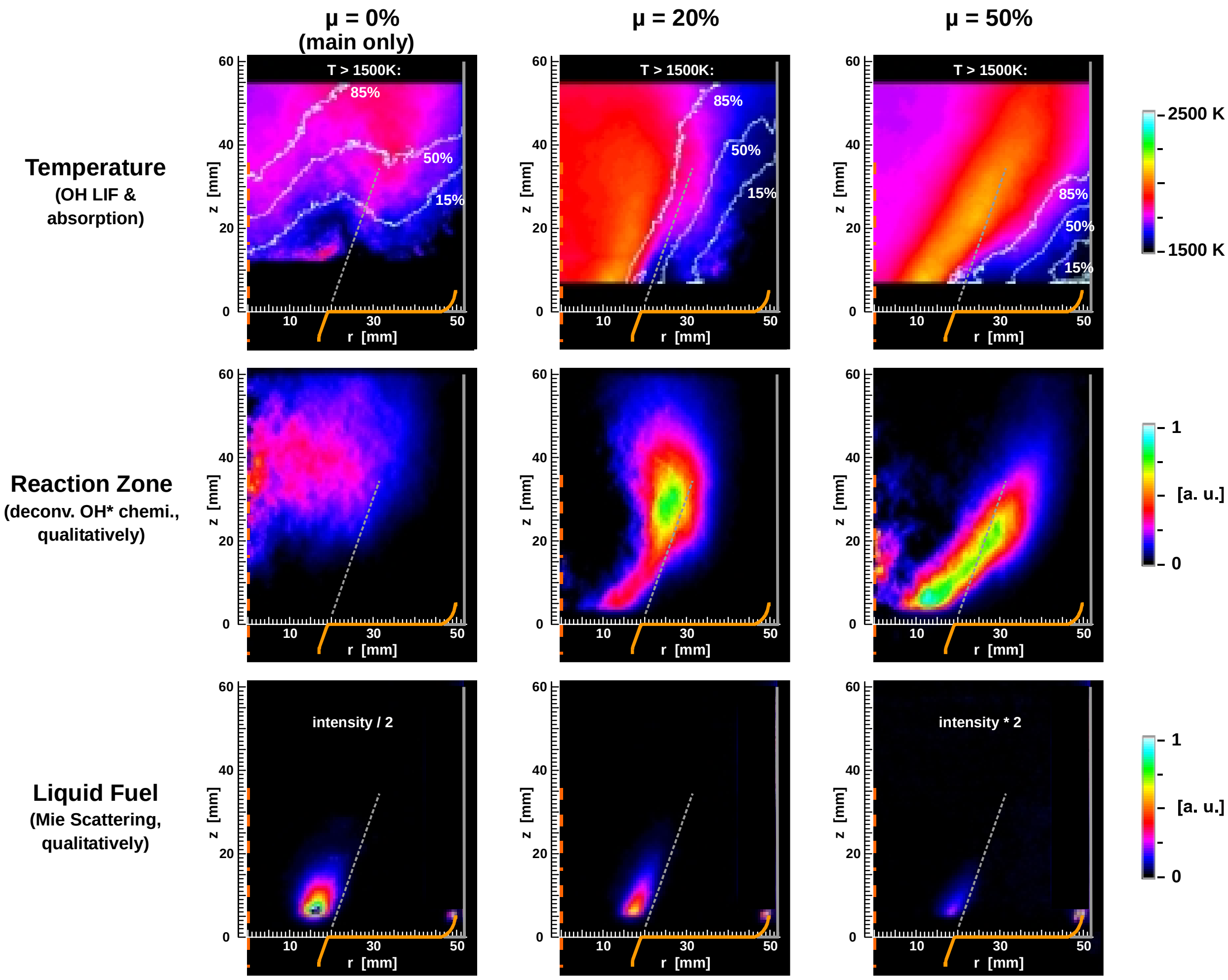

Figure 4: Effect of fuel flow split μ on time averaged liquid fuel distribution (Mie scattering), heat release (OH* chemiluminescence) and flame temperature (OH LIF) at P_{air}=6bar, T_{air}=822K, 92% AFR_d. The longitudinal section through one half of the axis symmetric flame is shown.

Mie-scattering provides qualitative information about the distribution of the liquid kerosene in the burner near field. The light of a pulsed, frequency doubled Nd:YAG laser was formed to a planar light sheet. The scattered light was detected perpendicular to the laser sheet by an intensified CCD camera. At least 150 single pulse images were taken to determine the time average of the Mie scattering. As a marker for the flame reaction zone the chemiluminescence of the OH* radical at 315±10nm was used [8] and detected by another ICCD camera. On the assumption of axial symmetry the average of 150 OH* images each having an exposure time of 10µs were deconvoluted to obtain a visualization of the reaction zone in a longitudinal section through the flame. Flame temperature is derived from the concentration of the OH radical. In lean pressurized flames the OH concentration increases nearly exponentially with temperature. By the combination of OH LIF and laser absorption measurements, absorption correction as well as absolute calibration of the OH image and therefore calculation of the spatially resolved absolute temperature becomes possible [9]. At temperatures below 1500K the OH concentration is too low for reliable temperature determination in kerosene/air flames. Despite the spectral interference of OH and kerosene LIF the simultaneous detection of the LIF signal by 2 cameras using different spectral filters enables an independent measurement of OH and kerosene. The time averaged mean and RMS values of the temperature and kerosene distribution were calculated of 200 single-pulse OH and kerosene LIF images.

Fig. 4 shows the effect of the fuel flow split µ on flame structure of the lean burner with the main fuel injector of concept (c), i.e. the prefilmer, at 6bar and an air inlet temperature of 822K. The density of liquid fuel is qualitatively indicated by Mie-scattering (Fig. 4, bottom), and the reaction zone by deconvoluted OH* chemiluminescence (Fig. 4, centre). The flame temperature (Fig. 4, top) is calculated from the OH concentration. The iso-lines represent the fraction of shots for each pixel in the OH-LIF images where a local temperature could be determined, i.e. where the local temperature was above 1500K. From left to right of Fig. 4 µ was increased from 0% up to 50%. The presented images correlate with the emission measurements in Fig. 5 and with PDA results shown later in Figs. 6 and 7. At a fuel split of µ=0% (Fig. 4, left column), i.e. only the main burner is operating, no blow out of the flame occurred for both air inlet temperatures (T_{air}= 700K, 822K). But the flame burned completely lifted off. As shown in the left column of Fig. 4 for T_{air}=822K, the reaction zone started 15mm above the burner, reached its maximum at a height of 40mm, and extended beyond a height of 60mm. The mean flame temperatures of less than 1840K inside the measurement window are low. Due to the geometric limitation of the measurement window at 55mm above the burner the temperature field of the detached flame could not be completely characterised. The qualitative Mie image indicates a broad spray distribution with more than twice the density of the test case µ=20% (Fig. 4, centre column).

The flame structure is changed at the higher fuel split due to the additional pilot flame anchored inside the burner. The reaction zone is more structured: beside the main reaction zone in a height of 30mm above the burner outlet an additional reaction zone at the inner side of the spray cone stabilizes the flame. Together with the recirculation of hot combustion gases (T<1910K) this reaction zone supports the evaporation of the spray whereas the highest time averaged flame temperature is 2020K. The distributions of fuel, reaction zone and temperature of the fuel split ratio µ=50% are shown in the right column of Fig. 4. A further reduction of Mie-signal by a factor of 4 is confirmed by the liquid fuel flux determined by the PDA measurements (see Fig. 6) as well the increase of the opening angle of the spray cone. The reaction zone moves to burner outlet and the highest mean values of the flame temperature reach 2080K.

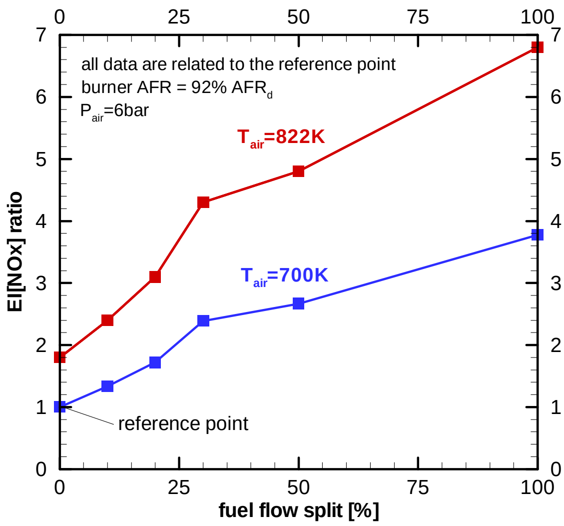

Figure 5: Effect of fuel split µ and T_{air} on measured EI[NO_x], concept (c) with main prefilmer, SSC rig.

Fig. 5 shows measured NO_x emissions at P_{air}=6bar and 92% AFR_d. All data are referenced to EI[NOx] at µ=0%, T_{air}=700K. For µ=0% and T_{air}=822K the low values of the temperature field of Fig. 4 confirm the low NO_x emission when the pilot injector is not operating. If the fuel flow to the pilot injector is increased up to µ=20%, NO_x emissions are raised by ca. 70%. A further increase of the pilot flow leads to a nearly linear increase of EI[NO_x]. For µ=100% the highest temperatures grow only slightly, but the high temperature area (T>2000K) inside the measurement window doubles in size, leading to an additional EI[NO_x] increase of 28%.

3.3. Results – Droplet Characterisation

For a detailed characterisation of the fuel spray, phase-Doppler anemometry (PDA) measurements were performed using a 2-component Dantec system with covariance processor. The receiving optics were positioned at Brewster's angle for kerosene (i.e. 68° off-axis), so that only light scattered by first-order refraction could be detected and the effect of changes of droplet refractive index on measured drop size was eliminated. At each node of the measurement grid covering one quarter of a cross-sectional plane of the two-phase flow, 20'000 events were recorded. Some results are shown in Figs. 6 and 7, where the Sauter Mean Diameter (SMD) of the spray droplets and the axial flux of the liquid fuel are plotted as a function of radial coordinate. Due to the impossibility of measuring the exact flow path of any given droplet through the PDA measurement volume in the highly turbulent, swirling flow with a 2-component PDA system and the resulting uncertainty of the detection area of the measurement, the liquid fuel flux data is presented for qualitative comparison only. Measurements were taken in a plane oriented normal to the burner axis and located 10mm downstream of the burner exit with different fuel splits (Fig. 6). Additionally, air inlet temperature was varied between 700K and 822K (Fig. 7).

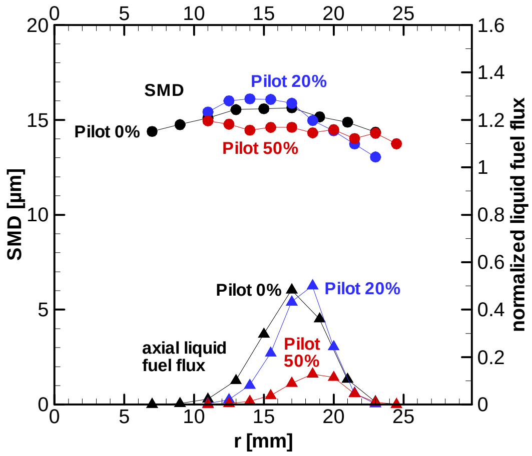

Figure 6: Effect of fuel split μ on SMD and axial liquid fuel flux at 6bar, 822K, 92% AFR_d

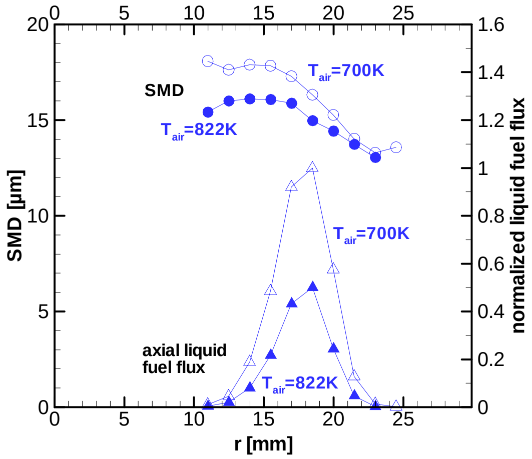

Figure 7: Effect of T_{air} on SMD and axial liquid fuel flux at μ=20%, 6bar, 92% AFR_d.

The figures show that the measured liquid fuel flux decreases as the percentage of fuel passed through the pilot is increased. Due to the pilot flame, which is anchored deep inside the burner, the pilot fuel evaporates and possibly even disappears by chemical reaction before reaching the measurement plane, and heat transfer from the pilot flame increases evaporation of the main fuel. Increasing the percentage of fuel fed to the pilot also leads to a decrease of mean diameters of the droplets that are still present in a given measurement plane. Air inlet temperature has a significant effect on the fuel spray in the sense that a lower preheat will give rise to larger droplets and especially higher values of the measured liquid fuel flux.

4. EMISSION MEASUREMENTS AT HIGH PRESSURE

In addition to the SSC test campaign emission measurements of CO, CO_2, NO, NO_x, O_2, UHC and soot were carried out in a high-pressure-single sector (HPSS) rig at DLR Institute of Propulsion Technology for 16 burner variants. The water cooled combustor has a cylindrical cross section with a diameter of 90mm. Maximum operating conditions are P_{air}=40bar and T_{air}=920K. In Fig. 8, NO_x emission index vs. burner AFR for different burner configurations is shown. The tests were performed at P_{air}=20bar, T_{air}=822K and μ=10%. Both EI[NO_x] and burner AFR are normalized: burner AFR is related to AFR_d, EI[NO_x] is referred to the measured NO_x emission for central fuel injection at 80% AFR_d. The upper curve (red line, open symbols) corresponds to the central fuel injection i.e. the main burner is switched off. NO_x emissions are decreased considerably when transitioning from the rich to lean burner operation. A significant reduction of NO_x is achieved if the main injector is switched on. Here, the dependency of the NO_x emissions on burner AFR is more pronounced. At a pilot split of μ=10% and AFR=AFR_d the prefilmer offers a NO_x reduction of 52% compared to central fuel injection. A swirled fuel injection with concept (a) leads to a further significant reduction of NO_x emissions.

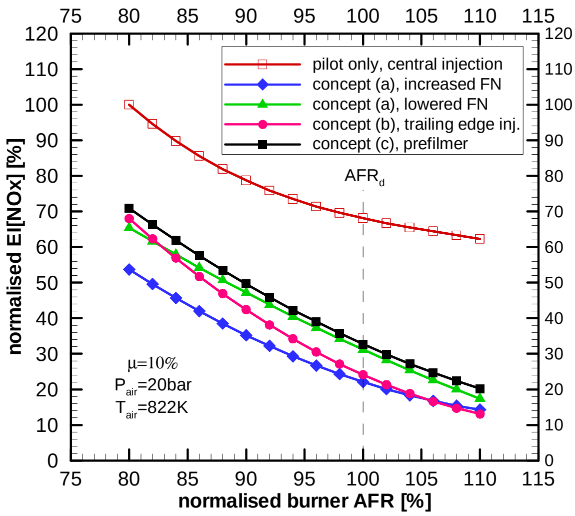

Figure 8: measured NO_x emission index vs. burner AFR, pilot only, burner concepts (a) – (c), HPSS rig.

The two lines shown for concept (a) correspond to a variant with a lowered fuel flow number (green) and with an increased fuel flow number (blue) of the main burner. Compared to concept (a) and (b) with the design fuel flow number the main fuel injection at the trailing edge of the atomizer lip with concept (b) shows the lowest NO_x emissions over most of the burner operating range. In the lean region above a burner AFR of 105% the trailing edge injection is better than concept (a) with increased fuel flow number. At 100% burner AFR a NO_x reduction of 68% compared to the central injection was achieved.

5. SUMMARY

In the present study, different types of main injections for a lean burner were investigated in detail by application of planar non-intrusive measurement techniques up to P_{air}=6bar and T_{air}=822K. Emission measurements were carried out in parallel at P_{air}=6bar in the SCC rig and at up to P_{air}=20bar in the HPSS rig. The main results can be summarized as follows:

a) Lowest NO_x emissions are observed with main burners offering a low fuel penetration into the central recirculation zone at the burner axis. A swirled fuel injection and an increased fuel flow number via increased port diameters have shown a significant NO_x reduction of ca. 68% compared to central fuel injection.
b) As shown for the prefilmer concept (c), the fuel split has a significant effect on the flame structure, the location of the reaction zone, and the evaporation behaviour of the "mixed" flame. Consequently, the NO_x emissions increase strongly with higher fuel splits. At the same time, the flame position changes from a lifted flame to an anchored flame with increased spray angle.
c) A trailing edge injection of the main fuel with no premixing of the main fuel and air within the burner has demonstrated lowest NO_x emissions in the lean regimes at higher operating conditions up to 20bar.

The work has shown that a detailed investigation of liquid fuel placement for a lean burner using both non-intrusive measurement methods and conventional emission measurements will improve the understanding of the "mixed" flame behaviour. It has to be mentioned, that 3D CFD methods has been used extensively to optimise initial fuel placing of the main stage. Whereas NO_x was reduced significantly, some effort will be made to extend the operating envelope of the burner with respect to lean burnout at low power and low fuel split conditions.

6. ACKNOWLEDGEMENT

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7. NOMENCLATURE

$AFR_{(d)}$	-	(design) air-to-fuel-ratio [-]
CAEP	-	committee on aviation environmental protection
EI[x]	-	emission index of species x [g of species x/kg fuel]
FN	-	fuel flow number of a burner [igph/√psid]
HPSS	-	high-pressure-single sector
LIF	-	laser induced fluorescence
LPP	-	lean premixed prevaporized
NO_x	-	oxides of nitrogen (NO and NO_2)
P_{air}	-	combustor inlet pressure [bar]
PDA	-	phase doppler anemometry
SMD	-	sauter mean diameter [µm]
SSC	-	single sector combustor
T_{air}	-	air inlet temperature [K]
μ	-	fuel flow split [%]

8. REFERENCES

1. L. Rackwitz, T. Doerr, T. Schilling, J. Heinze, M. Jarius, and K. Stursberg, Experimentelle und theoretische Untersuchung der Brennstoffaufbereitung in mager vorgemischten Flammen, *DGLR 2002*, Germany, Stuttg.
2. S. Bake, M. Gerendas, W. Lazik, Th. Doerr, Th. Schilling, Entwicklung eines Magerverbrennungskonzeptes zur Schadstoffreduzierung im Rahmen des nationalen Luftfahrtforschungsprogramms Engine 3E, *DGLR 2004*, Germany, Dresden.
3. G.A. Hussein, A.K. Jasuja, and R.S. Fletcher, Penetration and breakup behaviour of a discrete liquid jet in a cross flowing airstream – a further study, *The American Society of Mechanical Eng.*, ASME 83-GT-170.
4. P.-K. Wu, K.A. Kirkendall, and R.P. Fuller, Breakup processes of liquid jets in subsonic crossflows, *Journal of Propulsion and Power*, vol. 13, no. 1, pp. 64-73, 1997.
5. J. Becker and C. Hassa, Breakup and atomization of a kerosene jet in crossflow at elevated pressure, *Atomization and Sprays*, vol. 11, pp. 49-67, 2002.
6. R.P. Fuller, P.-K. Wu, and K.A. Kirkendall, Effects of injection angle atomization of liquid jets in transverse airflow, *AIAA Journal*, vol. 38, no. 1, pp. 64-72, 2000.
7. T. Behrendt, M. Frodermann, C. Hassa, J. Heinze, B. Lehmann, and K. Stursberg: Optical measurements of spray combustion in a single sector combustor from a practical fuel injector at higher pressures, *RTO Meeting Proceedings 14*, pp. 43/1-43/12, 1999.
8. H. N Najim, P. H. Paul, C. J. Mueller, P. S. Woyckoff: On the adequacy of certain experimental observables as measurements of flame burning rate, Combustion and Flame, **113**, pp. 312-322, 1998.
9. T. Behrendt, J. Heinze, Ch. Hassa: Experimental investigation of a new LPP injector concept for aero engines at elevated pressures; *Proceedings ASME* GT2003-38444, pp. 1-10, 2003.