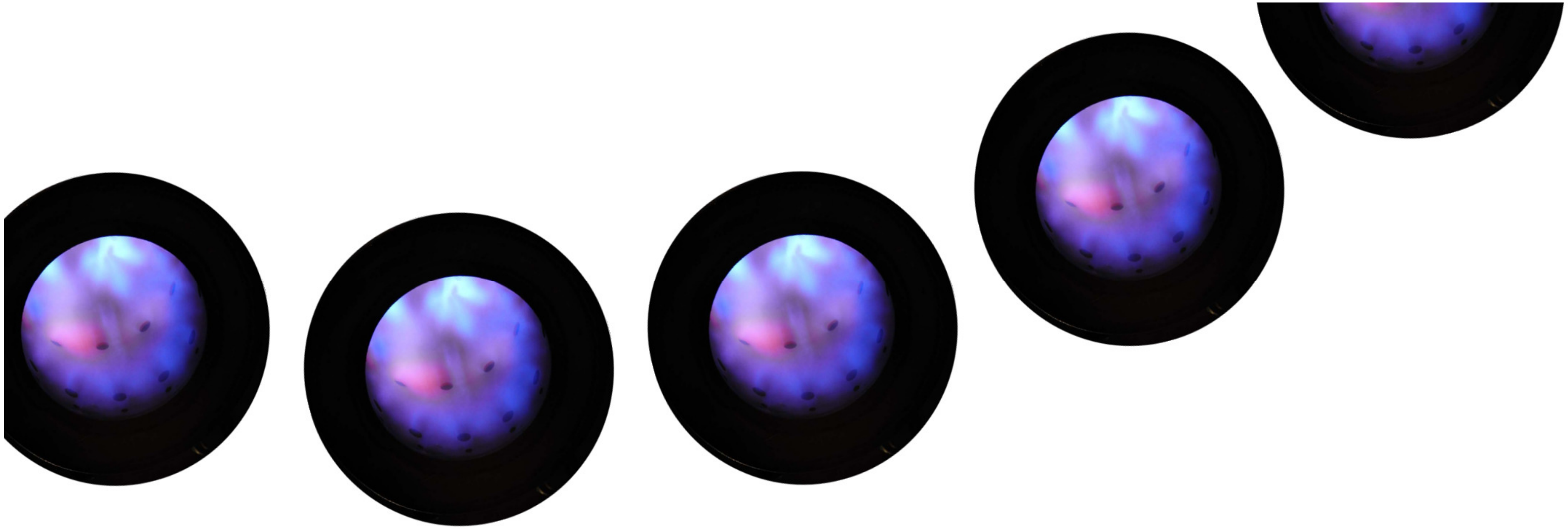


COMBUSTION BAY ONE

Advanced combustion management for propulsion and power

COMBUSTION BAY ONE

A analysis on evaporation of replacement fuels for aviation

Fabrice Giuliani,

Johannes Fritzer, Alain Strzelecki, Virginel Bodoc

Co-authors and partners

- TU Graz:
  - Johannes Fritzer
- ONERA Centre de Toulouse
  - Alain Strzlecki
  - Virginel Bodoc
- This presentation
- Project financing
  - More under

  alfa-bird.eu-vri.eu

TU Graz
Graz University of Technology

Institute for Thermal Turbomachinery and Machine Dynamics

Combustion Department

COMBUSTION BAY ONE

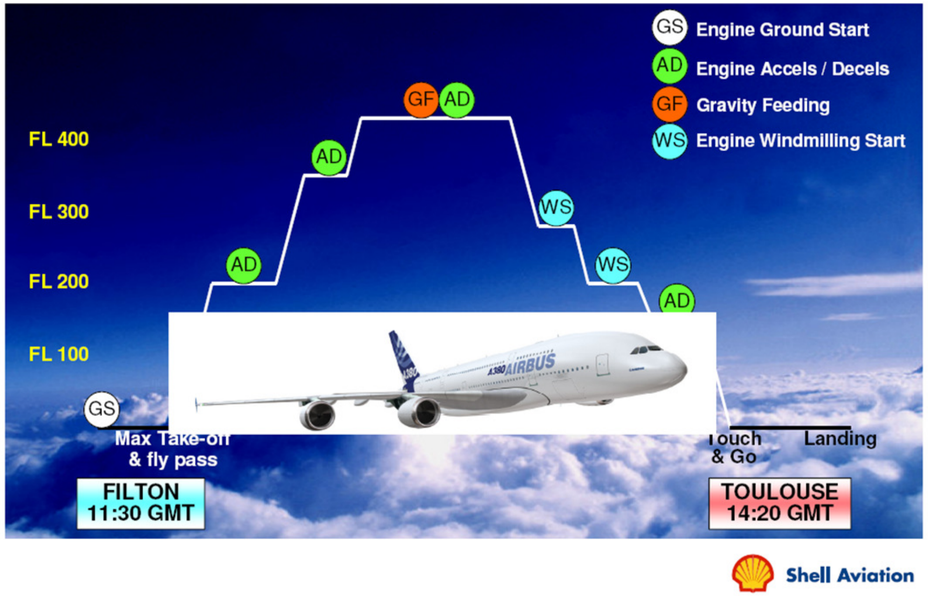
SEVENTH FRAMEWORK PROGRAMME

alfa bird

Incentive

- An airplane constructed today will fly about 30 years
- Is it able to make use of other fuels than kerosene?
- What are the adaptations to be done?

A380 MSN 004 Feb. 1st, 2008 Flight



- First flight of an A380 on the 1rst of February 2008
- GTL Jet Fuel blended with conventional kerosene

Alfa Bird stands for **Al**ternative **F**uels **a**nd **Bi**ofuels **I**n ai**r**craft **d**evelopment (FP7)

- Multi-disciplinary consortium with industrial partners from aeronautics, fuel industry and research organizations

- Main objective: Development of the whole chain of clean alternative fuels for aviation with a long term perspective

In particular:

- Identification and evaluation of possible alternative fuels to kerosene (mainly Fischer-Tropsch fuels such as GTL, CTL, BTL and FAME blended with kerosene)
- Selection of 12 (Ph1), 4 (Ph2) alternative fuels with aircraft requirements
- Evaluation of the environmental and economical performance
- Setting the path towards industrial use of ‚best' alternative fuels

Tasks of TU-Graz in the frame of Alfa Bird

- Adaptation of the test rig to the injection design:
  - Fuel supply
  - Combustion chamber for isothermal spray analysis of alternative and biofuels
  - Dimensioning and integration of an afterburner

- Injector selection (Cooperation with Onera)
- Construction of the test rig
- Planning, validation and installation of the measurement technique
  (Investigation on the IRE technique at Onera Toulouse in the frame of Eccomet FP6)

- Testing (4 fuels and 3 pressure variations at elevated temperature (750 K))
- Interpretation of the results

Replacement fuels considered for aviation

Initial fuel selection 12 fuels:

- FSJF (CTL)
- FT-SPK (GTL)
- blends of FT-SPK with naphtenic-cut
- blends of FT-SPK with hexanol
- blends of FT-SPK with furane
- blends of FT-SPK with FAE

Final fuel selection 4 fuels:

- FSJF (CTL)
- FT-SPK (GTL)
- blend of FT-SPK with 50 % naphtenic-cut
- blends of FT-SPK with 20 % hexanol

Reference fuel:

FSJF (due to large variability of Jet A1 according to the crude oil and the production process)

- Homogeneity
- Identified refinery with a controlled process

Selected replacement fuels

Name	Bezeichnug	Zusammensetzung
FSJT (CtL)	8040	100%
FT-SPK (GtL)	8069	100%
GtL + 50% naphthenic cut	8075	GtL + 50% naphthenic cut
GtL + 20% 1-hexanol	8074	GtL + 20% 1-hexanol

Tabelle 1: Alfa Bird Kraftstoffmatrix

FSJT:	Fully Synthetic Jet Fuel
FTSPK:	Fischer Tropsch Synthetic Parafinic Compound
CTL:	Coal To Liquid
GTL:	Gas To Liquid

Operating test conditions

Test conditions based on similarity rules:

- constant reduced mass-flow rate WR = 0,3
- constant reference velocity v_{ref} = 33,36 m/s
- constant equivalence ratio Φ = 1

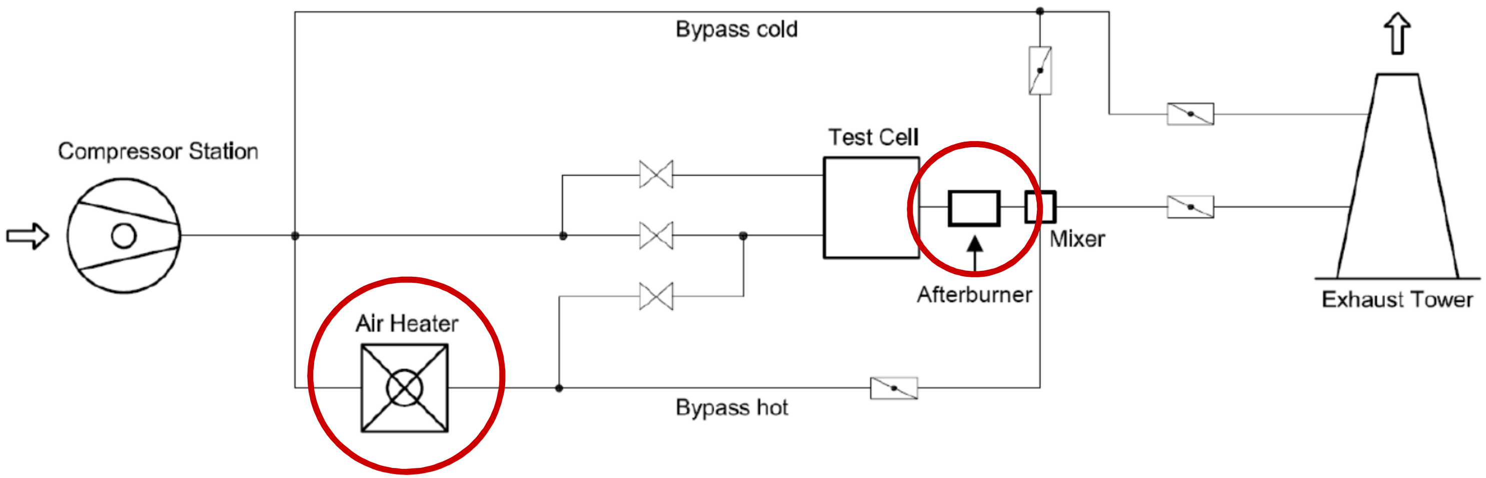
$$WR = \dot{m}_L \cdot \frac{\sqrt{T_1}}{p_1}$$

Tests for 4 Fuels	P [bar]	T [K]	Vref [m/s]	Mair [g/s]	Kero [g/s]
TESTS LP	1	750	33,4	11	0,76
TESTS HP	3	750	33,4	33	2,27
TESTS VHP	5	750	33,4	55	3,78

Alfa Bird test-matrix

Test rig at TU Graz

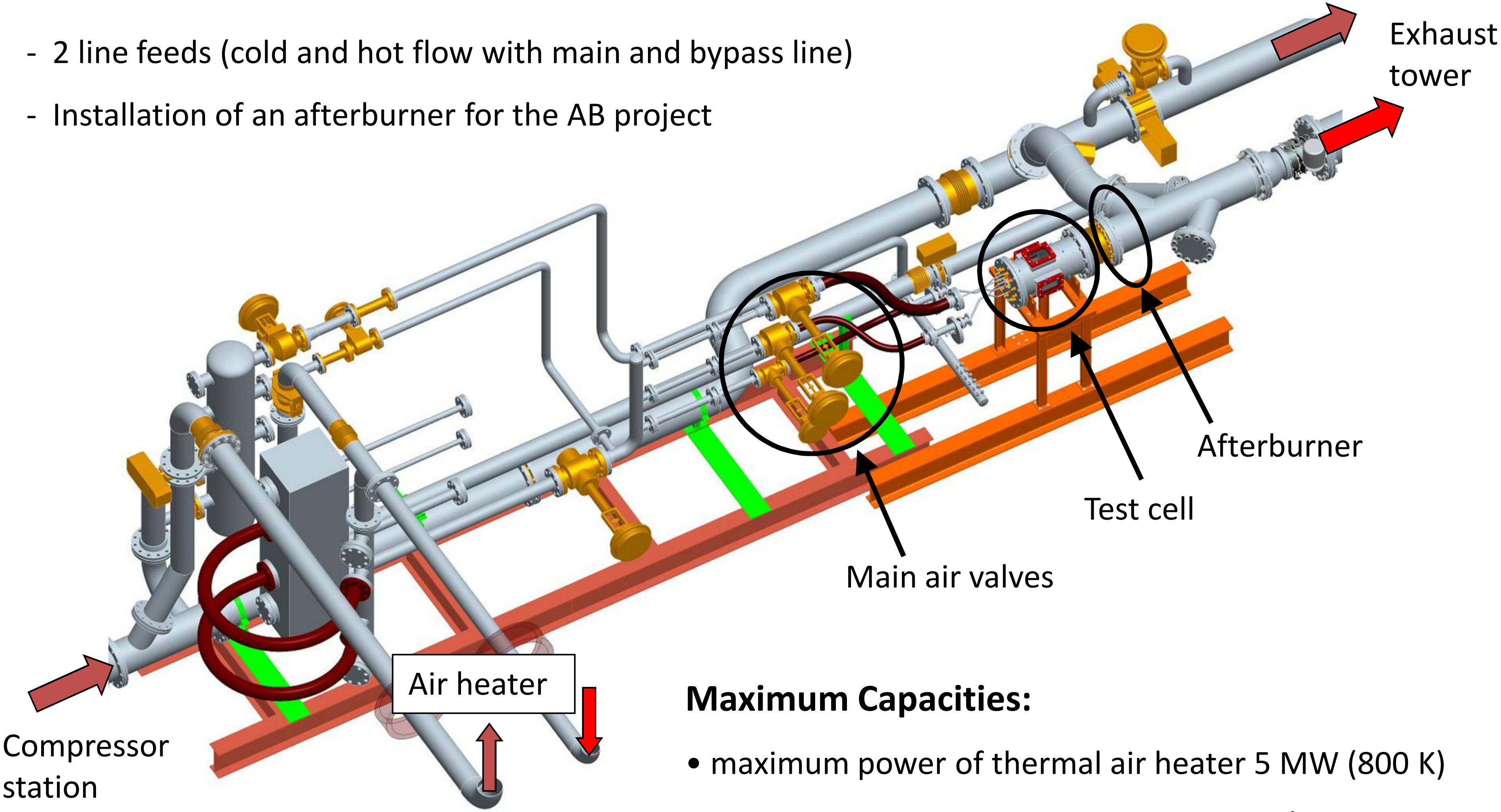
- Test Rig in the combustion laboratory of the ITTM is part of an open circuit plant for sub- and transsonic flow investigations



- Originally cold flow investigations → extended by a separate piping system over thermal air heater
- Built in parallel to current system→ all operational modes can be used

High-pressure and temperature air feed

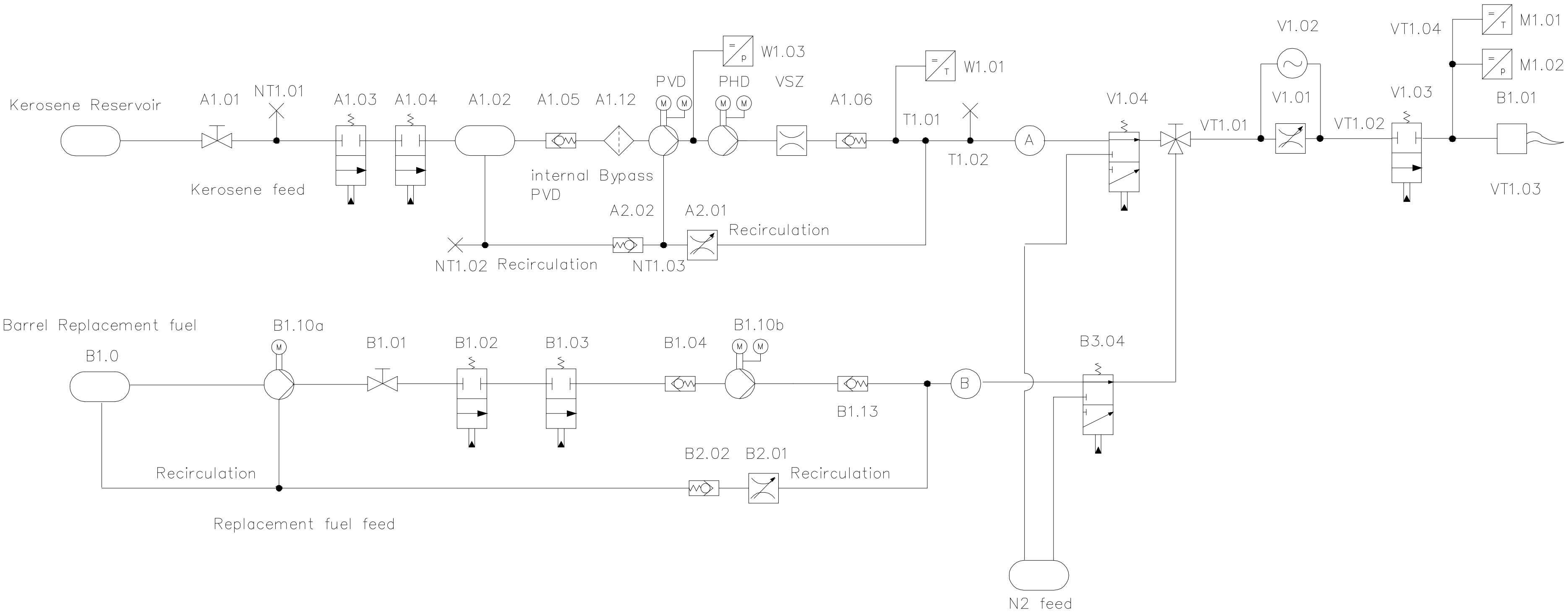
- 2 line feeds (cold and hot flow with main and bypass line)
- Installation of an afterburner for the AB project



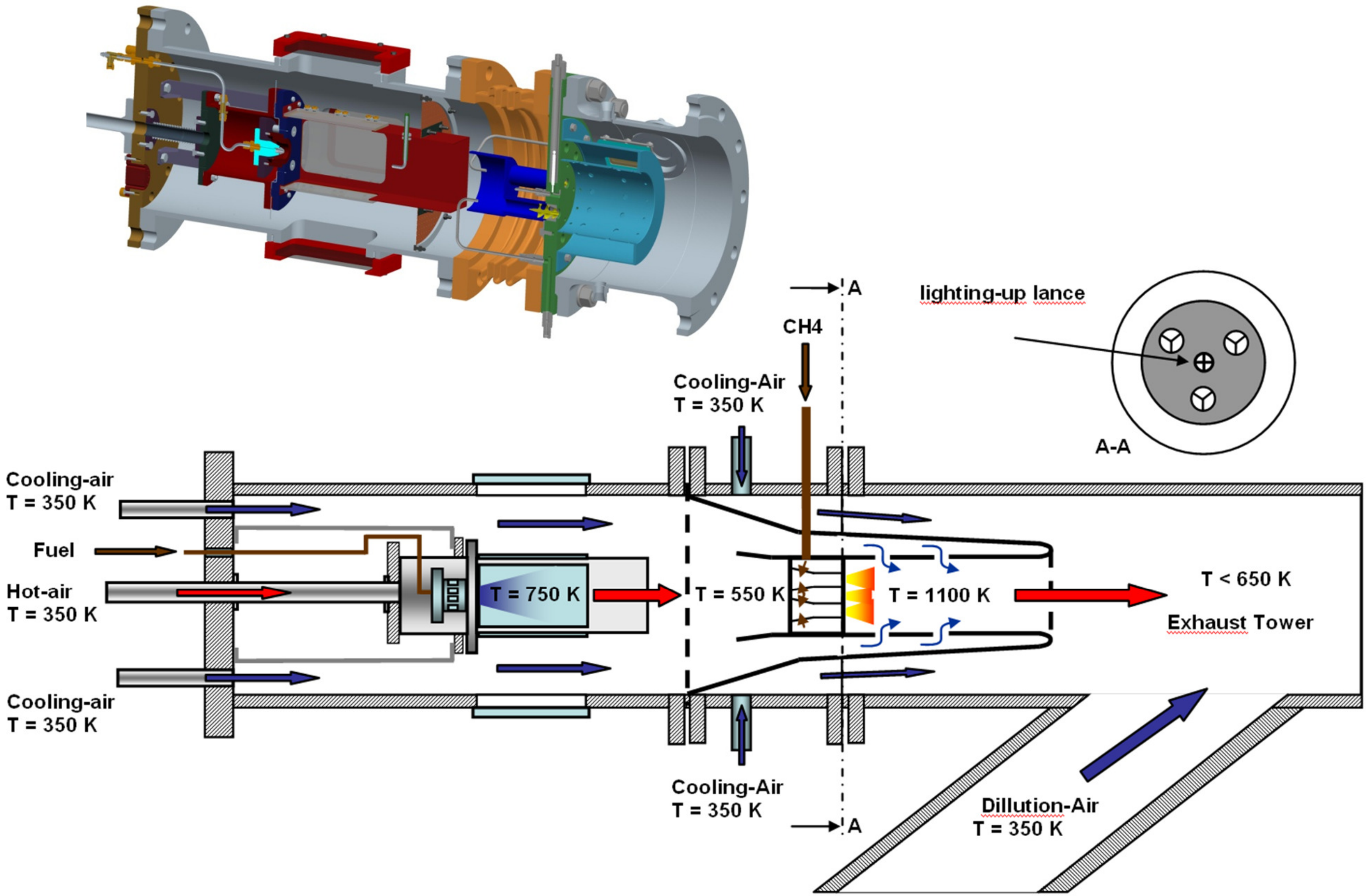
Maximum Capacities:

- maximum power of thermal air heater 5 MW (800 K)
- maximum hot pressurized air-flow 3,5 kg/s
- maximum pressure level 10 bar system pressure

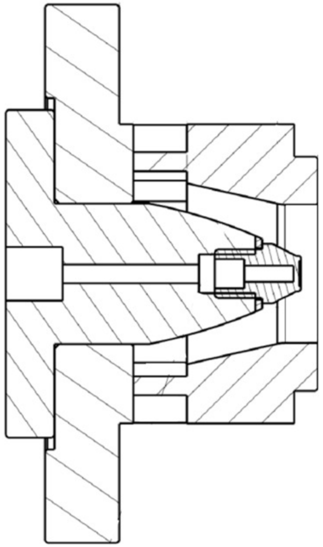
Fuel supply


Kerosene Reservoir
A1.01
NT1.01
A1.03
A1.04
A1.02
A1.05
A1.12
PVD
PHD
VSZ
W1.03
A1.06
W1.01
T1.01
T1.02
A
V1.04
VT1.01
V1.02
V1.01
VT1.02
V1.03
VT1.04
M1.01
M1.02
B1.01
VT1.03
Kerosene feed
internal Bypass PVD
A2.02
A2.01
Recirculation
NT1.02
Recirculation
NT1.03
Barrel Replacement fuel
B1.0
B1.10a
B1.01
B1.02
B1.03
B1.04
B1.10b
B1.13
B
B3.04
B2.02
B2.01
Recirculation
Recirculation
Replacement fuel feed
N2 feed

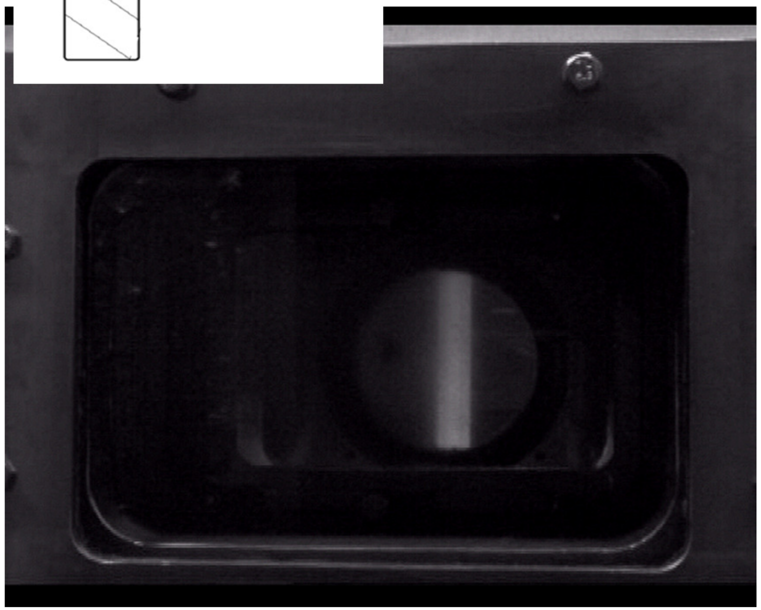
Test cell arrangement

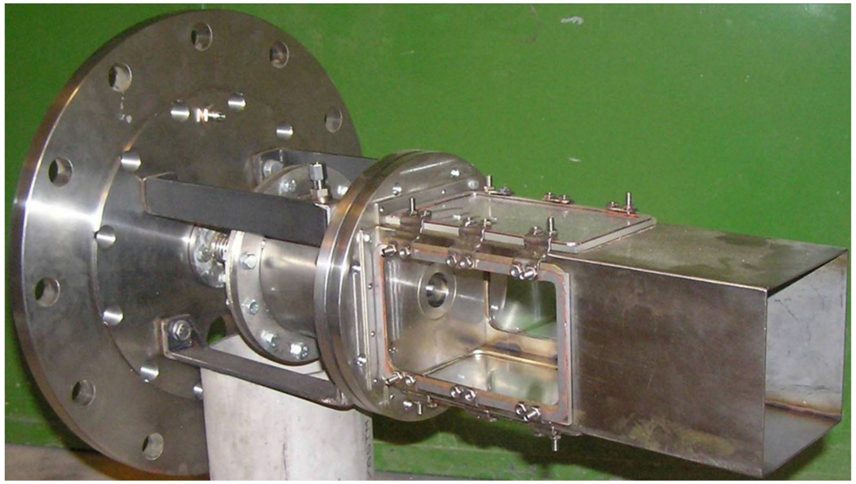


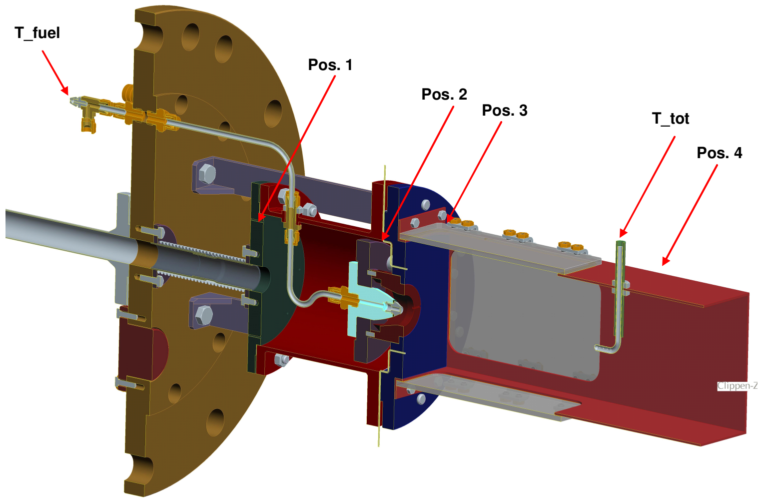
Detail test cell



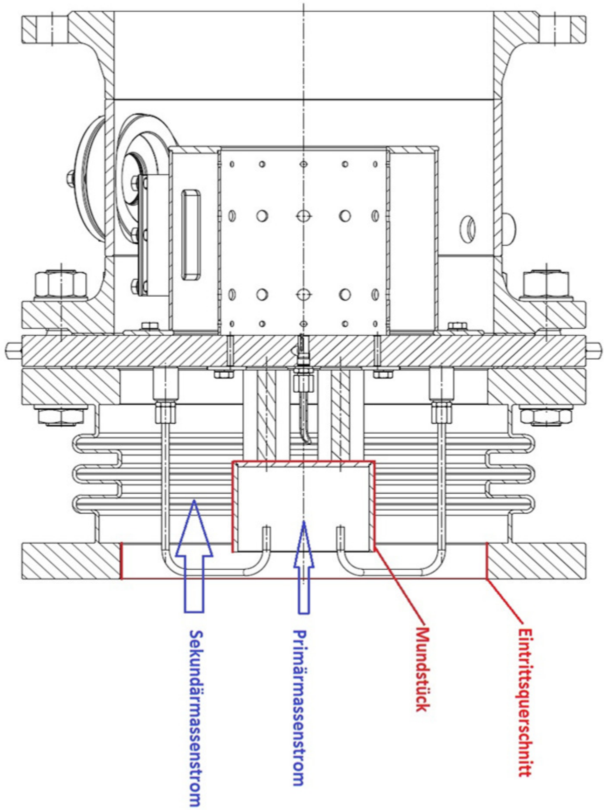
Generic research liquid fuelled burner from the LOPOCOTEP study, reengineered at TU Graz

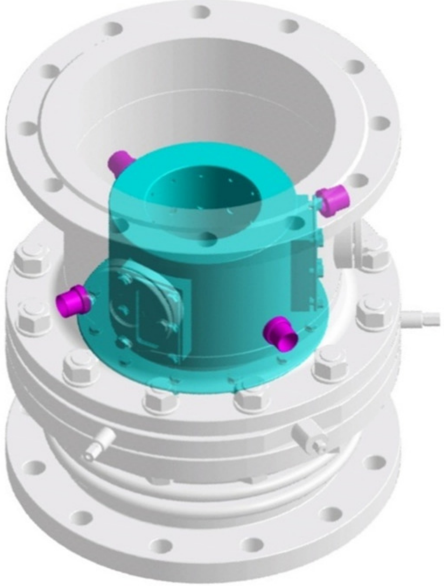


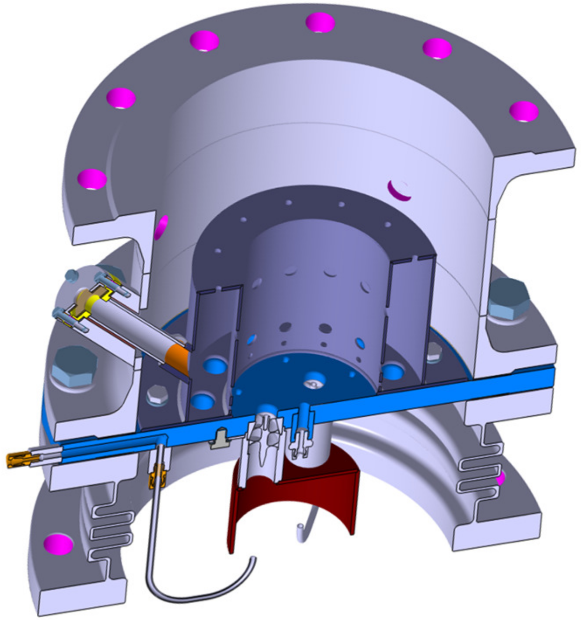




Detail afterburner

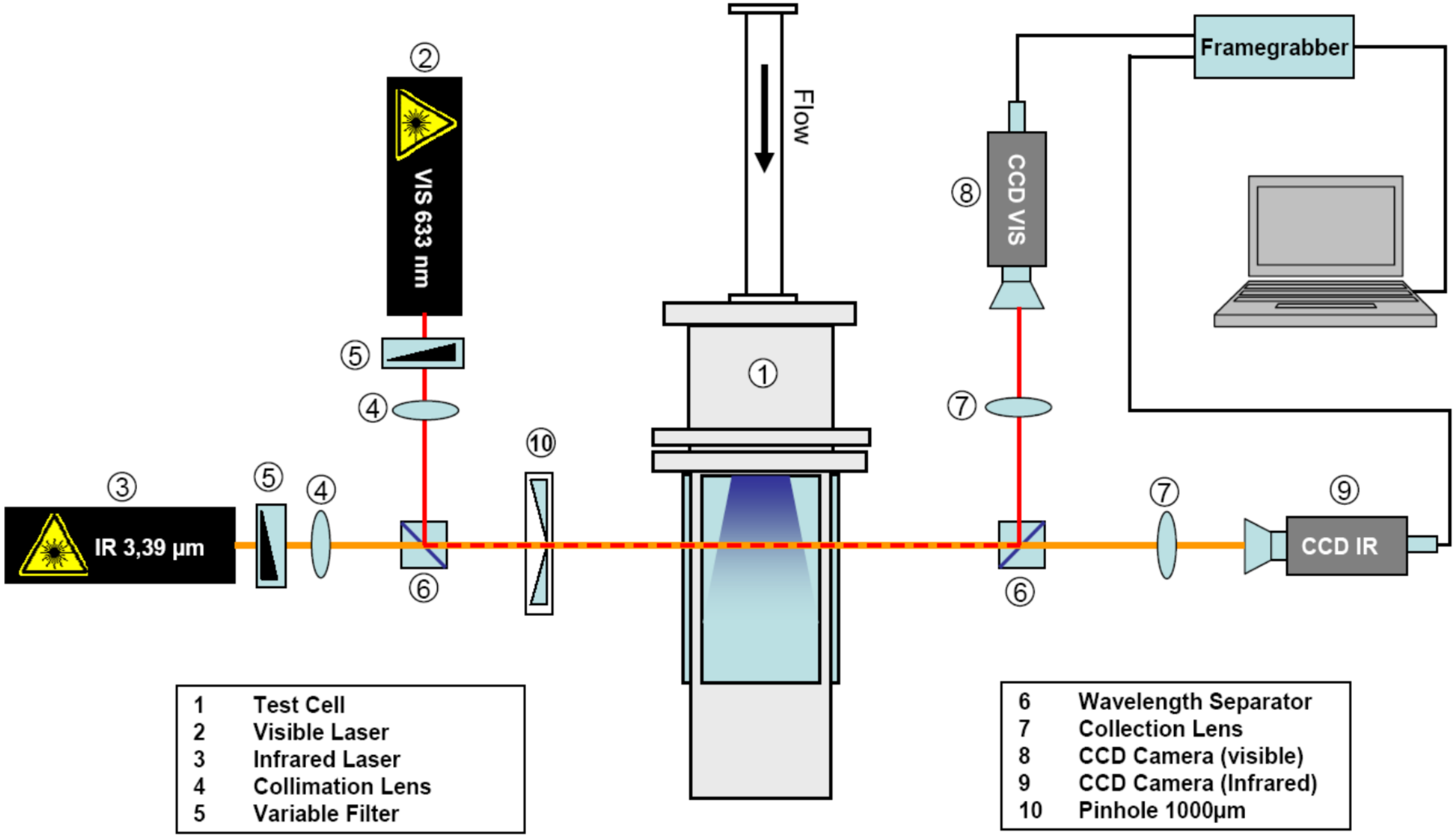






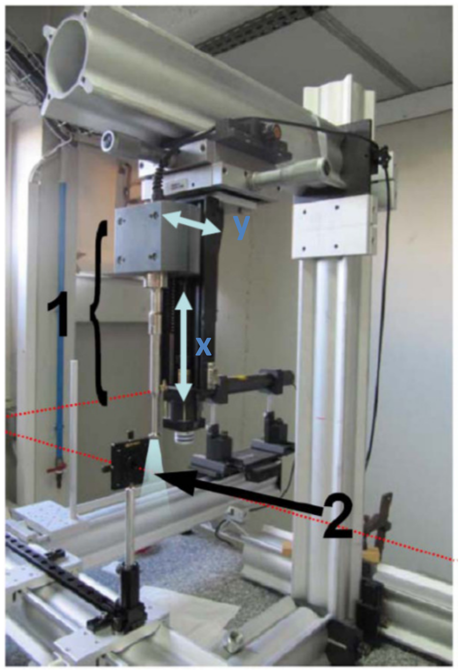
See the test session: CLICK HERE

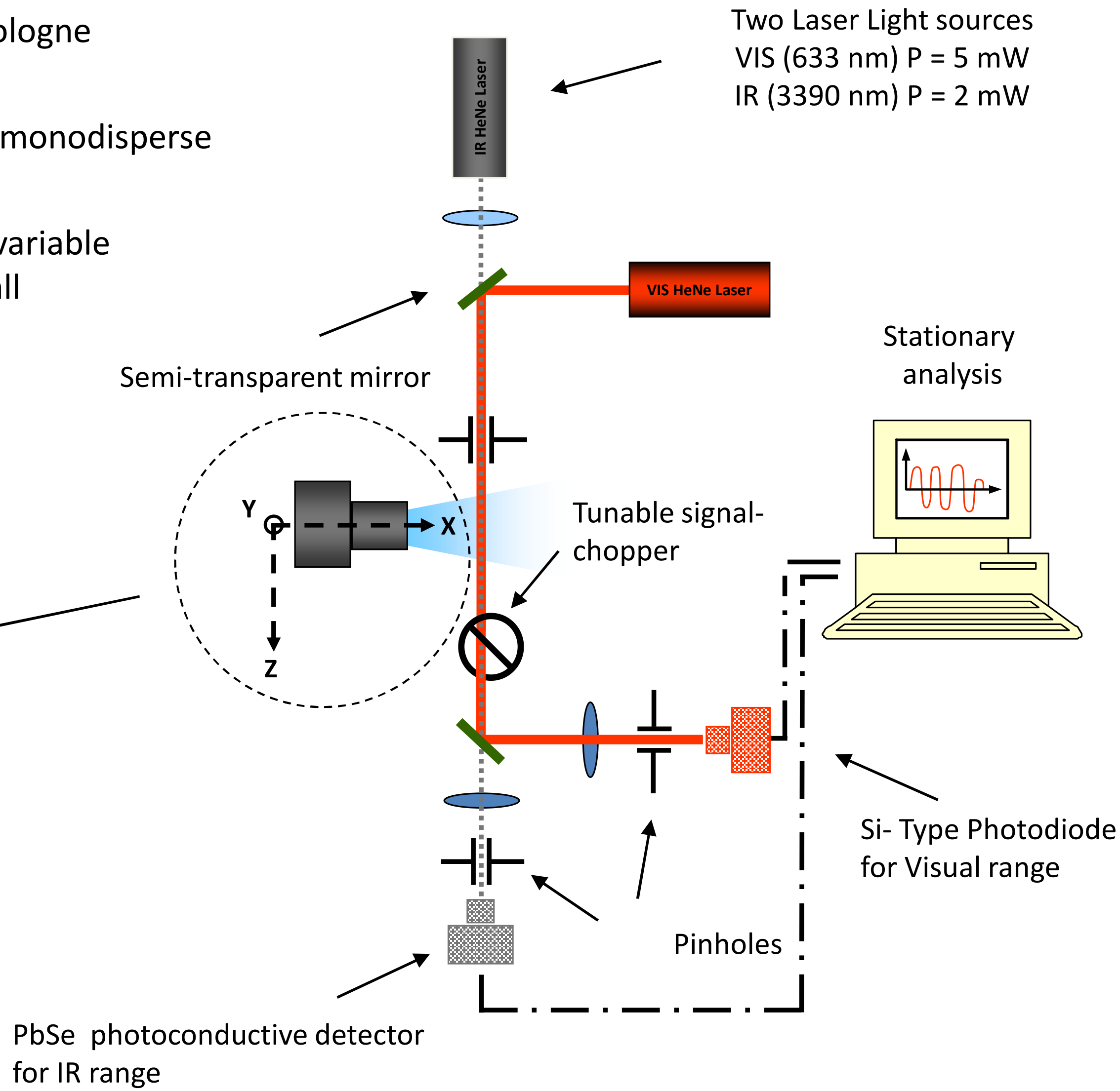
Measurement of fuel vapour contents: Infrared exctinction technique (IRE)



Validation of the measurement technique at ONERA

- Based on original setup used at DLR Cologne Hassa/Giuliani
- Investigation of fuel concentrations in monodisperse and polydisperse fuel sprays
- Labview based data acquisition tool / variable acquisition frequency and time intervall

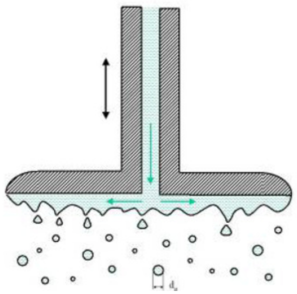




Validation of the measurement technique at ONERA

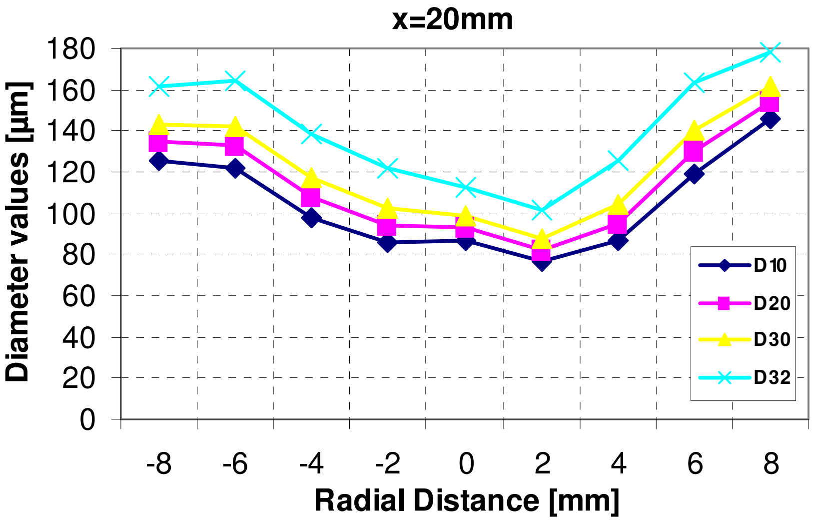
Injector:

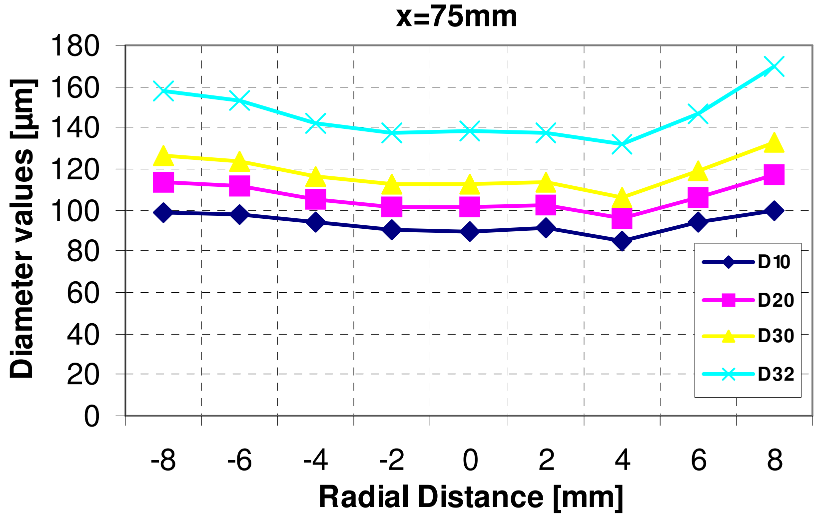
- Flat-tip-nozzle atomizer (Sonics USVC 130 AT) with piezoelectric ceramic to generate oscillations (20 kHz)
- Oscillations transferred to the liquid film cause wave pattern → critical amplitude, waves degenerate →droplets ejected
- Size distribution controlled by amplitude and massflow



Sonics ©

Mean values of droplet diameters n – octane 35 ml/min



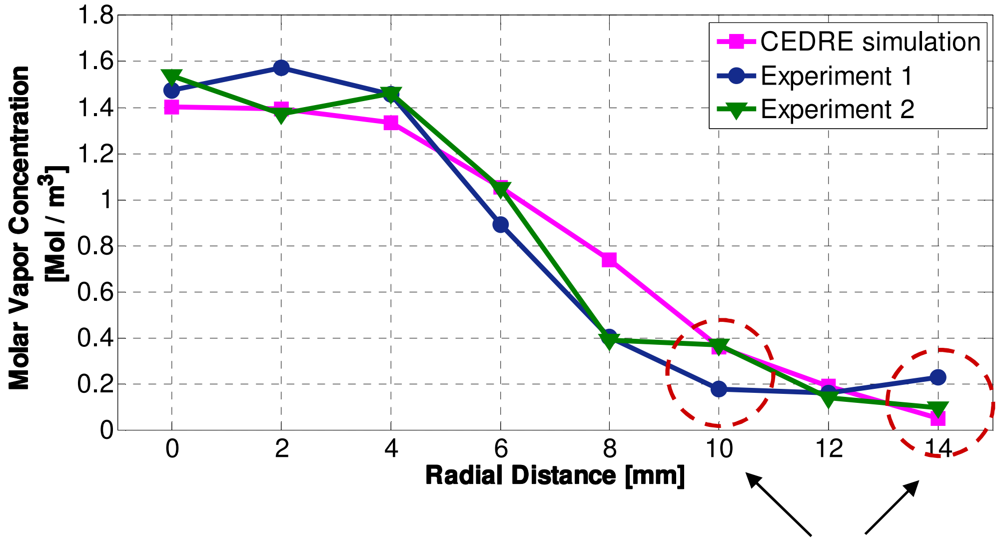


Validation of the measurement technique at ONERA

Spray Tests:

- Extinction measurement
- n-octane 60° C, 1.5 bar
- Atmospheric conditions
- Stable operation point at 35 ml/min mass flow
- Comparison with CEDRE Simulation results
- Injector is moved stepwise through coaxial laser beams (-20 - 20 mm radial distance from spray center)

Comparison of deconvoluted measurement results with simulation results



Good accordance except for point 10 and 14

Characterisation of chosen operating points

Flame dynamics

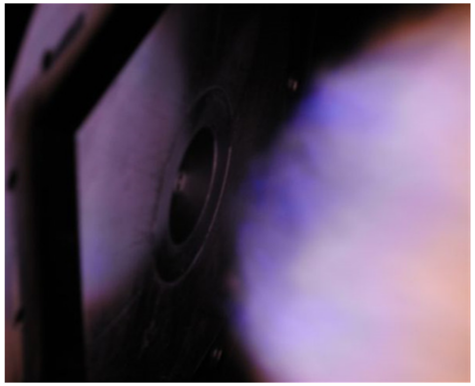
- Adressing to reduced mass flow rate WR = 0.3 at ambient conditions
- Free jet / Confined-Jet with ethanol

m_air = 6.08 g/s
v_ref = 7.16 m/s
m_eth = 1.2 g/s

attached flame

m_air = 11.3 g/s
v_ref = 13.4 m/s
m_eth = 1.2 g/s

transition



m_air = 12.69 g/s
v_ref = 14.96 m/s
m_eth = 1.2 g/s

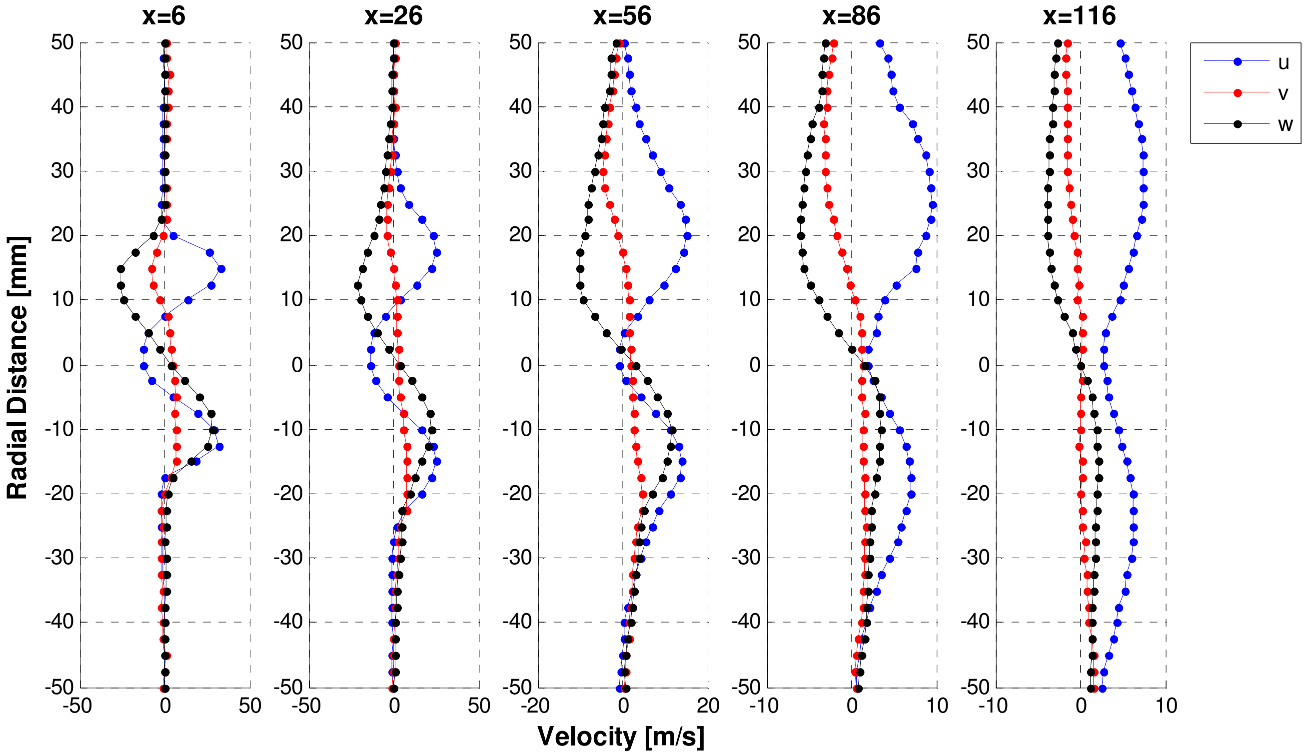
lifted

Characterisation of chosen operating points

Jet aerodynamics

- Two component LDA System (Dantec FiberFlow)
- Data Acquisition with BSA-Flow software
- Seeding with DEHS oil

S(D) = 0,74



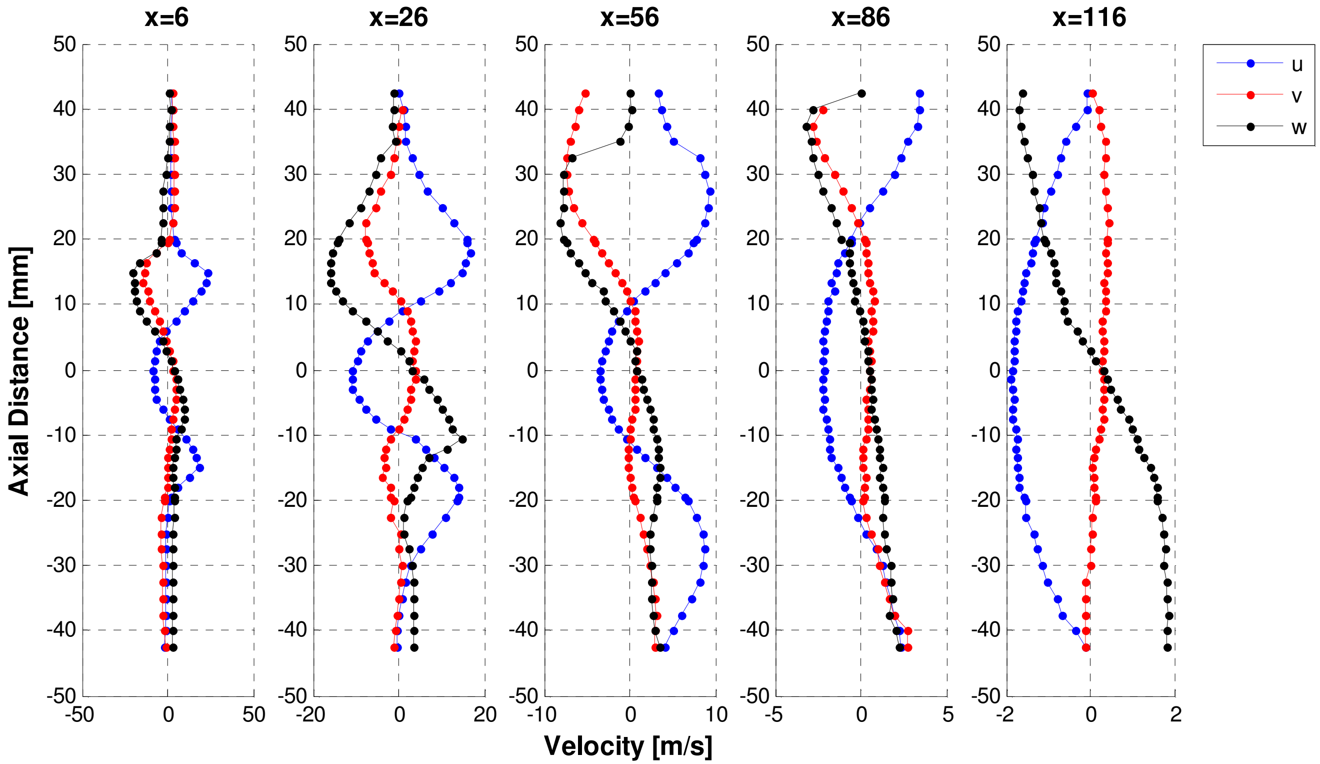
Radial-distribution of the velocity-components u, v, w free-jet configuration

Characterisation of chosen operating points

Jet aerodynamics

- Two component LDA System (Dantec FiberFlow)
- Data Acquisition with BSA-Flow software
- Seeding with DEHS oil

S(D) = 0,78



Radial-distribution of the velocity-components u, v, w confined-jet configuration

Conclusion an perspectives

- Technical decisions fullfilled
- Technical set-up constructed and operational
- Measurement technique validated
- Work in progress:
  - Comparison of the fuel evaporation (publication of the results October 2012)
  - Study on pollutant emissions while using replacement fuels for aviation

Thank you for your attention

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COMBUSTION BAY ONE

BACK UP

About COMBUSTION BAY ONE

FUNDAMENTAL RESEARCH

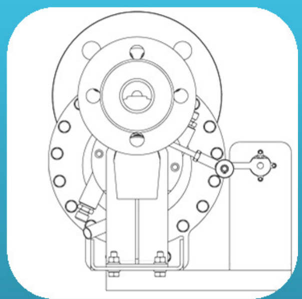
Key Competences developed at the Combustion Department, TU Graz, 2004-2011

APPLICATIONS

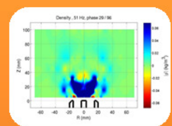
Advanced combustion management at Combustion Bay One

Combustion Bay One e.U. (2012)

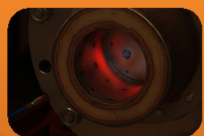
PRODUCTS



ENGINEERING



Tailored solutions



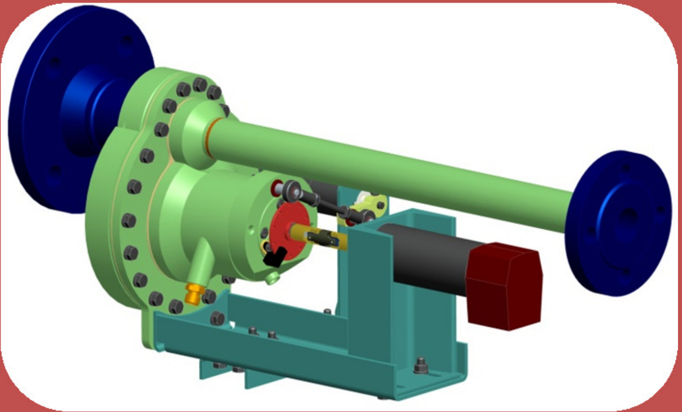
RESEARCH AND DEVELOPMENT

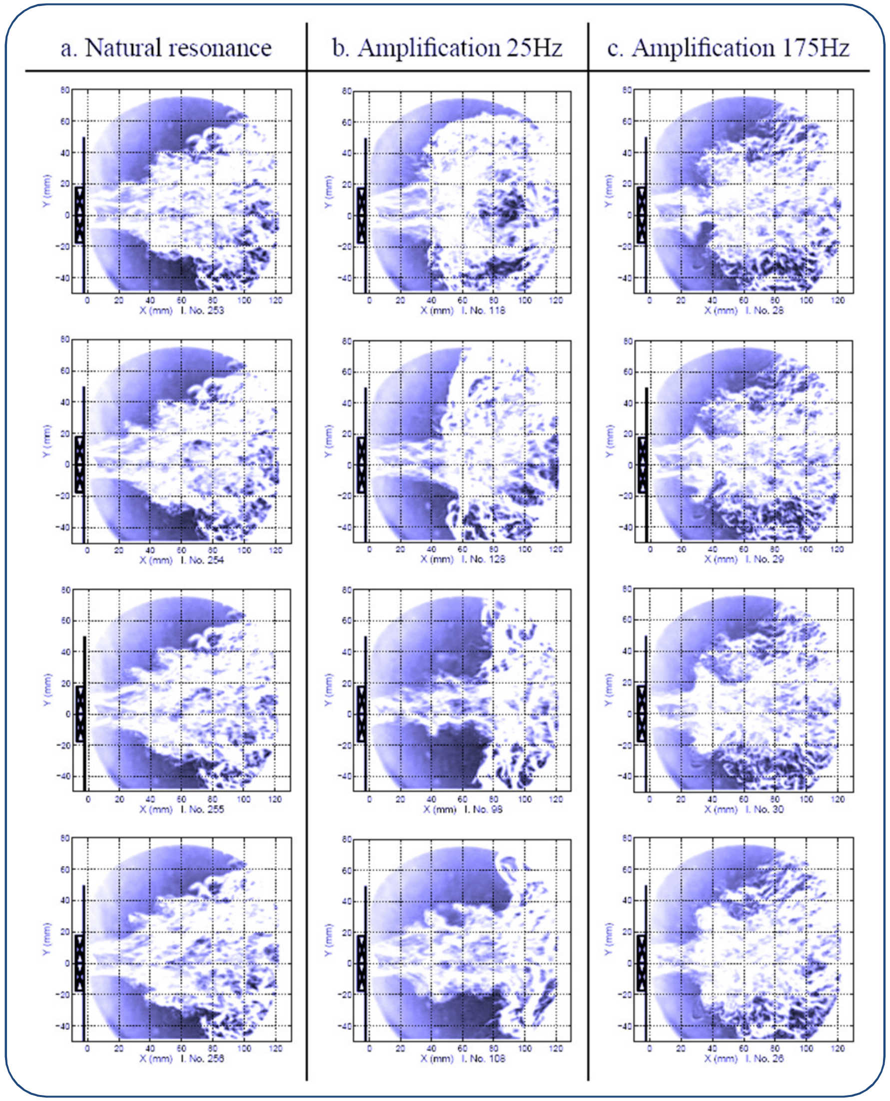
New sensors
New actuators
New burners

Innovation : testing the dynamic stability of burners

ACTUATOR FOR PRECISE AIR FEED FLOW MODULATION

- simulate combustion instability
- identify critical operation
- control flame dynamics





CBOne's panel

- Competences & expertise
  - Engineering for combustion test rigs
  - Low-emission burner design (gas &liquid fuel)
  - Flame diagnostic (sensing & advanced measurement techniques)
  - Flow control (actuation, quasi-static, dynamic)
  - Replacement fuels
  - Security & Norms

- Strong experience in:
  - Networking – good visibility in the combustion society
  - Litterature survey
  - Project planning
  - Design and construction of protypes
  - Combustor testing
  - Data Mining
  - Modelling
  - Dissemination

Market

Gas turbines for aviation

Gas turbines for power

Aerospace combustion laboratories

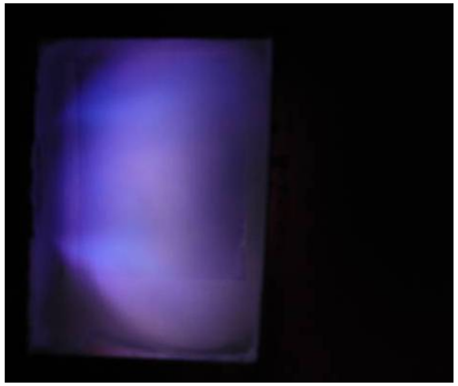
Heavy industry applications

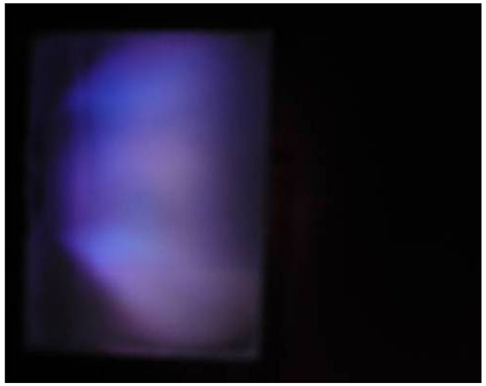
- Fuel consumption and emissions in thermal processes
- Technology „from the air to the ground" and vice-versa

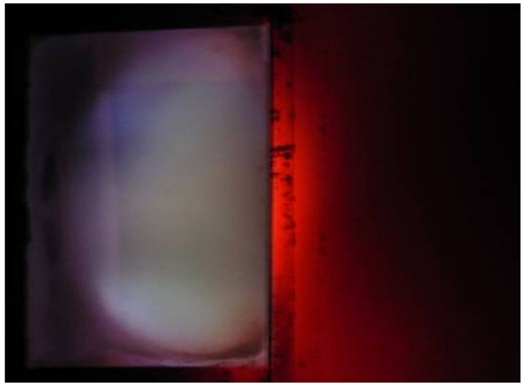
Preliminary tests

Verification of chosen operating points by combustion test and LDA measurements:

- Adressing to reduced mass flow rate WR = 0.3 at ambient conditions
- Freejet / Confined-Jet with ethanol







m_air = 10.42 g/s
v_ref = 12.2 m/s
m_eth = 0.87 g/s

m_air = 13.5 g/s
v_ref = 15.9 m/s
m_eth = 0.87 g/s

m_air = 13.67 g/s
v_ref = 16.12 m/s
m_eth = 0.87 g/s

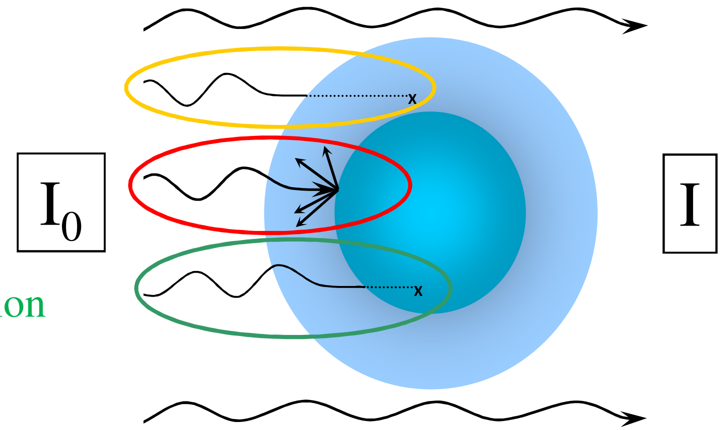
Constant flame profile attached at outer injector diameter

Expansion of the BBL for 2-phase flow:

$$\left(\frac{\bar{I}_{(x)}}{I_0}\right)_{\lambda_{abs}} = \exp\left[-\bar{C}_n \cdot l \cdot \frac{\pi}{4} \cdot \int_0^\infty Q_{sca} \cdot D^2 \cdot N(D) \cdot dD\right] \quad \text{Scattering}$$

$$\cdot \exp\left[-\bar{C}_n \cdot l \cdot \frac{\pi}{4} \cdot \int_0^\infty Q_{abs} \cdot D^2 \cdot N(D) \cdot dD\right] \quad \text{Liquid absorption}$$

$$\cdot \exp\left[-\int_0^l \alpha_{(\lambda,p,T)} \cdot c_{m(x)} \cdot dx\right] \quad \text{Vapor absorption}$$



Dependent on: Averaged number density C_n [m^{-2}], drop diameter distribution N(D) and absorption/scattering efficiencies Q_{sca} and Q_{abs}

N(D) → laser diffraction technique
Q_{sca}/Q_{abs} → Mie calculations
C_n → non-absorbing wavelength

2 extinction measurements,
1 diffraction measurement and
2 calculations to determine c_m !!

Definition of the optical thickness of the droplets « t »

$$\left(\frac{\bar{I}_{(x)}}{I_0}\right)_{\lambda_{abs}} = \exp\left[-\underbrace{\bar{C}_n \cdot l \cdot \frac{\pi}{4} \cdot \int_0^\infty Q_{sca} \cdot D^2 \cdot N(D) \cdot dD\right] \cdot \exp\left[-\bar{C}_n \cdot l \cdot \frac{\pi}{4} \cdot \int_0^\infty Q_{abs} \cdot D^2 \cdot N(D) \cdot dD}_{\tau_{ABS}}\right] \cdot \exp\left[-\int_0^l \alpha_{(\lambda,p,T)} \cdot c_{m(x)} \cdot dx\right]$$

Absorbing wavelength

$$\tau_{ABS} = \bar{C}_n \cdot l \cdot \frac{\pi}{4} \cdot \int_0^\infty Q_{ext} \cdot D^2 \cdot \bar{N}(D) \cdot dD$$

$$Q_{ext} = Q_{abs} + Q_{sca}$$

Resulting expression for the concentration

$$\Longrightarrow \boxed{\bar{c}_{m_{(x)}} = \frac{1}{\alpha \cdot l}\left[-\tau_{ABS} - \ln\left(\frac{\bar{I}_{(x)}}{I_0}\right)_{\lambda_{ABS}}\right]}$$

Source: Drallmeier 1994

Non-absorbing wavelength

$$\tau_{NA} = \overline{C}_n \cdot l \cdot \frac{\pi}{4} \cdot \int_0^{\infty} Q_{sca} \cdot D^2 \cdot N(D) \cdot dD = \ln\left(\frac{I}{I_0}\right)_{NA}$$

<u>Introduction of both wavelengths:</u>

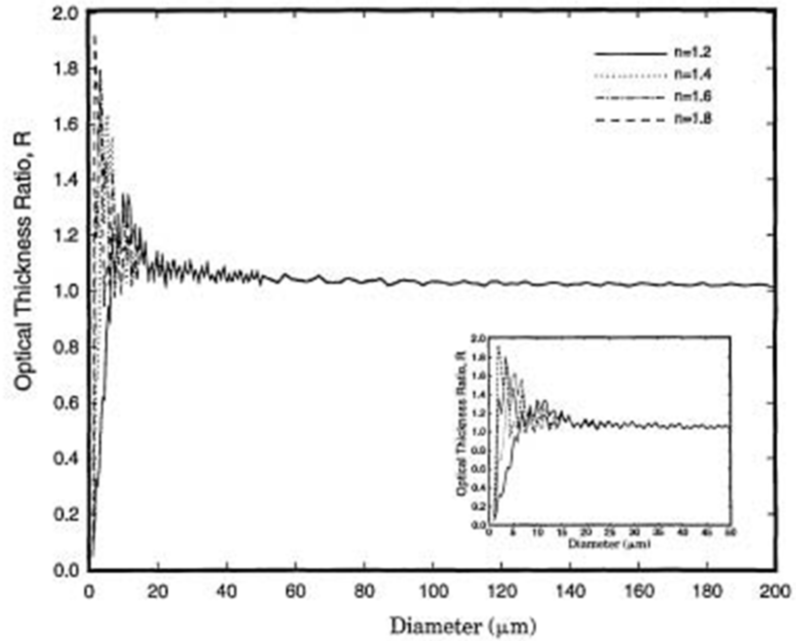
$$\overline{c}_m = \frac{1}{\alpha \cdot l}\left[-\tau_{NA}\left(\frac{\tau_{ABS}}{\tau_{NA}}\right) - \ln\left(\frac{I}{I_0}\right)_{ABS}\right]$$

$$= \frac{1}{\alpha \cdot l}\left[-\ln\left(\frac{I}{I_0}\right)_{NA} R - \ln\left(\frac{I}{I_0}\right)_{ABS}\right]$$

R … optical thickness ratio

If the $D_{20} > 30\mu m$ the concentration can be obtained from two simultaneous absorption measurements only! (accepting a 10% error)

Calculation of R for several refractive indices



Source: Drallmeier 1994

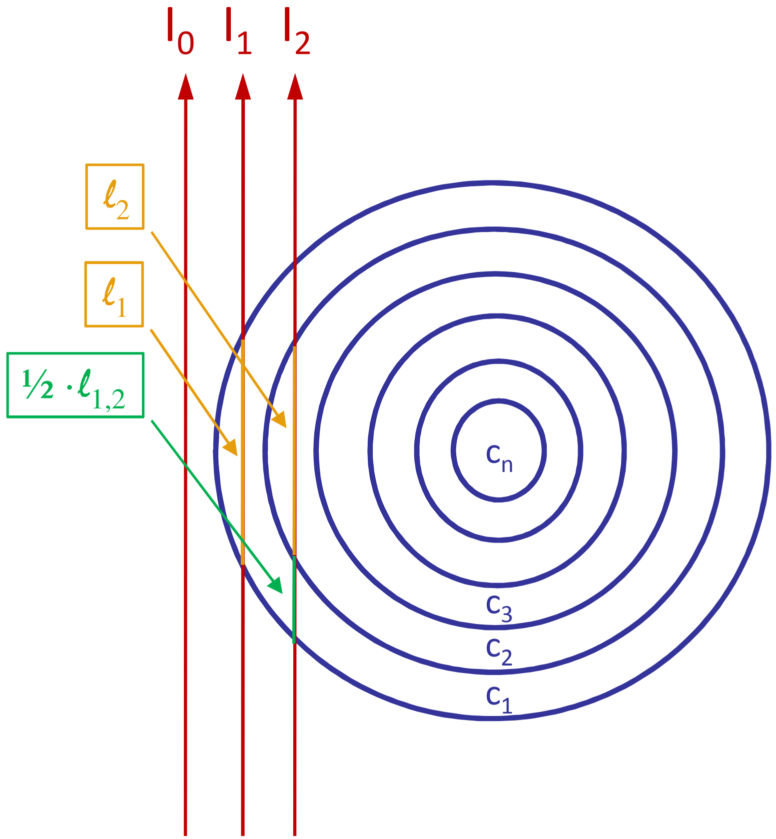
For infrared extinction on sprays a matrix-based Abel inversion for axisymmetric geometries is often employed
(Hammond 1980, Chraplyvy 1981, Drallmeier 1994)

$$c_{m-1} = -\frac{1}{l_1 \cdot \alpha} \cdot \ln \frac{I_1}{I_0}$$

$$c_{m-2} = -\frac{1}{l_2 \cdot \alpha} \cdot \left(\ln \frac{I_2}{I_0} + \alpha \cdot l_{1,2} \cdot c_{m-1} \right)$$

$$\vdots$$

$$c_{m-n} = -\frac{1}{l_n \cdot \alpha} \cdot \left(\ln \frac{I_n}{I_0} + \sum_{i=1}^{n-1} \alpha \cdot l_{i,n} \cdot c_{m-i} \right)$$



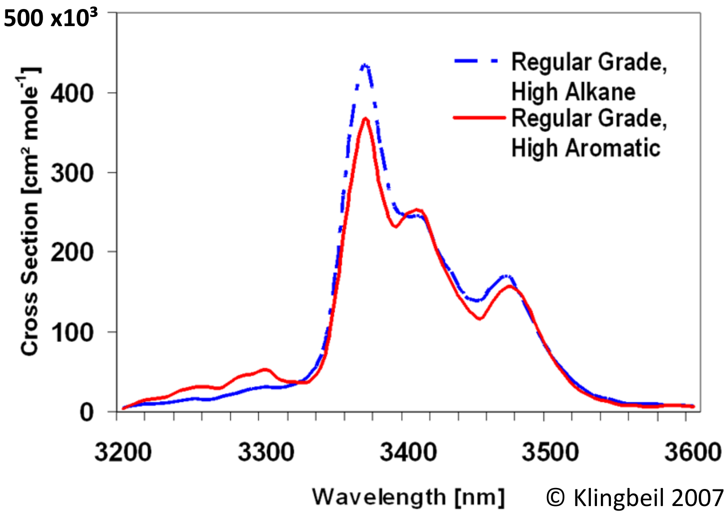
$\Rightarrow$ System of n equations for n unknown concentrations

Technical fundamentals

Principle of infrared absorption:

- Line of sight non intrusive laser method
- Comparison of in-line extinction of visible light [633 nm (non-absorbing wavelength)] with IR light [3390 nm (absorbing wavelength)]
- Relative fuel vapor concentration in two phase flow (derived from Beer-Bouguer-Lambert law)
- Line-of-sight integral concentration measurement → deconvolution technique (Abel transform)

Absorption Spectrum of Gasoline



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Simplified Beer-Bouguer-Lambert law

$$\bar{c}_m = \frac{1}{\alpha_{IR} L} \ln\left(\frac{\left(I/I_0 \right)_{VIS}}{\left(I/I_0 \right)_{IR}} \right)$$

$\bar{c}_m$	Integral Vapor Concentration
α_{IR}	Absorption Coefficient
L	Length of Laser Penetration
λ_{abs} and λ_{na}	Absorbing and Non-absorbing Wavelength

Technical fundamentals

Beer-Bouguer-Lambert law

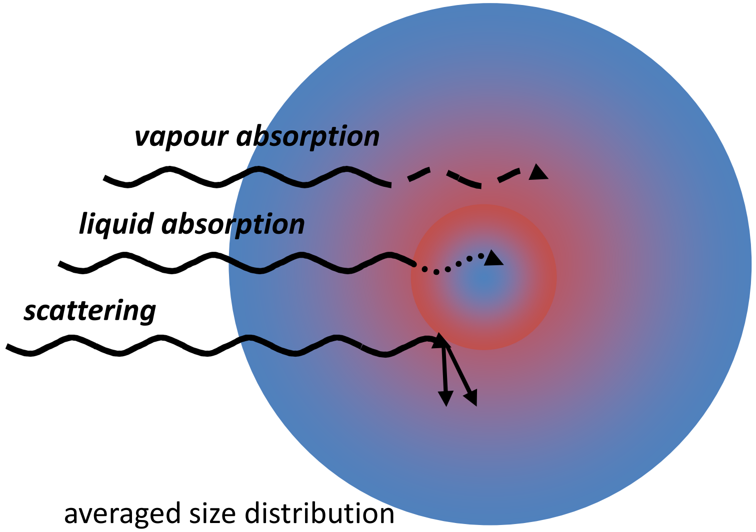
$$\frac{\bar{I}(x)}{I_0} = e^{-\int_0^L \alpha(\lambda,p,T)\cdot c_m(x)\cdot dx}$$

Extended Beer-Bouguer-Lambert law for absorbing wavelength

$$\left(\frac{\bar{I}_{(x)}}{I_0}\right)_{\lambda_{abs}} = \exp\left(-\bar{C}_n \cdot L \cdot \frac{\pi}{4} \cdot \int_0^\infty Q_{sca} \cdot D^2 \cdot N(D) \cdot dD\right) \quad \textit{scattering}$$

$$\cdot \exp\left(-\bar{C}_n \cdot L \cdot \frac{\pi}{4} \cdot \int_0^\infty Q_{abs} \cdot D^2 \cdot N(D) \cdot dD\right) \quad \textit{liquid absorption}$$

$$\cdot \exp\left(-\int_0^l \alpha_{(\lambda,p,T)} \cdot c_{m(x)} \cdot dx\right) \quad \textit{vapor absorption}$$



averaged size distribution

N(D) → **laser diffraction technique**

Q_{sca}/Q_{abs} → **Mie-scattering calculations**

C_n → **non-absorbing wavelength**

averaged number density

2 extinction measurements,
1 diffraction measurement and
2 calculations to determine c_m

Technical fundamentals

Simplification:

Hypothesis

- If line-of-site extinction due to Mie-scattering for both wavelengths is similar because of the presence of the spray only IR light will be absorbed by fuel vapor
- Comparison of the line of sight intensities I_{IR} / I_{0IR} , I_{VIS} / I_{0VIS} → estimation of vapor concentration

Beer-Bouguer-Lambert law for Non-Absorbing Wavelength

$$\left(\frac{I}{I_0}\right)_{\lambda_{NA}} = \exp\left(\overline{C}_n \cdot L \cdot \frac{\pi}{4} \cdot \int_0^{\infty} Q_{sca} \cdot D^2 \cdot N(D) \cdot dD\right)$$

Reformulation of the BBL law

Optical thickness τ_{abs}

$$\left(\frac{\overline{I}_{(x)}}{I_0}\right)_{\lambda_{abs}} = \exp\left(-\overline{C}_n \cdot L \cdot \frac{\pi}{4} \cdot \int_0^{\infty} Q_{sca} \cdot D^2 \cdot N(D) \cdot dD\right)$$

$$\cdot \exp\left(-\overline{C}_n \cdot L \cdot \frac{\pi}{4} \cdot \int_0^{\infty} Q_{abs} \cdot D^2 \cdot N(D) \cdot dD\right)$$

$$\cdot \exp\left(-\int_0^{l} \alpha_{(\lambda,p,T)} \cdot c_{m(x)} \cdot dx\right)$$

$$Q_{ext} = Q_{abs} + Q_{sca}$$

$$\tau_{ABS} = \overline{C}_n \cdot L \cdot \frac{\pi}{4} \cdot \int_0^{\infty} Q_{ext} \cdot D^2 \cdot \overline{N}(D) \cdot dD$$

$$\overline{c}_m(x) = \frac{1}{\alpha \cdot L}\left(-\tau_{ABS} - \ln\left(\frac{\overline{I}_{(x)}}{I_0}\right)_{\lambda_{ABS}}\right)$$

Source: Drallmeier 1994

Technical fundamentals

Optical thickness τ_{na}

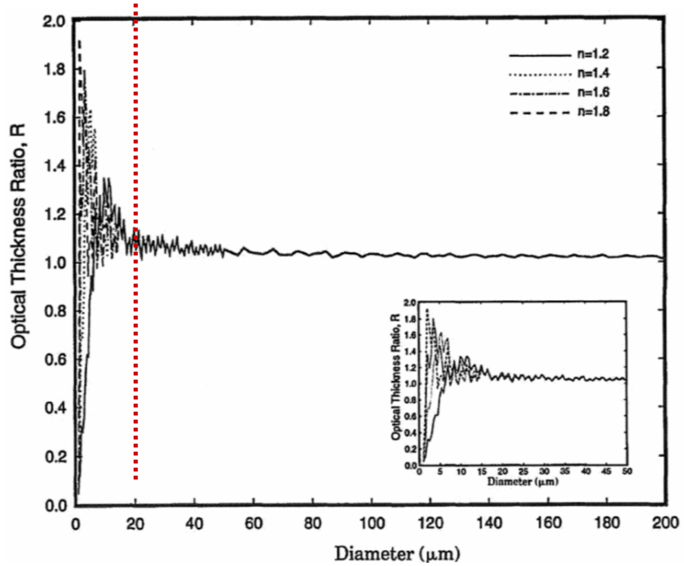
$$\tau_{NA} = \overline{C}_n \cdot L \cdot \frac{\pi}{4} \cdot \int_0^\infty Q_{sca} \cdot D^2 \cdot N(D) \cdot dD = \ln\left(\frac{I}{I_0}\right)_{NA}$$

Introduction of both wavelengths:

$$\overline{c}_m = \frac{1}{\alpha \cdot L}\left[-\tau_{NA}\left(\frac{\tau_{ABS}}{\tau_{NA}}\right) - \ln\left(\frac{I}{I_0}\right)_{ABS}\right]$$
$$= \frac{1}{\alpha \cdot L}\left[-\ln\left(\frac{I}{I_0}\right)_{NA} \cdot R - \ln\left(\frac{I}{I_0}\right)_{ABS}\right]$$

R … optical thickness ratio

Calculation of R for variation of liquid phase complex refractive index



If the D_{20} > 20 µm the concentration can be obtained from two simultaneous absorption measurements only (taking a 10% error into account)

Source: Drallmeier 1994

Technical fundamentals

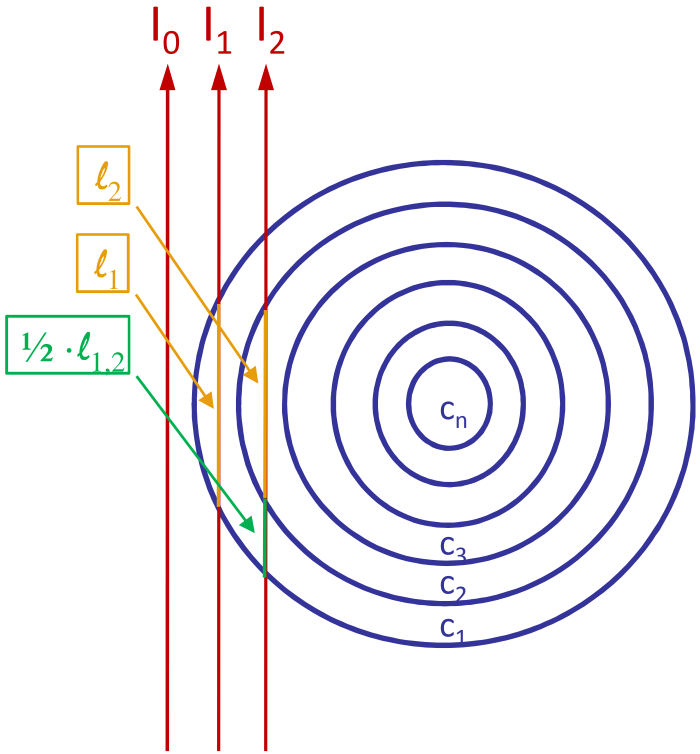
- Line-of-sight integrated measurements → deconvolution technique necessary
- For infrared extinction on sprays a matrix-based Abel inversion for axisymmetric geometries is often employed
  (Hammond 1980, Chraplyvy 1981, Drallmeier 1994)

$$c_{m-1} = -\frac{1}{l_1 \cdot \alpha} \cdot \ln \frac{I_1}{I_0}$$

$$c_{m-2} = -\frac{1}{l_2 \cdot \alpha} \cdot \left(\ln \frac{I_2}{I_0} + \alpha \cdot l_{1,2} \cdot c_{m-1} \right)$$

$$\vdots$$

$$c_{m-n} = -\frac{1}{l_n \cdot \alpha} \cdot \left(\ln \frac{I_n}{I_0} + \sum_{i=1}^{n-1} \alpha \cdot l_{i,n} \cdot c_{m-i} \right)$$



→ System of n equations for n unknown concentrations