Concept for a versatile spray test rig for comparison of evaporation between kerosene and replacement fuels for aviation

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Abstract

This contribution is about the development and construction aspects of a spray test rig with multi-fuel capacity (kerosene, replacement fuels, surrogates) for the experimental analysis of liquid fuelled gas turbine injection systems. It is capable to handle systematic comparative investigations on the evaporation of hydrocarbons. The installation comprises high pressure and high temperature air line feeds, two high pressure fuel lines and an afterburner to oxidize unburned hydrocarbons. The test cell comprises optical access. In case of evaporation analysis a laser-optical measurement unit that is based on the Infrared Extinction method is used. This development is part of a general investigation on the use of alternative and bio-fuels in aeronautics called Alfa Bird (Alternative Fuels and Bio-fuels in Aircraft Development), which is a multi-disciplinary consortium with industrial partners from aeronautics, fuel industry and research organizations consolidated by the 7th research framework programme of the European Comission.

Introduction

Due to an increasing oil price and the probable impact of the combustion of fossil fuel-derivatives on climate change on one hand and the depletion of hydrocarbon natural resources and the steady growth of transportation needs on the other, there is a need to develop alternatives to oil also in terms of aeronautics.

For this purpose a specific research programme on the investigation of adequate alternatives to oil for aircraft implementation has been founded by the European Commission's Framework Programme. It is called Alfa Bird (Alternative Fuels and Bio-fuels in Aircraft Development). This consortium is made up of several industrial partners, research and educational institutions on aeronautics as well as oil companies and aims to investigate the adaptability of conventional aircraft engines to the use of alternative fuels such as GTL, CTL, Naphtenic Cut and blendings of GTL with HVO (Hydrogenated Vegetable Oils). Due to the very long lifetime of current civil aircraft and because of very strict operational constraints (e.g. flight in very cold conditions) it is a great challenge to use bio-fuels and alternative fuels in aircrafts.

The main objectives of this project are an identification of possible alternative fuels to kerosene, the investigation of the adequacy of the selected ones, an evaluation of the environmental and economical performance of those and finally the creation of a future perspective for the industrial use of the "best" alternative. The main part of the investigation activities in the Department of Thermal Turbomachinery and Machine Dynamics at the TU Graz, in cooperation with ONERA Centre de Toulouse and Fauga-Mauzac on these specific topics consists of the analysis of the evaporation of the previously chosen fuel types in comparison to conventional Jet A1 fuel. Therefore a highly versatile test rig has been installed in the combustion-laboratory of the Technical University in Graz. With this test rig it is possible on one hand to use several different measurement techniques, such as Phase-Doppler-Anemometry, Laser-Doppler-Anemometry and the Infrared-Extinction-Method to evaluate the vaporisation and the atomization of fuels under continuous hot-flow high-pressure conditions and on the other hand to simultaneously work on different projects due to its ability to switch test cells very quickly. There is as well a special fuel line feed installed which can switch immediately between fuel types, in case of the Alfa Bird project between a reference fuel (Jet A1) and the chosen replacement fuels.

This article details the technical aspects of special installations in the laboratory of our department, its abilities and the main objectives of our work in the ongoing Alfa Bird project. There will be a few preliminary results presented but the main focus is set on a technical description of the test rig, the test cell and the measurement techniques that will be used.

Test rig, Capacities and Structure

The test rig in the laboratory of the Institute for Thermal Turbomachinery and Machine Dynamics is part of an open-circuit plant which had initially been installed for experimental investigations on cold subsonic and transonic flows.

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To fulfil the demands on a modern flow test facility the plant has been extended by an additional piping part which is able to lead the pressurized air flow over a thermal air heater that has been installed on the outside of the department building. The high pressure air-flow is delivered by a separate compressor station.

The maximum capacity of this compressor station is denoted with 3MW electrical power. Leading the pressurized air suchlike by the piping system over the thermal air heater, whose maximum thermal power is denoted with 5MW, allows us to realize a maximum system pressure level of 10 bar abs and a maximum temperature level of 750 K in the test cell. The maximum air flow over the air heater at this test condition is around 3.5 kg/s hot air.

The additionally installed part of the open circuit plant is built in parallel of the current system. All operational modes of the compressor station [1] can be used as the adaptation comprises a connection to the high- and low-pressure lines.

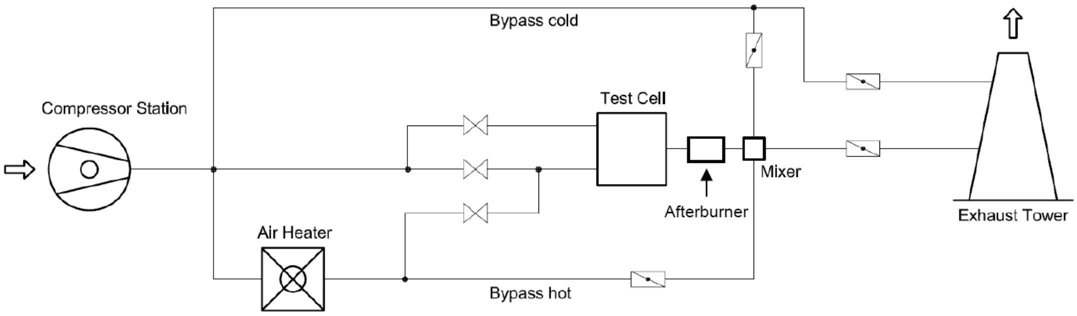


Figure 1: schematic of the test facility

The test rig circuit comprises mainly two line feeds, a hot flow and a cold flow line (Figure 1)[1]. Each of these consists of a main line and a corresponding bypass line.

The main line for the cold flow is leading directly from the compressor station to the test cell while the hot main line is routed through the air heater first. The bypass lines are split from the main lines before the test cell and are afterwards mixed with the gases obtained by the test rig. The main intention is to cool down the exhaust gases. The pressure level can be set by a water-cooled butterfly valve. The air flow from the bypass lines to the test cell is regulated by electro-pneumatic valves (Figure 2)[1]. The bypass lines and the piping of the air heater are permanent installations. Depending on the application of the test cell the remaining piping can be rearranged or adapted. In case of the investigations for the Alfa Bird project an afterburner (Figure 1) is installed which is run by methane in order to reduce unburned hydrocarbons in the exhaust-tube, which will later be detailed. A vital arrangement in the whole circuit plant has been the installation of a new fuel supply concept (see below).

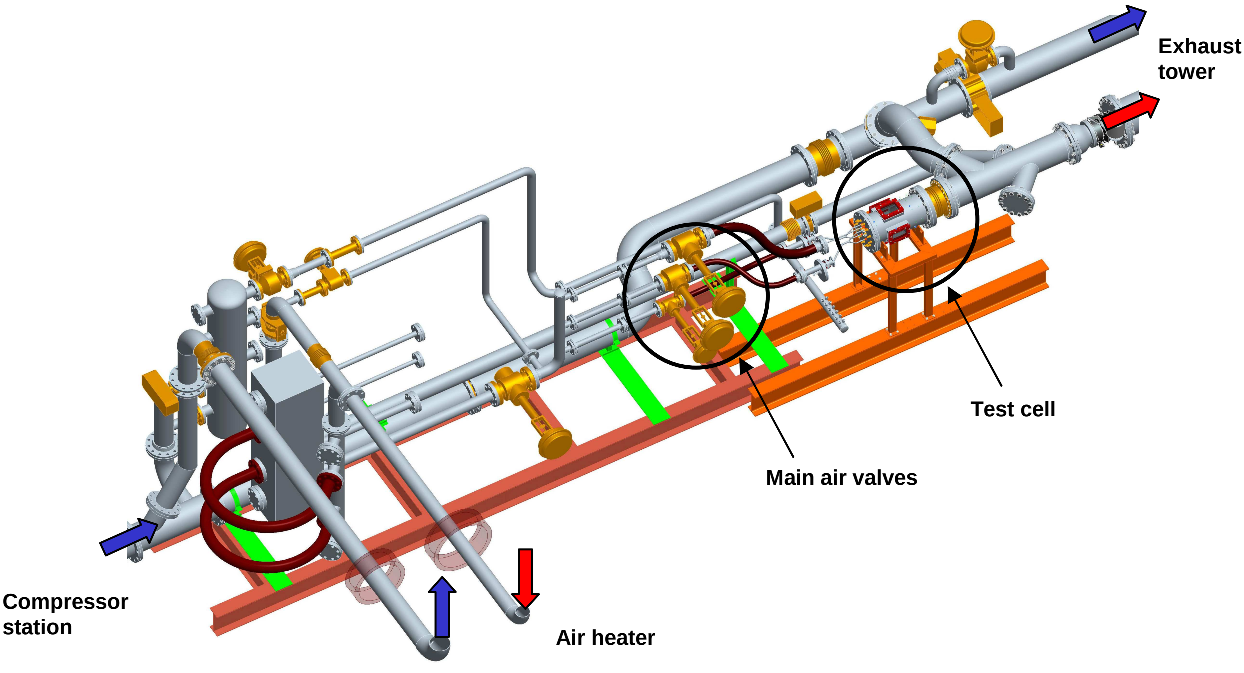
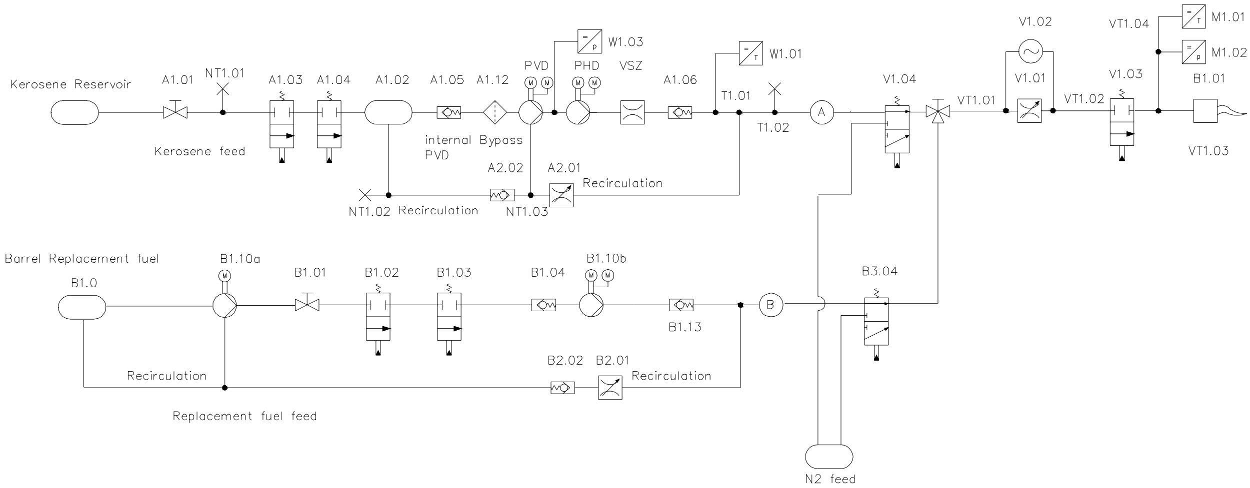


Figure 2: 3D Design of the test facility [1]

Fuel Supply

Figure 3 shows ostensively the structure of the new fuel supply concept. The main innovation here is represented by the multifuel capacity of the circuit. It is possible to handle two different fuel types simultaneously which aims to facilitate comparison-investigations. Pertaining to the Alfa Bird project, it will be necessary to switch between the chosen alternative and the reference fuel if a certain test-condition has been reached in order to assure comparability of the received results.

The circuit consists of two separate line feeds, one for each fuel type. These feeds are both independently operable and consist of a main feed and a recirculation feed which leads the fuel back to the reservoir depending on the operation point.



A/B1.01	Manual blocking valve	W1.01	Temperature sensor
A/B1.02	Surge tank	A/B2.01	Pressure reducer (tunable between 0-6.8 bar
A/B1.03/4	Safety valves (electromagnetic)	A/B2.02	Non-return valve
A/B1.05	Non-return valve	V1.03	Two-way valve to lock circuit
A/B1.12	Fuel filter	V1.04	Flush valve for nitrogen
PVD/PHD	Fuelpumps (low and high pressure)	V1.01	Coriolis flow regulator
W1.03	Pressure sensor	M1.01	Temperature sensor
VSZ	Volumeflow-meter	M1.02	Pressure sensor

Figure 3: Schematic of the fuel supply

In the kerosene feed the fuel is aspired by a low pressure pump from the reservoir over a manually regulated lock-valve and two electromangnetic safety-valves into the surge tank. These valves avoid an overfilling of the tank and are as well connected to the fire prevention installation of the combustion latoratory in order to block the circuit in case of emergency. From this intermediate tank, into which also the recirculated fuel is leaded, the mass flow is sucked by a low pressure toothed wheel pump through a non-return valve and a fuel filter (7 micron) into the radial piston pump which is able to provide a hydraulic pressure level of 40-100 bar. Subsequently the flow passes a volumeflow-meter, another non-return valve avoiding a backflow into the fuel pumps, a junction, which is connected to the recirculation feed (where the recycled fuel flow is regulated by a pressure balance) and an electromagnetic three-way valve. This valve is used to connect the further part of the circuit with its integrated nitrogen supply in order to flush the tubes in case of changing between fuel types.
After the nitrogen 3-way valve a further valve switches between the fuel types. The latter part of the circuit consists of a combined Coriolis mass flow meter/regulation valve, another lock valve and a temperature and pressure measurement device. The pressure is measured using a piezoresistive sensor and the temperature using a Pt-100 resistance temperature sensor.

The replacement fuel feed is mostly build up comparably, the only difference to mention is that there is no feed orifice to the kerosene reservoir. It is connected directly to a barrel. The standard operating fuel-supply capacity of this unit is denoted with 10 g/s fuel.

Test cell and After-burner

The main objective of the Alfa Bird project concerning the field of responsibility of the Technical University of Graz is to obtain qualitative results of the comparison of the evaporation mechanisms of several fuel-types. As a consequence it was decided to use an already existing burner-geometry for these investigations. The TIME-COP-AE injection system by TURBOMECA and the MERCATO (Moyen Expérimental de Recherche en Combustion Aérobie par Techniques Optiques) flame tube geometry at ONERA Fauga Mauzac [6] have been chosen to be the best compromise. The burner design (Figure 4) is based on a radial swirler with a hollow cone pressure fuel nozzle [5].

However some modifications have been made to the flame tube, such as the change of the rectangular design of the airbox to a cylindrical one for manufacturing reasons, also the Delavan pressure atomizer has been replaced by an equivalent from Parker to fit a SMD (Sauter Mean Diameter) below 50 µm.

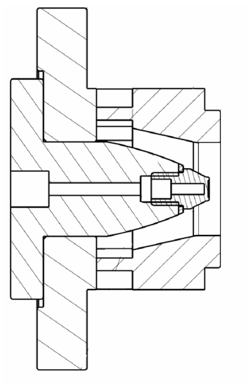


Figure 4: Cross-section of the burner geometry

The flame tube has been integrated into the existing pressure casing of the test bench, allowing very quick changing intervalls in case of the necessity of simultaneous investigations in the laboratory. This has been acquired by using an adapter-flange construction. The whole conglomerate is heatstrain-insensitive due to an axial-compensator integrated between the main flange and the air-box (Figure 5). This design can compensate the calculated heatstrain of approximately 2 mm, which is important due to the highly displacement-sensitive Infrared Extinction measurement method [2] which will be discussed later.

The liner is rectangularly shaped and made of 2 mm metal sheet which is bolted to the flange of the air-box (Figure 5). It has four perpendicular windows which allow a centered optical access of 180 x 100 mm on each side flush with the entrance plane. The window panes are made of quartz-glass which is highly pressure and temperature resistive and has a wide range of light transmission according to the interesting wavelengths of 633nm and 3,39µm used for the Infrared Extinction measurement method. The test specimen is applicated with 4 piezoresistive absolute pressure sensors detecting the rotational symmetric mean-value of the pressure and 15 thermocouples on the interesting positions (Figure 5) as well as a Pt-100 total-temperature sensor positioned in the middle of the flow.

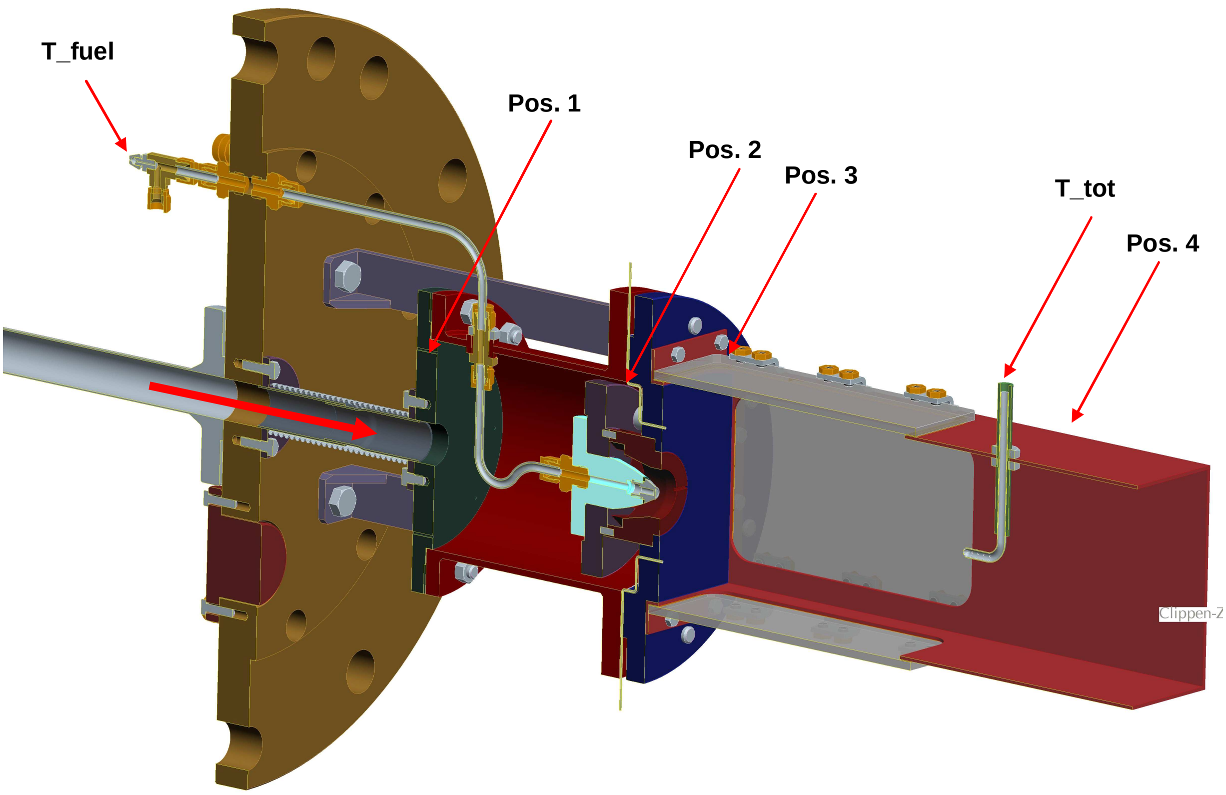


Figure 5: Cross-section of the burner geometry

In the dilution zone an afterburner has to be installed in order to reduce the unburnt hydrocarbons by a controlled pyrolysis, which is necessary according to the Alfa-Bird-related isothermal vaporisation investigations without combustion. Figure 6 shows the concept of the test cell and the afterburner.

The hot compressed air is guided through the main-tube into the airbox and cooling air is passing alongside the flame tube. Passing the radial swirler, the hot flow is mixed with the investigated fuel using an equivalence ratio of $\Phi = 1$. After the liner, the hot fuel / air mixture is diluted by the cooling air. In order to avoid flashback the blend is attenuated till $\Phi = 0{,}5$. The suchlike conditioned flow is introduced into the after burner. To produce a pyrolysis the whole mixture has to be heated up to at least 1100 K. The required thermal power of the burner has been calculated to be approximately 120 kW. To reach this thermal power it is planned to use a triangular arrangement of three "Lang-burners" [10], which have been developed at the Combustion Department. The functionalitity and the stability of the existing burner geometry is well known and the burner stability has been proven. The burners are operated with methane provided by the internal gas circuit of the laboratory, the operation point is regulated with a pressure reducer and a V-cone flow meter. The mixture is ignited with a lighting-up lance which is combined with a flame surveillance detector in the middle of the burners. A built-in UV flame detector and a set of pressure taps and thermocouples serve for process control.

The exhaust gases coming out of the burner-conglomerate have to be highly diluted because of the uppermost allowed temperature level in the exhaust tower of max. 670 K. For this purpose compressed dilution air is leaded into the exhaust tube coming from a side junction.

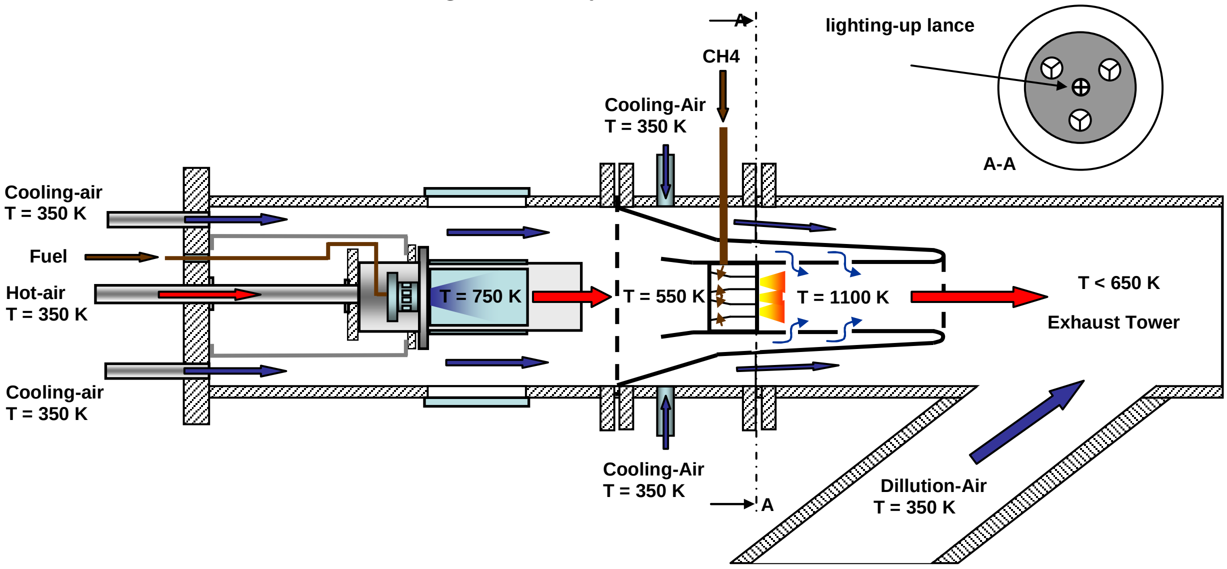


Figure 6: Schematic of the test cell and the afterburner

Test Conditions and Fuel-selection

The chosen test conditions in the Alfa Bird project are based on certain similarity rules, more precisely a constant reduced mass flow-rate WR = 0.3, a constant reference velocity v_{ref} = 33,36 m/s, a constant equivalence ratio of $\Phi = 1$ and a constant temperature of 750 K in order to match realistic gas turbine conditions. Based on this similarity rules the pressure levels in the system are going to be changed, varying between atmospheric pressure level, 3 bar absolute pressure and 5 bar absolute pressure. Each of the 4 chosen fuels is going to be tested under these operating conditions.

Tests for 4 Fuels	P	T	Vref	Mair	Kero
	[Pa]	[K]	[m/s]	[g/s]	[g/s]
TESTS LP	1,00E+05	750	33,36	10,95	0,76
TESTS HP	3,00E+05	750	33,36	32,86	2,27
TESTS VHP	5,00E+05	750	33,36	54,77	3,78

Table 1: Alfa Bird test-matrix

Based on an initial fuel selection of 12 fuel-blends and an evaluation of these in terms of their quality as jet fuel, the responsible department has selected 4 fuels that will be tested in detail. The 12 blends consisted of FSJF, FT-SPK, blends of FT-SPK with naphtenic-cut or hexanol or furane or FAE, in different amounts. The 4 fuels selected are FSJF, a blend of FT-SPK with 50 % naphtenic cut and a blend of FT-SPK with 20 % hexanol. Because of Jet A-1 having a large variability according to the crude oil and the process (sweetening, hydroprocessing, etc.) which results in a variation in the level of aromatics and sulphur, FSJF was chosen to represent the reference fuel due to its homogeneity and the fact that it comes from an identified refinery with a controlled process.

Measurement techniques

For the investigations within the Alfa Bird project 3 different measurement techniques are going to be used. Firstly the Laser Doppler Anemometry (LDA) to analyse the flow velocity components u v w as well as the turbulence levels, secondly the Phase Doppler Anemometry (PDA) to analyse particle-size and -number and thirdly the Infrared Extinction Method (IRE) to detect the concentration gradients in the flow. It is presumed that the first two measurement techniques are widely known and don't need any further explanation. Main focus of attention in the AB-project is directed on the third method.

The Infrared Extinction method is a line-of-sight, non-intrusive laser method that provides the relative fuel vapour concentration in a two-phase flow with evaporation by comparing Intensity values of two laser beams (visible λ = 633 nm and infrared λ = 3390 nm) directed through the investigated medium [2]. A few different configurations have been carried out since it was originally developped by M.S.A.Skinner in the late 70's. The Latest configuration known has been tested in the past three years at the Onera in Toulouse (B.Wagner et al. [8]) to investigate the fuel vapor concentration on droplets.

$$C = \frac{1}{\alpha_{IR} L} \ln\left(\frac{\left(I/I_0\right)_{VIS}}{\left(I/I_0\right)_{IR}}\right) \qquad \textbf{(1)}$$

The principle is based on a simplification of the Beer-Bouguer-Lambert law (Equation 1) (Drallmeier et al [7]). The main Hypothesis is that if the line-of-sight extinction due to Mie-scattering is similar for both infrared and visible wavelengths because of the presence of the spray, only infrared light will be absorbed by the vapour fuel, being transparent to visible light. A comparison between line-of-sight intensities of both wavelengths allows to estimate the vapour concentration C. These intensities will always be normalised with a reference signal in absence of the spray, which represent the direct transmission intensities that are marked with a "0" underscript. As a consequence the line-of-sight intensities I_{VIS}, I_0 VIS, I_{IR} and I_0 IR have to be measured. α_{IR} is the vapour absorption coefficient in the IR range, and L is the length of laser penetration through the medium. While the product α_{IR} L is constant at isothermal conditions, the relative concentration can be computed.

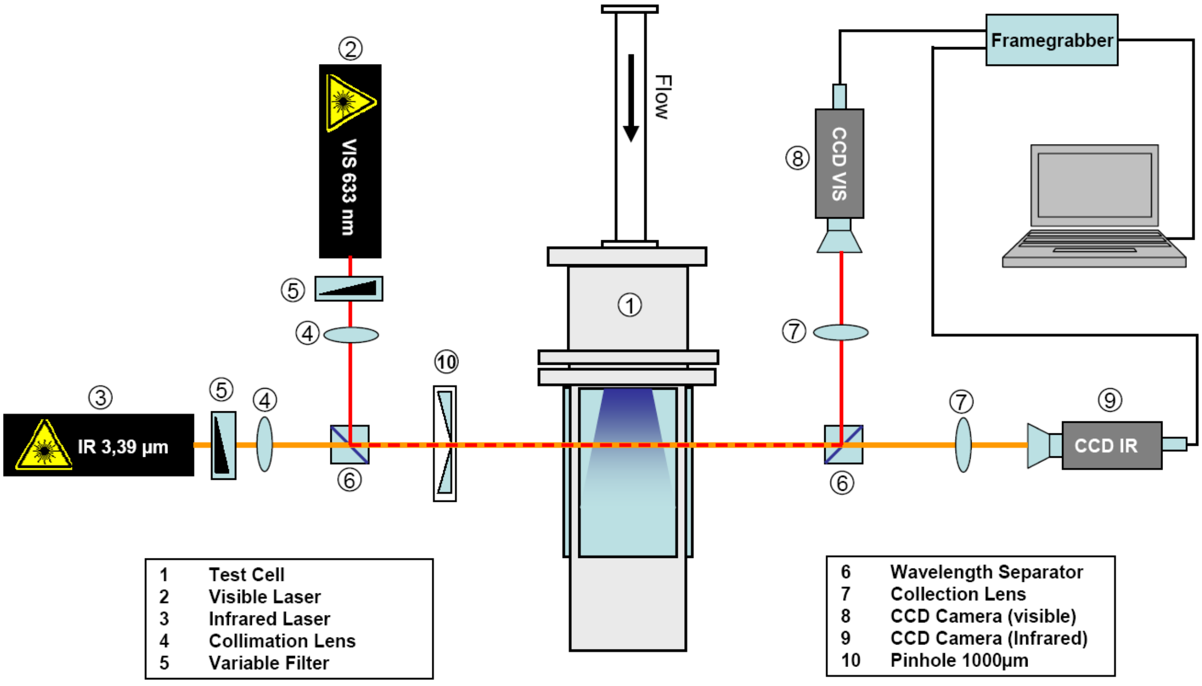


Figure 7: IRE test configuration

In the usual set-up in former configurations a cooled diode for the infrared and a photodetector for the visible range have been used in order to detect the laser signal emmitted by the class 2 lasers. In this type of configuration it is necessary to place pinholes in front of the detector-entrance in order to ensure that the same amount of scattered light fraction for both wavelengths is detected. The problematics are a very high displacement sensitivity on one hand and the disability of the system to detect a general diffraction on the other. Because of these facts the technology is problematic for regular test bench operations.

Therefore, as figure 7 indicates, a new concept has been developped, replacing the sensitive diodes by CCD cameras. The optical setup has not been changed in comparison to the configuration of the investigations of Giuliani et al.[2], only the pinholes in front of the detectors are being removed, which makes the system more stable concerning signal-diffraction and displacement. The optical setup consists of four lenses (two collimation- and two collection-lenses with focal lengths of 300 mm, 100 mm and 50 mm made of CaF2 for the IR and BK7 for the visible range) and two semitransparent mirrors which reflect visible light and are transparent for IR-light. Due to the sensitivity of CCD chips concerning blooming it is necessary to lower the light-intensities, therefore variable filters are integrated into the system beeing placed in front of the lasers. The analog CCD cameras are connected to an external A/D converter module (framegrabber) which is connected to an USB Interface in the test bench processor. The data acquisition is performed with a Labview 8.2 routine.

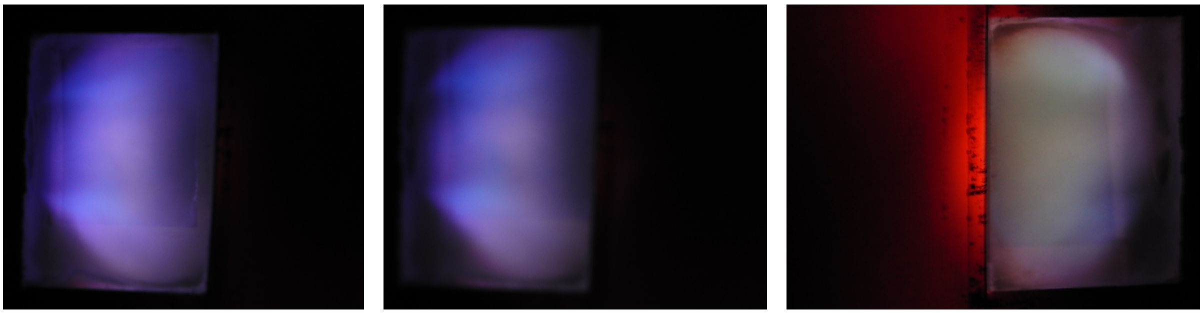
Preliminary Tests

In order to verify the the chosen operation points some preliminary tests have been made, all of them adressing to the reduced mass flow rate WR = 0.3 (see nomenclature). The first investigation covered a combustion test which was performed outside the laboratory at atmospheric pressure and ambient temperature T = 290 K. The burner was operated with ethanol due to ignition problems using kerosene. The tests have been made without liner (free-jet) and with liner (confined-jet), in the pictures below a variation of the airflow can be seen at constant fuel mass flow being regulated to the required reduced mass flow rate.

m_air = 6.08 g/s	m_air = 11.3 g/s	m_air = 12.69 g/s
v_ref = 7.16 m/s	v_ref = 13.4 m/s	v_ref = 14.96 m/s
m_eth = 1.2 g/s	m_eth = 1.2 g/s	m_eth = 1.2 g/s

Figure 8: Free-jet combustion-test varying air-mass flow

At ambient conditions and in absence of cooling air, a part load operation was chosen which explains the relatively low reference velocities in comparison to the test case. The flame attaches in free-jet-mode at the tip of the pressure nozzle at part load and stabilises around the internal recirculation zone. When augmenting the load, the flame gets a lifted structure (Figure 8). Under confined conditions, the absence of ambient surrounding air to be entrained allows the flame to attach to the outer diameter of the injector.



m_air = 10.42 g/s	m_air = 13.5 g/s	m_air = 13.67 g/s
v_ref = 12.2 m/s	v_ref = 15.9 m/s	v_ref = 16.12 m/s
m_eth = 0.87 g/s	m_eth = 0.87 g/s	m_eth = 0.87 g/s

Figure 9: Confined-jet combustion-test varying air-mass flow

Furthermore LDA measurements of the flow have been performed on free- and confined-jet mode under atmospheric conditions. The measurements were performed using a two-component LDA system (Dantec FiberFlow with two BSA processors) and the data acquisition was done using the BSA-Flow software. Droplets of DEHS oil (Di-Ethyl-Hexyl-Sebacin-Ester) with a nominal diameter of 0.3 µm were added to the flow before the entrance of the airbox. The mass flow rate (WR = 0.3) has been regulated with a V-cone flow-meter and a manual pressure reducer. Figures 10 and 11 show the radial distribution of the axial velocity in the positions 6 mm, 26 mm, 56 mm, 86 mm and 116 mm measured downstream of the entrance plane for free- and confined-jet configuration. The compressed air was taken from the internal air circuit of the department.

For further investigations the compressed air coming from the circuit plant will be used. The Swirl number (see nomenclature) at the position 26mm from the entrance plane has been calculated S = 0.78 for confined-jet and S = 0.74 for free-jet.

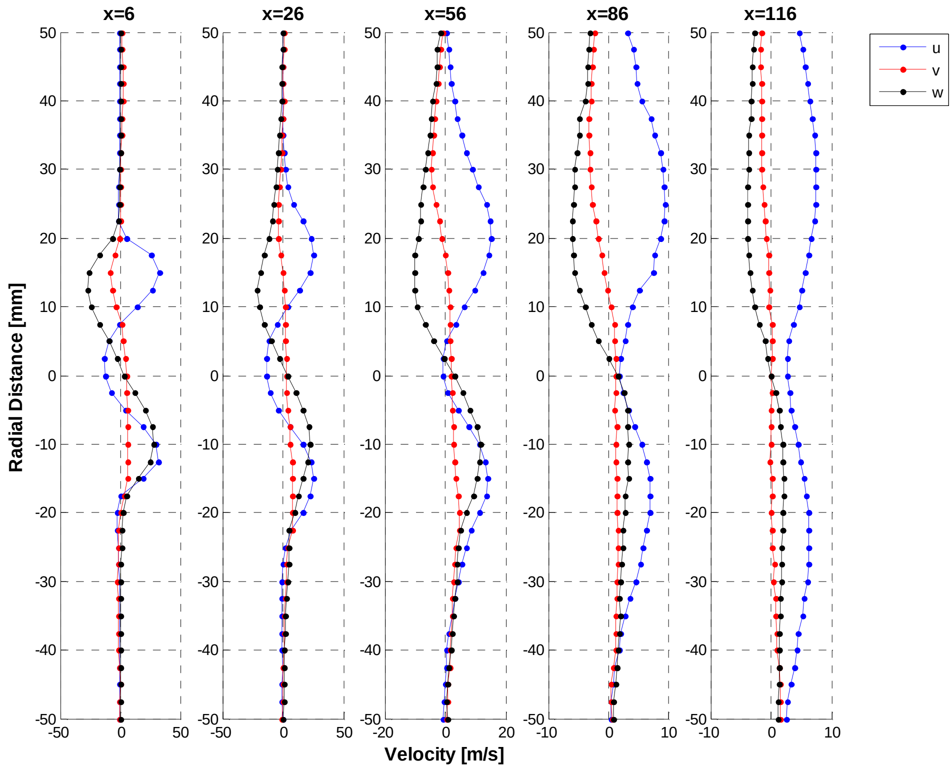


Figure 10: Radial-distribution of the velocity components u, v and w in free-jet configuration

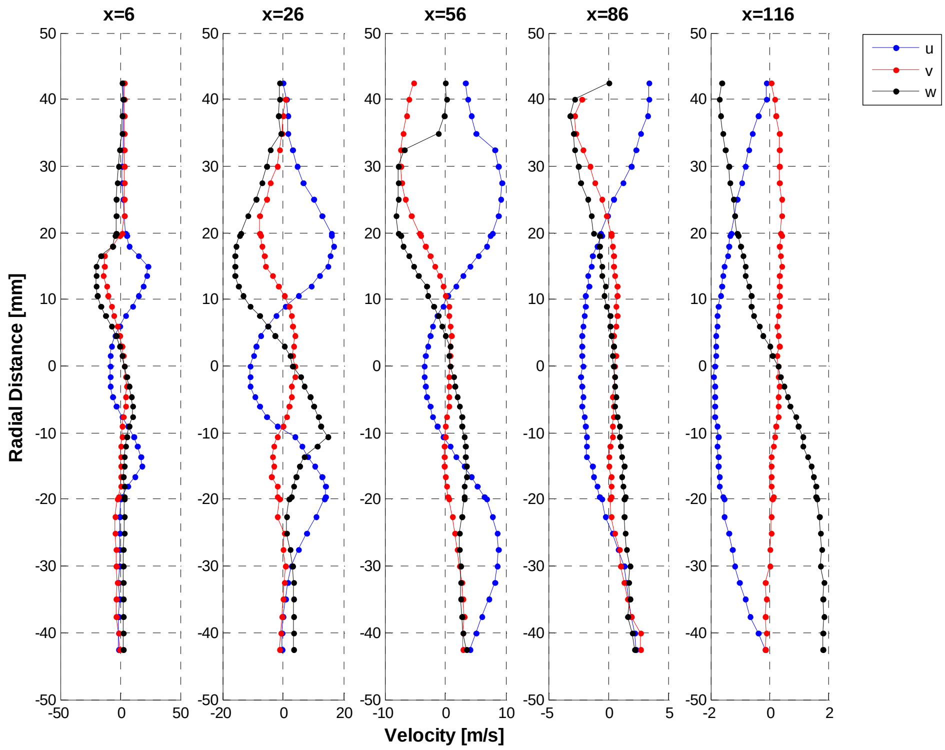


Figure 11: Radial-distribution of the velocity-components u, v and w in confined-jet configuration

Conclusion

Compared to existing well–established fuel spray test rigs at realistic operating conditions [3][4], the concept offers a multifuel capacity and is equipped for transient as well as modulated operation for injector stability analysis. The test rig is under construction, the Test cell and instrumentation are ready and the fuel supply is soon being completed. The IRE measurement technique is under development of Onera Centre Toulouse. The effort is being put at the moment on the design freeze of the afterburner, which is a critical milestone of this part of the Alfa-Bird project.

Nomenclature

FSJF	Fully Synthetic Jet Fuel
FT-SPK	Fischer Tropsch Synthetic Paraffinic Kerosene
FAE	Fatty Acid Ester
$WR = \dot{m}_L \cdot \sqrt{\frac{T_{t2}}{T_N}} \frac{p_N}{p_{t2}}$	Reduced Mass Flow
p_N	Atmospheric Pressure (1.01325 Pa)
T_N	Atmospheric Temperature (288.15 K)
p_{t2}	Systempressure
T_{t2}	Systemtemperature
$S = \frac{2}{D} \cdot \frac{\int_0^{x_{max}} w \cdot u \cdot x^2 dx}{\int_0^{x_{max}} u^2 x \cdot dx}$	Swirlnumber

Acknowledgements

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