Chapter 2: Benchmark Experiments

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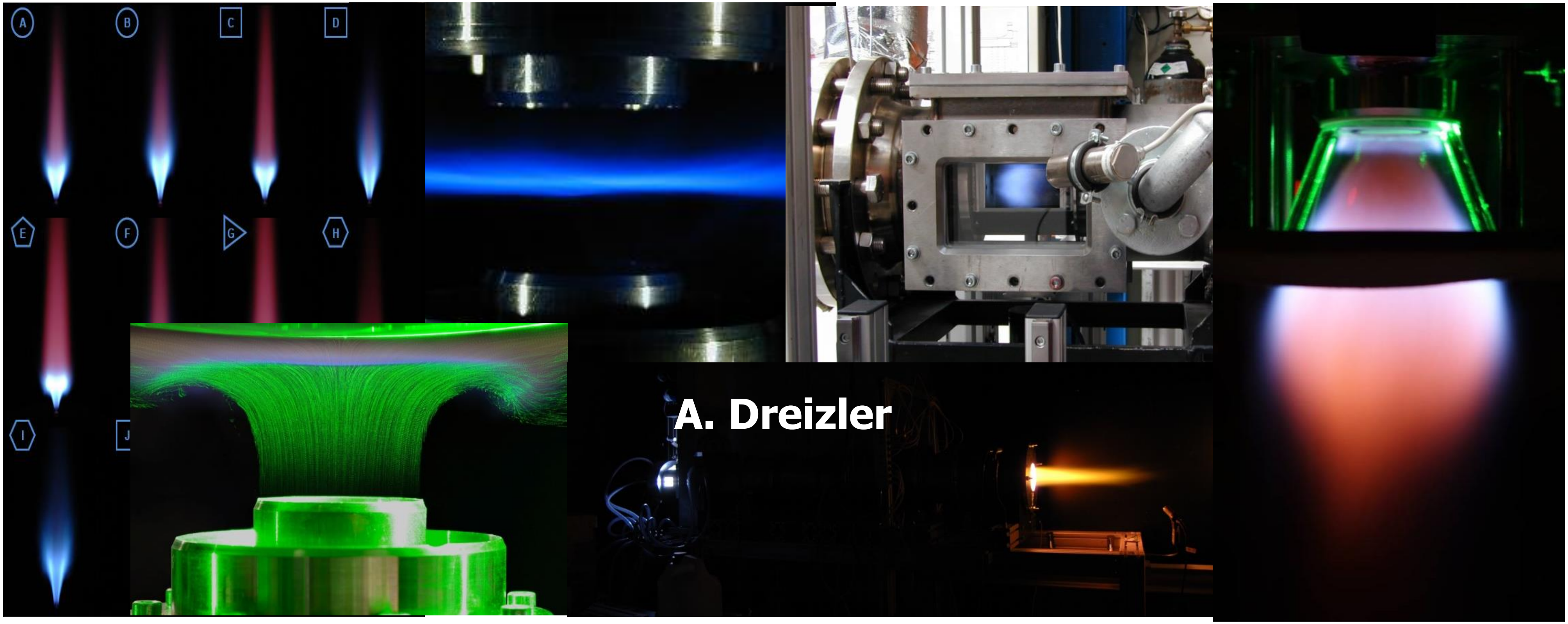
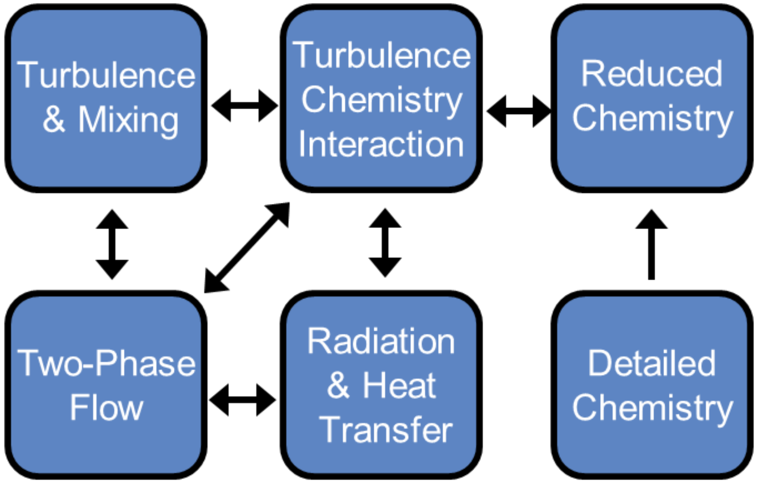


A. Dreizler

Validation of numerical simulations

- Experimental research in turbulent flames needs suitable generic combustion systems
- Numerical simulations are based on models
  - Turbulence model
  - Combustion model
  - Turbulence-chemistry interaction model
  - Spray model …

Holistic Model:
Composed of sub-models
and mutual interactions



Dreizler, Janicka. “Applied Combustion Diagnostics”, edited by K. Kohse-Höinghaus and Jay Jeffries, Francis and Taylor, New York (2002)

Validation of numerical simulations

- Experimental research in turbulent flames needs suitable generic combustion systems
- Numerical simulations are based on models
  - Turbulence model
  - Combustion model
  - Turbulence-chemistry interaction model
  - Spray model …

  →Comprehensive and reliable data sets for **validation** and improved understanding are a prerequisite

  →(Quantitative) Experiments in Combustion

→Need for suitable **benchmark experiments** mimicking specific aspects of real-world combustion systems

Dreizler, Janicka. “Applied Combustion Diagnostics”, edited by K. Kohse-Höinghaus and Jay Jeffries, Francis and Taylor, New York (2002)

Bench mark flames/ configurations

- **Requirements for optical diagnostics**
  - Optical access from three sides to enable application of different laser diagnostics
  - Nozzle exit accessible, such that radial profiles can be recorded as close as possible (~1mm)
  - Optical access to interior of nozzle (if possible)
  - In case of atmospheric flames shielding from the lab (co-flowing air)
  - Decoupling of the flame from the exhaust gas system
  - Fuel composition that does not interfere with the laser/ detection wavelength

Bench mark flames/ configurations

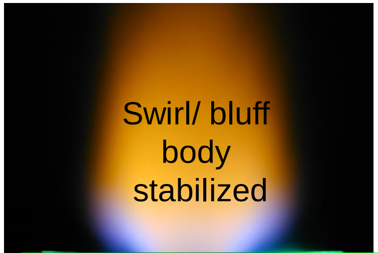
- **Requirements for validation of numerical simulations**
  - Known or measurable inflow conditions
  - Well-defined boundary conditions
  - Parametric variation (“flame sequence”) of key-quantities such as
    - Fuel composition, equivalence ratio
    - Reynolds-number, thermal load
    - Swirl intensity
    - Pressure
    - Geometry

    → **Identify sensitivities**

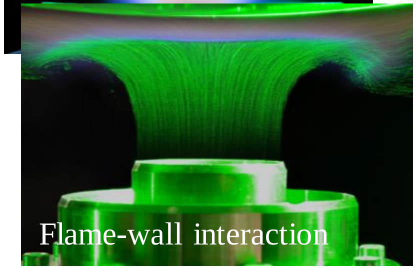
From simple to complex – benchmark configurations at TUD

Turbulent opposed jets

Fuel stratified jets, flame propagation



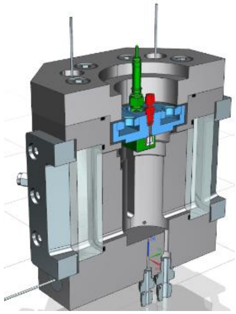
Swirl/ bluff body stabilized



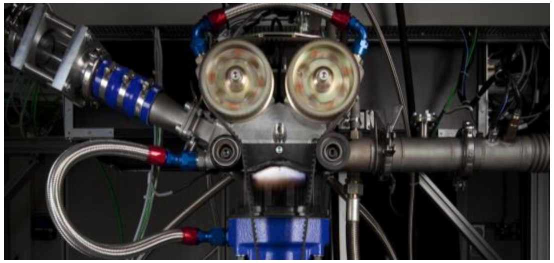
Flame-wall interaction

Auto ignition rig

Complexity

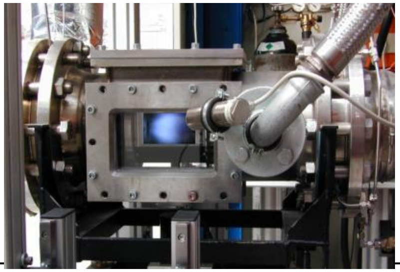


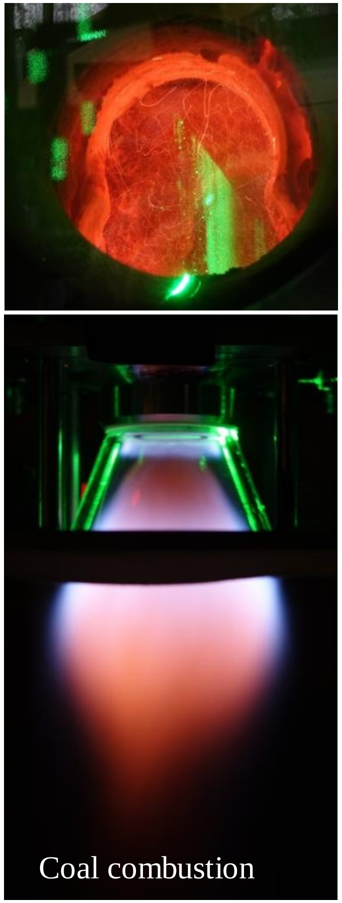
Supercritical droplets and droplet combustion



Transparent IC engine

Enclosed combustor/ GT conditions

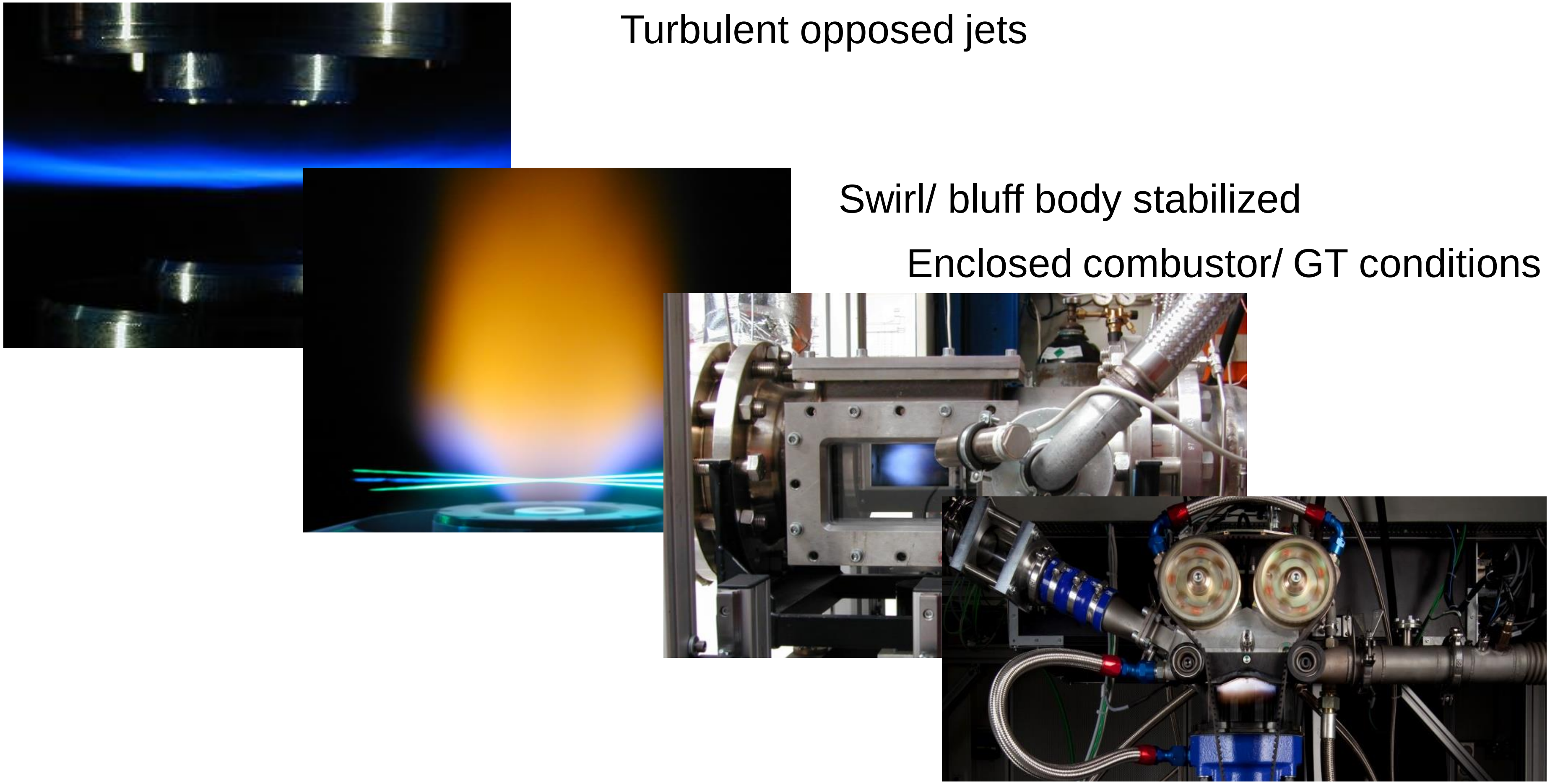




Coal combustion

Bench mark configurations

- **3 Examples of bench mark flames**
- **1 Example of optically accessible IC-engine**



Turbulent opposed jets

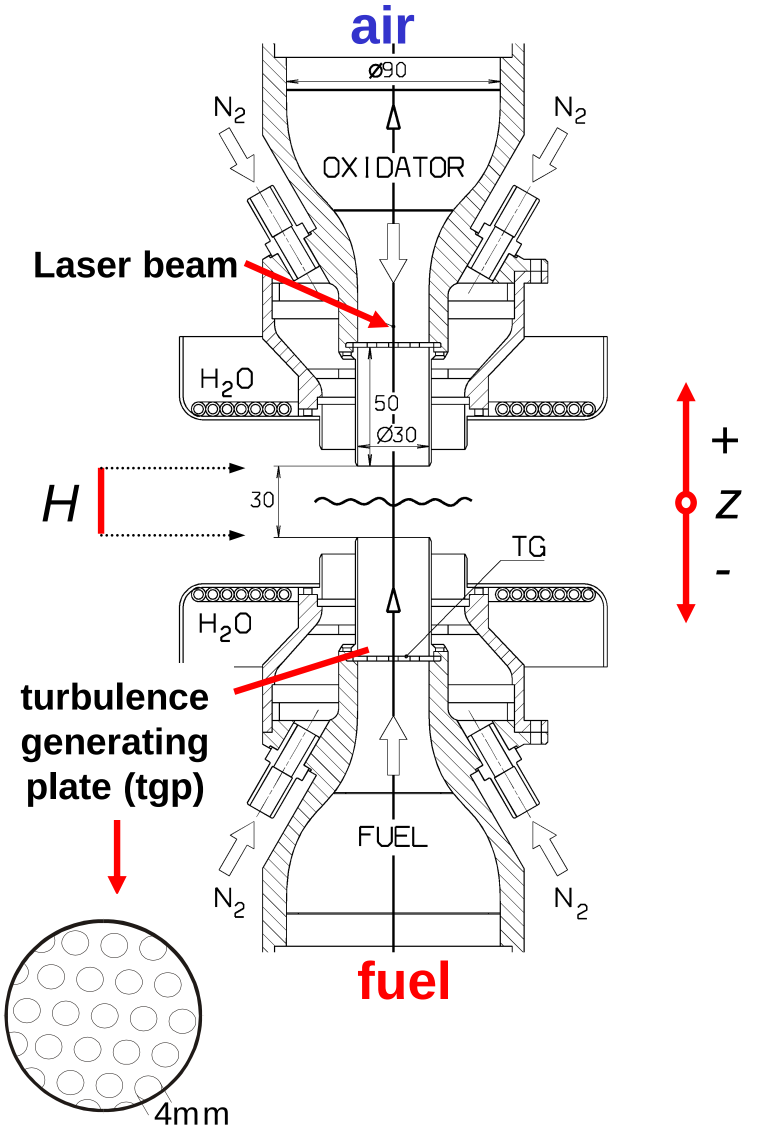
Swirl/ bluff body stabilized

Enclosed combustor/ GT conditions

Transparent IC engine

Example 1: Turbulent opposed jet flame

- Two identical opposed nozzles, D=H=30mm
- Turbulence intensity ~0.07 at nozzle exit, enhanced by turb. grid (tgp)
- N_2 coflow prevents ambient air mixing
- Access laser beam along burner axis → no beam steering
- Horizontal stagnation plane → symmetric influence of gravity
- Water cooling for stable long term operation
- **Parametric variation**
  - Fuel composition
  - Reynolds-No. (<u>stable to extinction</u>)



Geyer et int. Dreizler. CNF (2005) 143:524 – 548

Turbulent opposed jet flame

- “Flame sequence” → Variation of fuel composition and Re
- Fuel: partially premixed methane/air (avoiding soot)

	Re_{air}	a_m(1/s)	Φ = 3.18	Φ = 2.0	Φ = 1.6	Φ = 1.2
	3300	115	TOJ1A			
	4500	158	TOJ1B	TOJ2B	TOJ3B	TOJ4B
	5000	175	TOJ1C	TOJ2C		
	6650	235	TOJ1D	TOJ2D		
Extinction limit	7200	255		TOJ2E		

Turbulent opposed jet flame

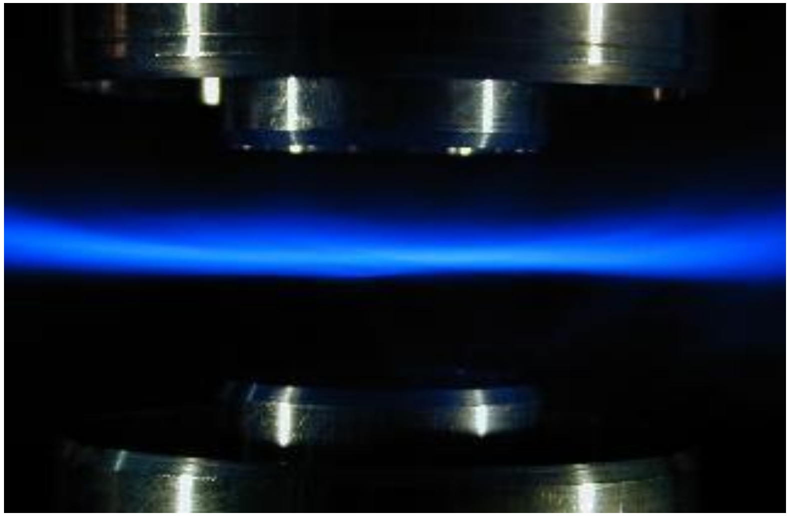
- Flow field quantities for TOJ2D

Bulk velocity W_b	3.4m/s
Turbulent Re-number Re_t	90
Bulk strain rate $a_b = \left(-W_{b,O} + W_{b,F}\right)/H$	$231 s^{-1}$
Residence time in mixing layers $t_{res} = a_b^{-1}$	4.3ms
Large-eddy turnover time $t_{ov} = l_0/(2k)^{1/2}$	16.2ms
Integral time scale T at nozzle exit	1.6ms
Integral length scale l_0 at nozzle exit	4.7mm
Kolmogorov length scale η_K at nozzle exit	0.16mm
Batchelor scale at nozzle exit η_c	0.18mm

Turbulent opposed jet flame

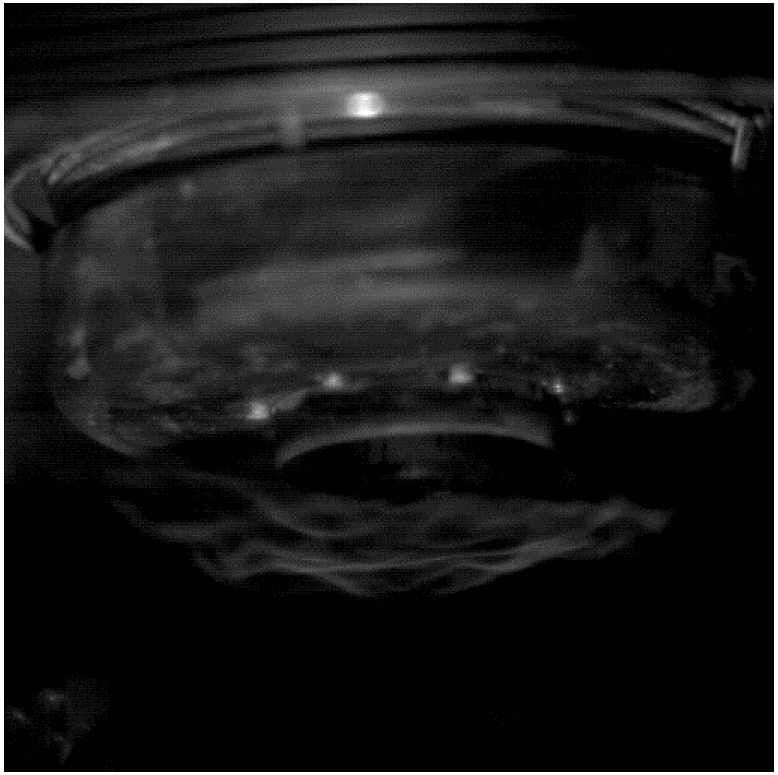
- **Visual impression**

Time-averaged flame luminosity



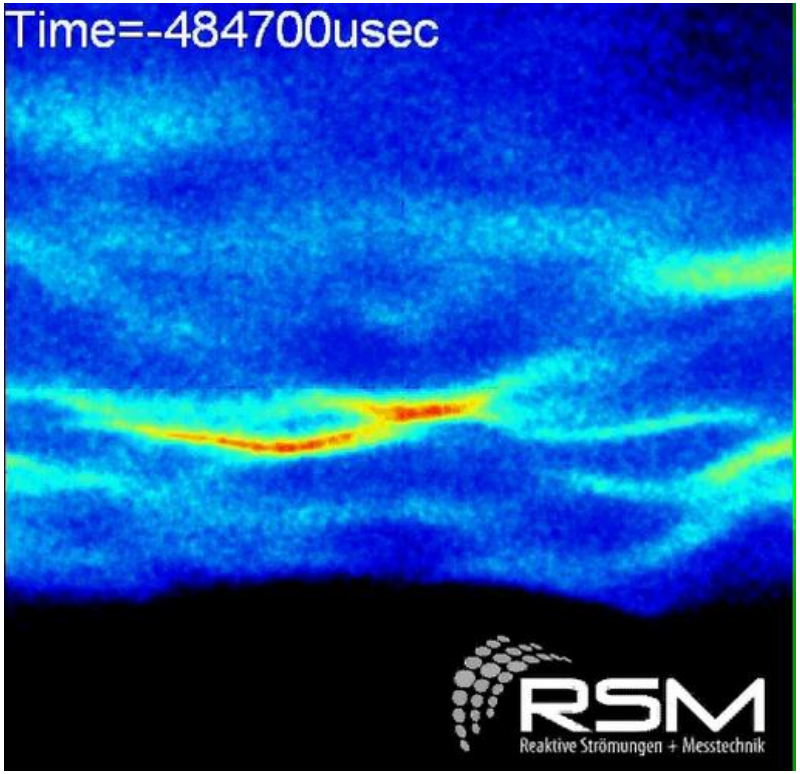
Transient flame luminosity

@ 500 Hz



Turbulent opposed jet flame

- Special feature of turbulent opposed jet flames:
  - Investigation of flame extinction by increasing strain close to critical value
  - Extinction monitored by temporally resolved chemiluminescence, **10 kHz**



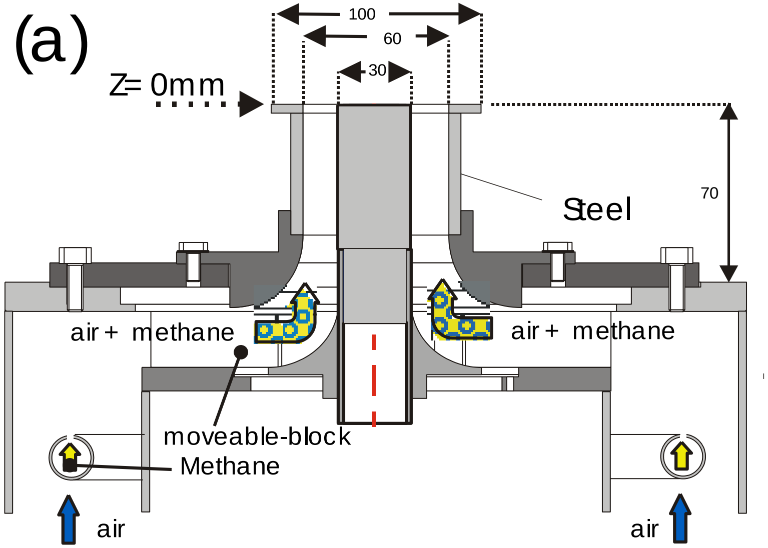
Bench mark configurations

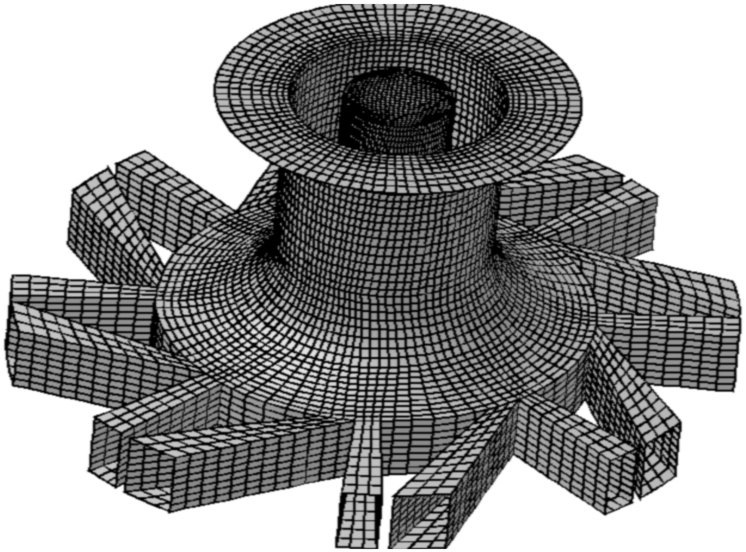
- **Example 2: Swirling lean premixed flame**
  - Relevant for flame stabilization in real combustors
  - Complex chemistry and complex flow field properties

Swirling lean premixed flame

- **Nozzle closer to practical applications**
- **Need for reliable data sets of premixed flames**
- **Parametric variation of**
  - Reynolds number
  - Swirl number
  - Equivalence ratio

(a)





Schneider et int. Dreizler. Flow Turbulence and Combustion (2005) 74:103 – 127

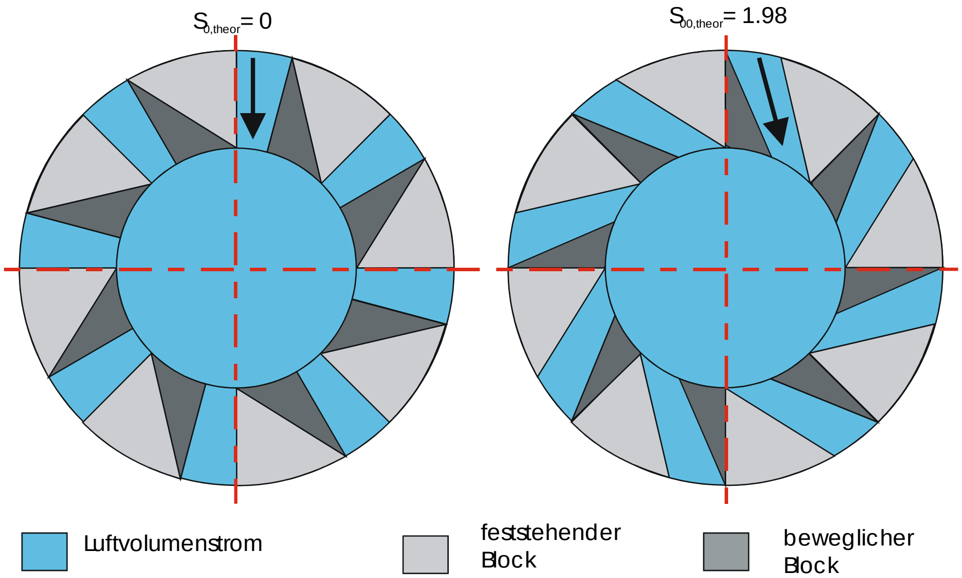
Swirling lean premixed flame

- **Swirl number**

$$S = \frac{G_\theta}{\frac{d}{2} \cdot G_x}$$

G_θ	Axial flux of tangential momentum
G_x	Axial flux of axial momentum

- **Variation by moveable block (motor driven, gear reduction)**



Swirling lean premixed flame

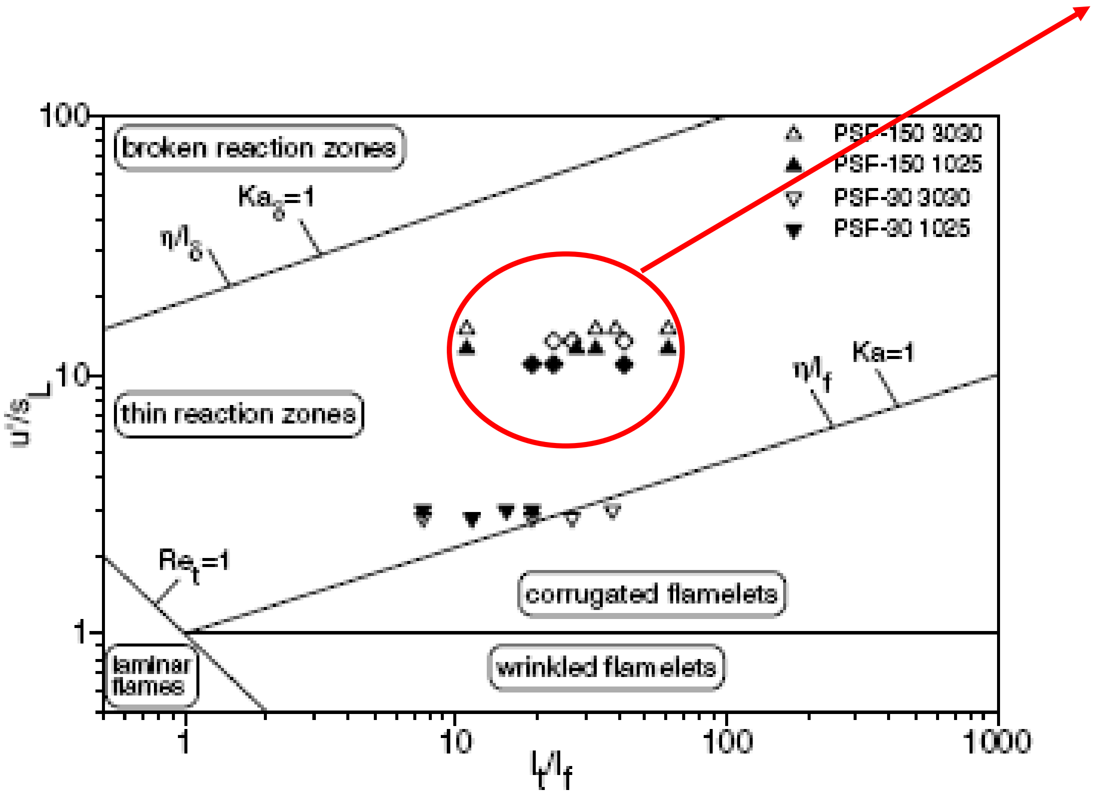
- **Parametric variation: Re**

		PSF-30	***PSF-90***	***PSF-150***
$S_{0,th}$	[-]	0.75	0.75	0.75
P	[kW]	30	90	150
ϕ	[-]	0.833	0.833	1.0
Q_{gas}	[m_n^3/h]	3.02	9.06	15.1
Q_{air}	[m_n^3/h]	34.91	104.33	145.45
$Re_{tot.}$	[-]	10000	29900	42300
s_L	[m/s]	0.36	0.36	0.42
l_F	[m]	$0.26 \cdot 10^{-3}$	$0.26 \cdot 10^{-3}$	$0.18 \cdot 10^{-3}$

Swirling lean premixed flame

- **Classification in regime diagram**

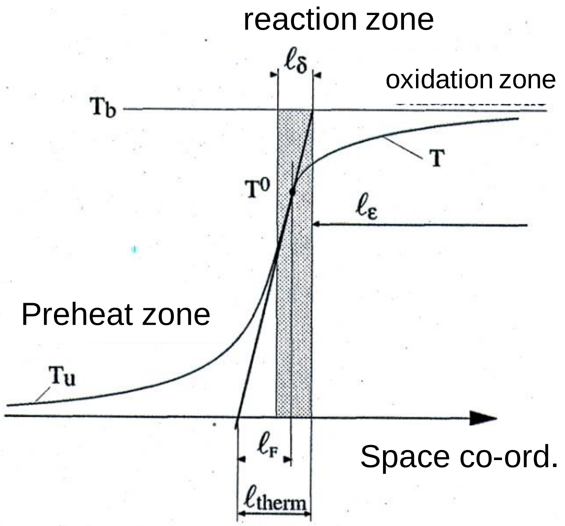
Velocity fluctuation/ laminar flame speed



Turbulent length scale/ laminar flame thickness

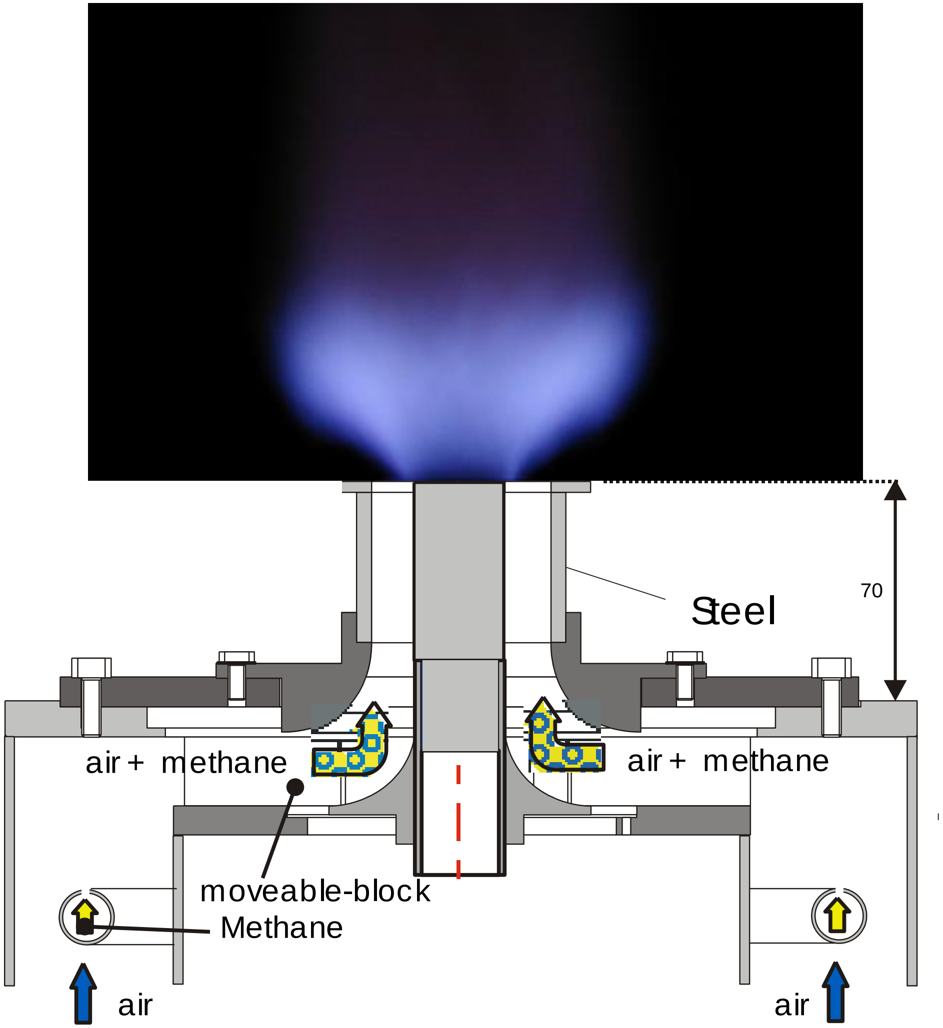
Small eddies penetrate only in preheat zone → flamelet-like-structure preserved

Laminar flame: T-profile



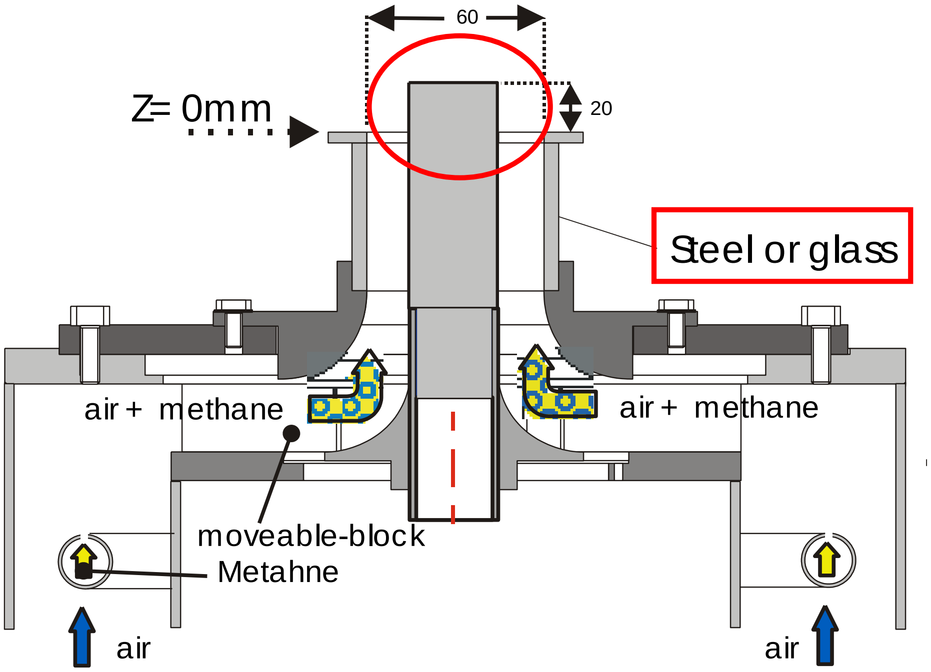
Swirling lean premixed flame

- **Visual impression**



Swirling lean premixed flame

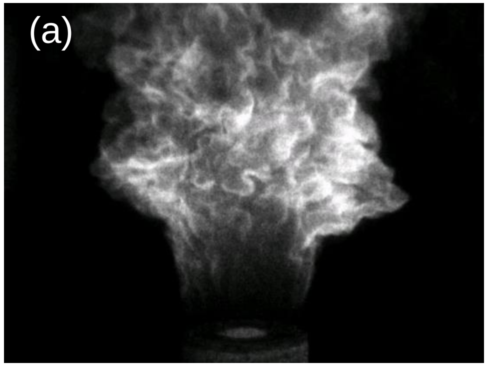
- **Transition into flashback**
  - Variation of swirl number
  - Variation of equivalence ratio
- **Slight adaptation of nozzle geometry**
  - Extension of bluff body



Heeger et int. Dreizler. Exp. in Fluids (2010) 49:853 – 864

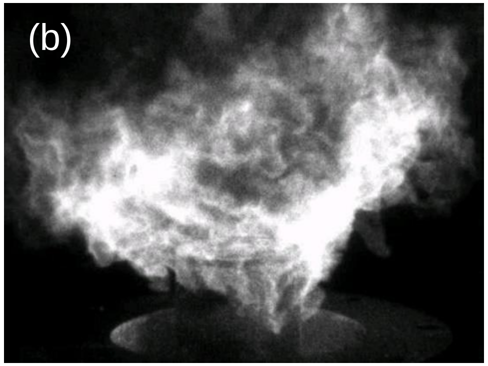
Swirling lean premixed flame

- **Three states of operation**



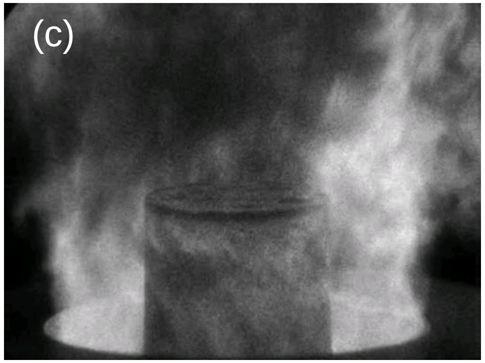
(a)

Stable: stabilization at the edge of the bluff body



(b)

Spinning: flame precesses around the shell of the bluff body



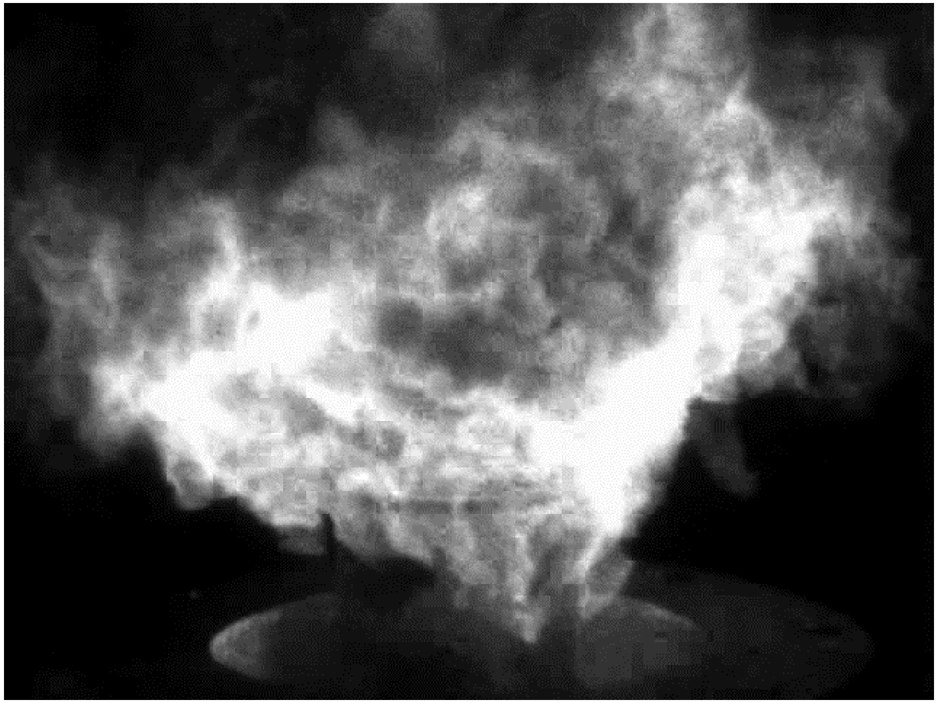
(c)

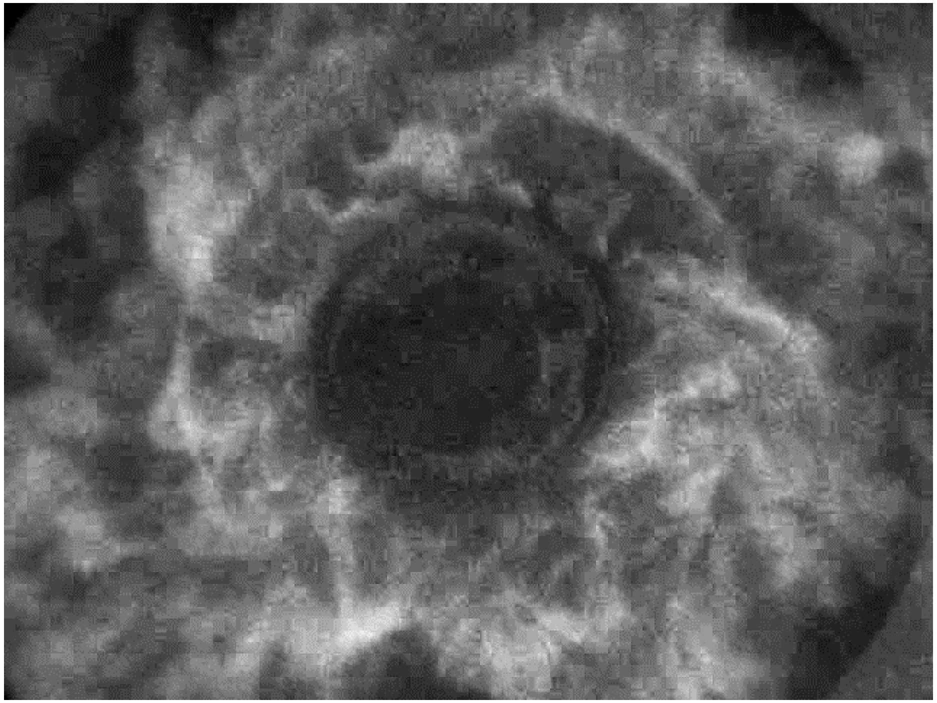
After flashback: the flame is stabilized at the swirler

Swirling lean premixed flame

- **Precessing flame**

Meta-stable





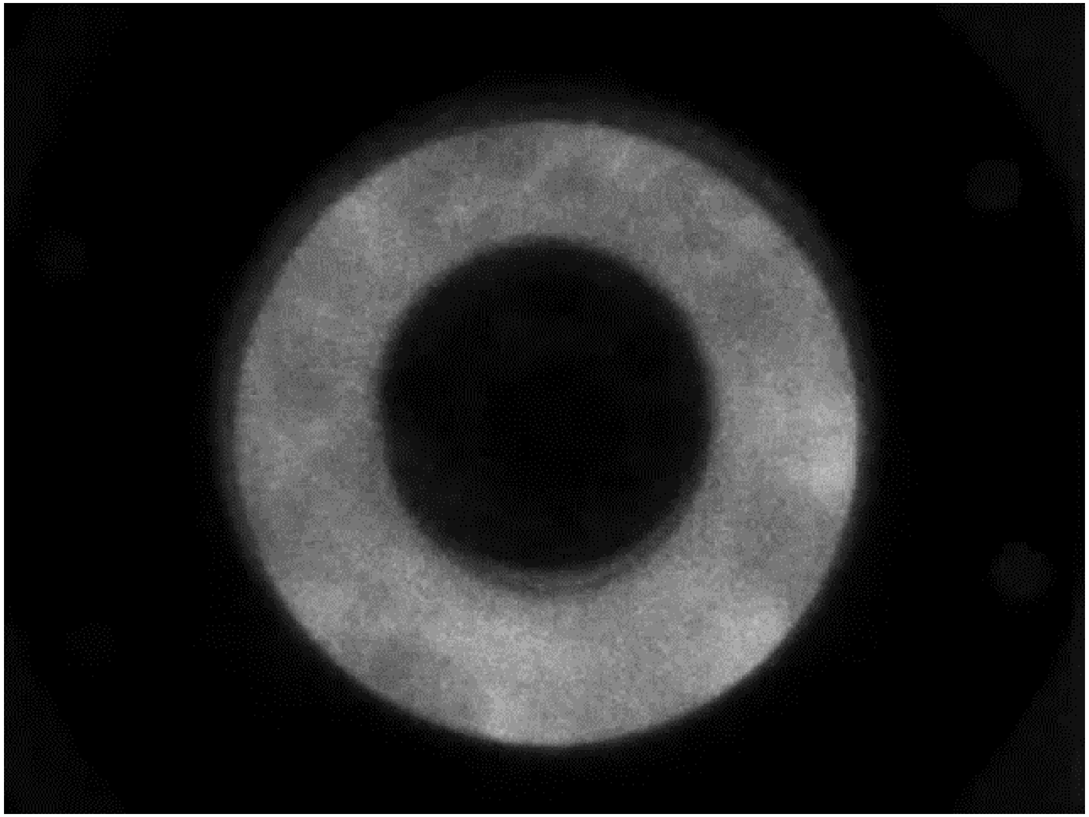
Swirling lean premixed flame

- **Precessing flame**

Flashback

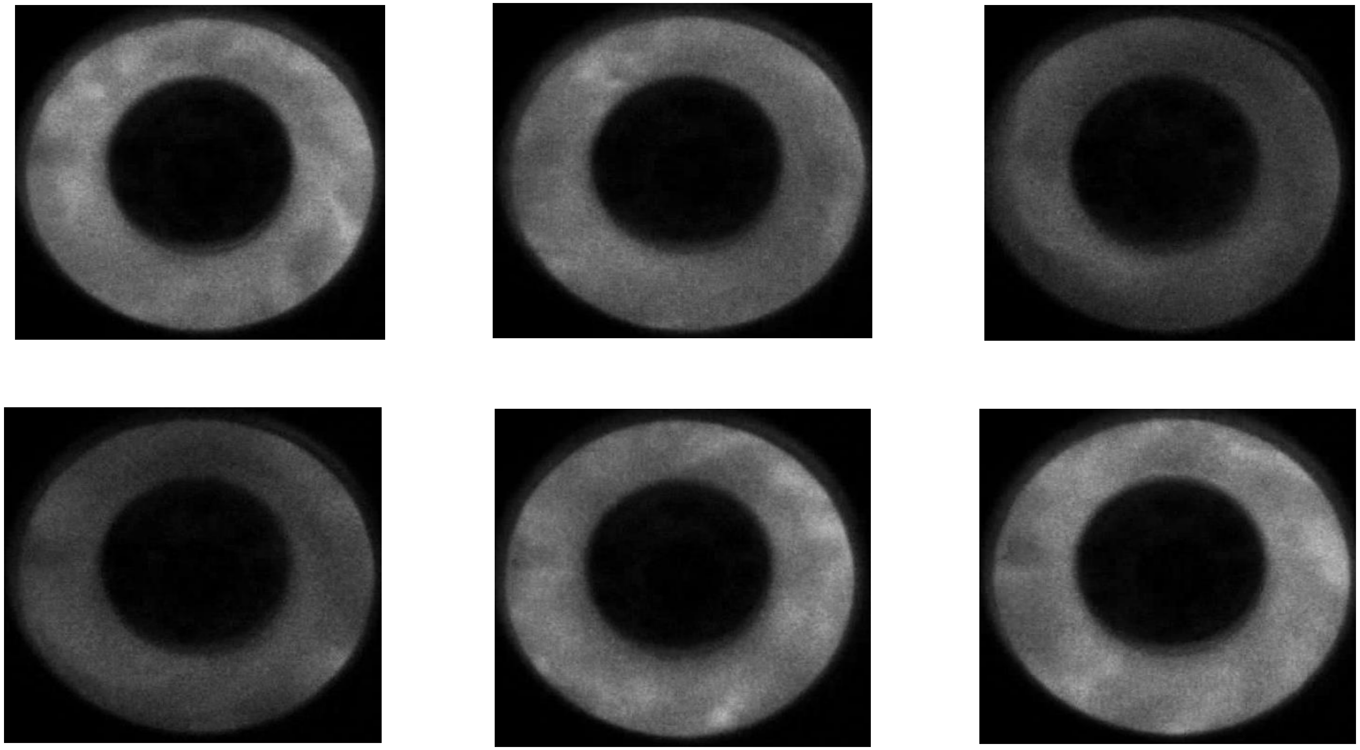
Swirling lean premixed flame

- **After flash back: view from top (slightly tilted)**



Swirling lean premixed flame

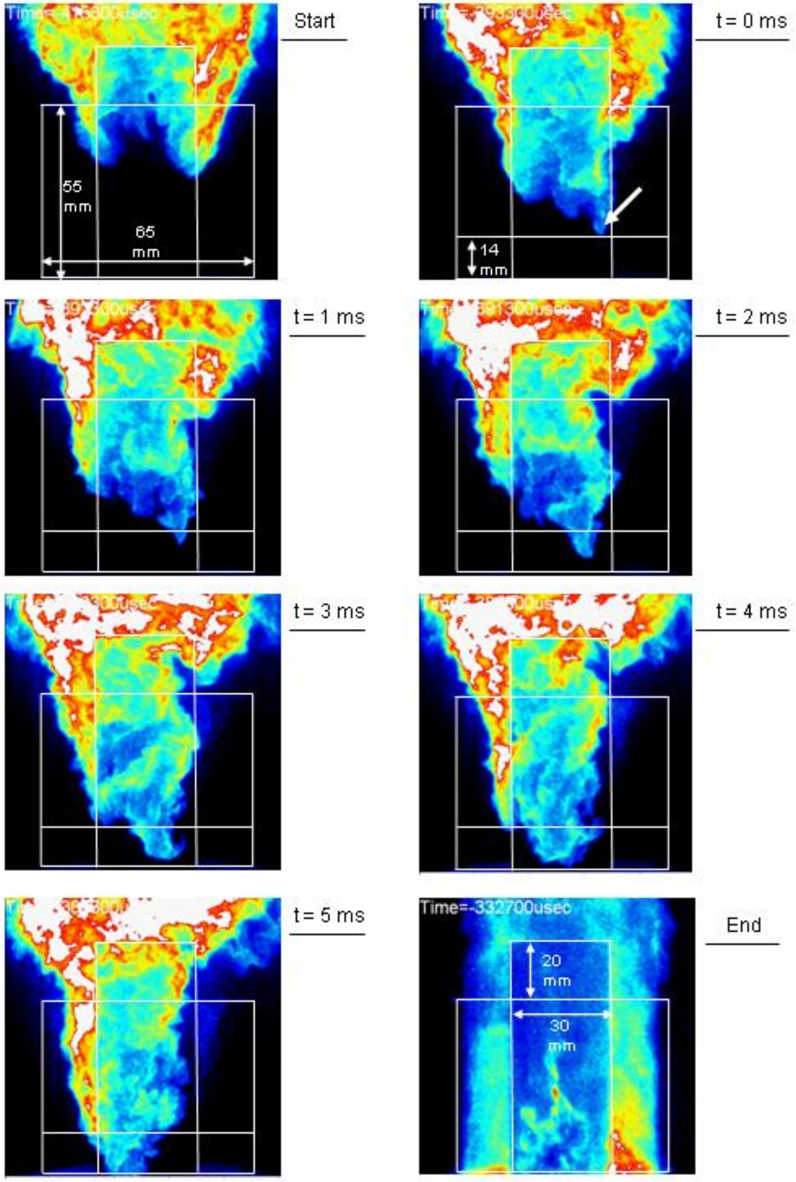
- **After flash back: view from top (slightly tilted)**



  - – Flame luminescence monitored by intensified CMOS-camera at a frame rate of 7kHz
  - – Only 6 exposures of a full cycle are shown
  - – Cycle duration ~7.5±0.6ms.

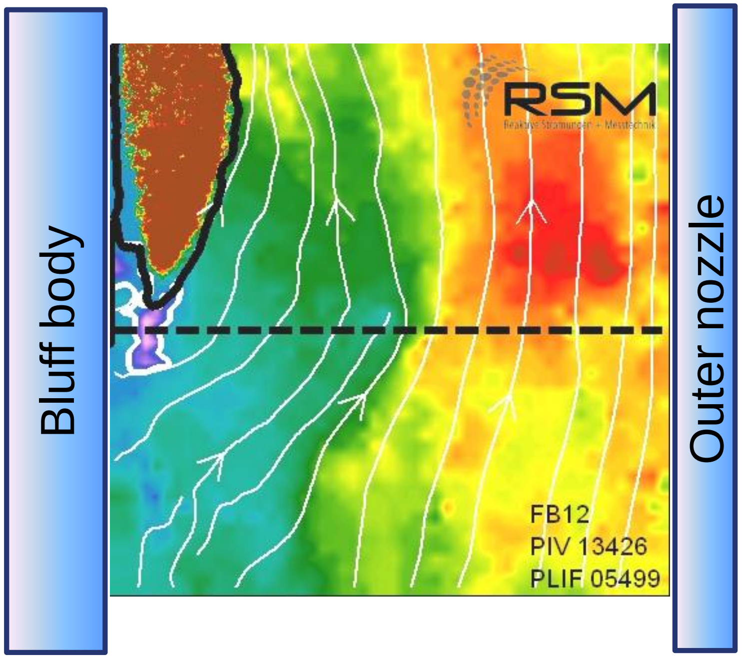
Swirling lean premixed flame

- **Transition from spinning into flashback**
  - Transparent nozzle
  - Chemiluminescence recorded at high repetition rates (kHz-regime)

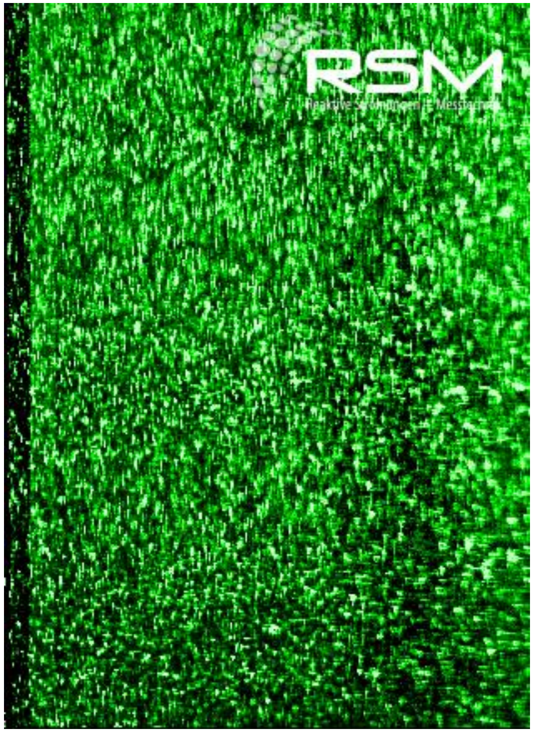


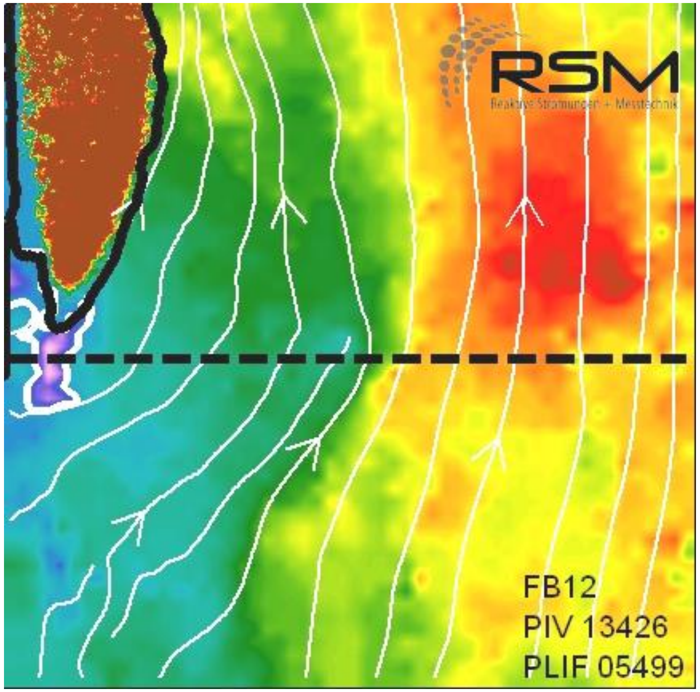
Swirling lean premixed flame

- **Transition from spinning into flashback**
  - Transparent nozzle
  - OH-PLIF and 2C-PIV recorded at high repetition rates (kHz-regime)



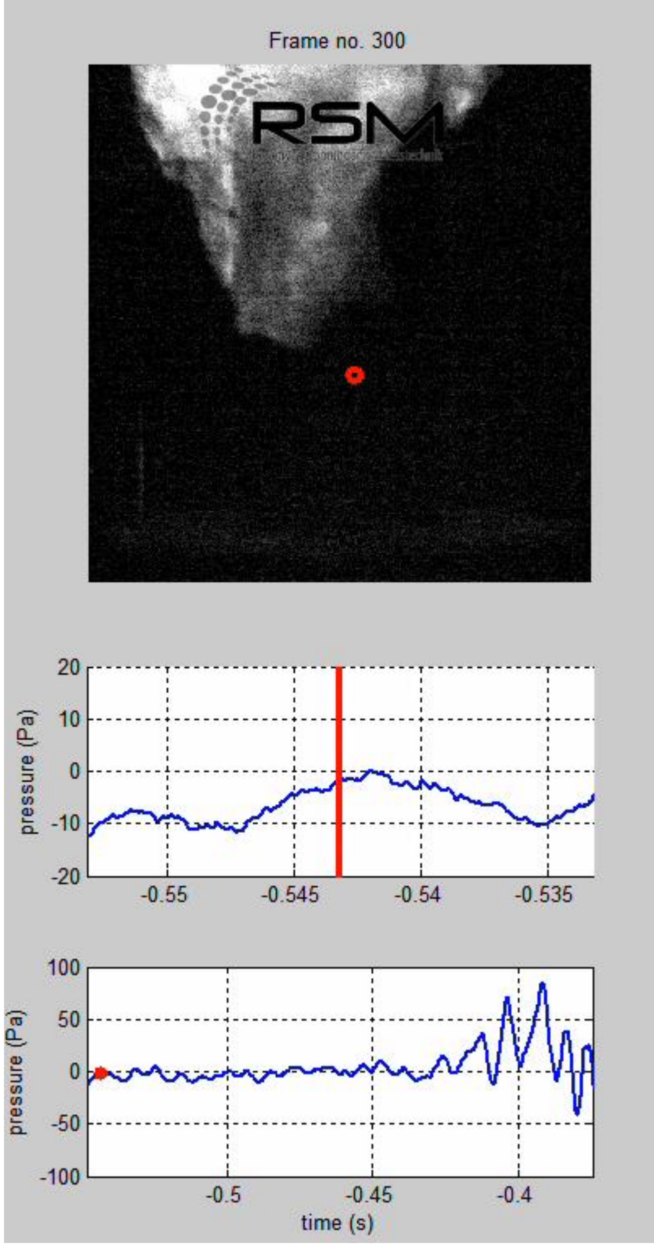
Swirling lean premixed flame





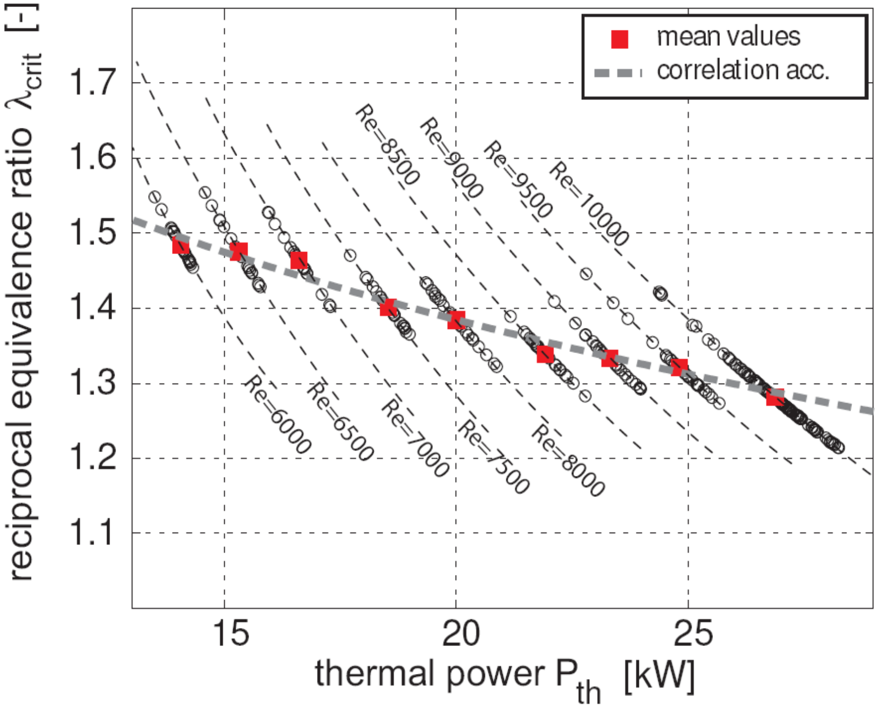
Swirling lean premixed flame

- **Transition from spinning into flashback**
  - Simultaneous optical and pressure measurements
  - Multi-parameter diagnostics crucial for better understanding



Swirling lean premixed flame

- **Stability map**
  - For fixed geometrical swirl number



  - Flashback is favored by
    - Lower Reynolds numbers
    - Higher laminar flame speeds
    - Higher swirl intensity (not shown in this graph)

Bench mark configurations

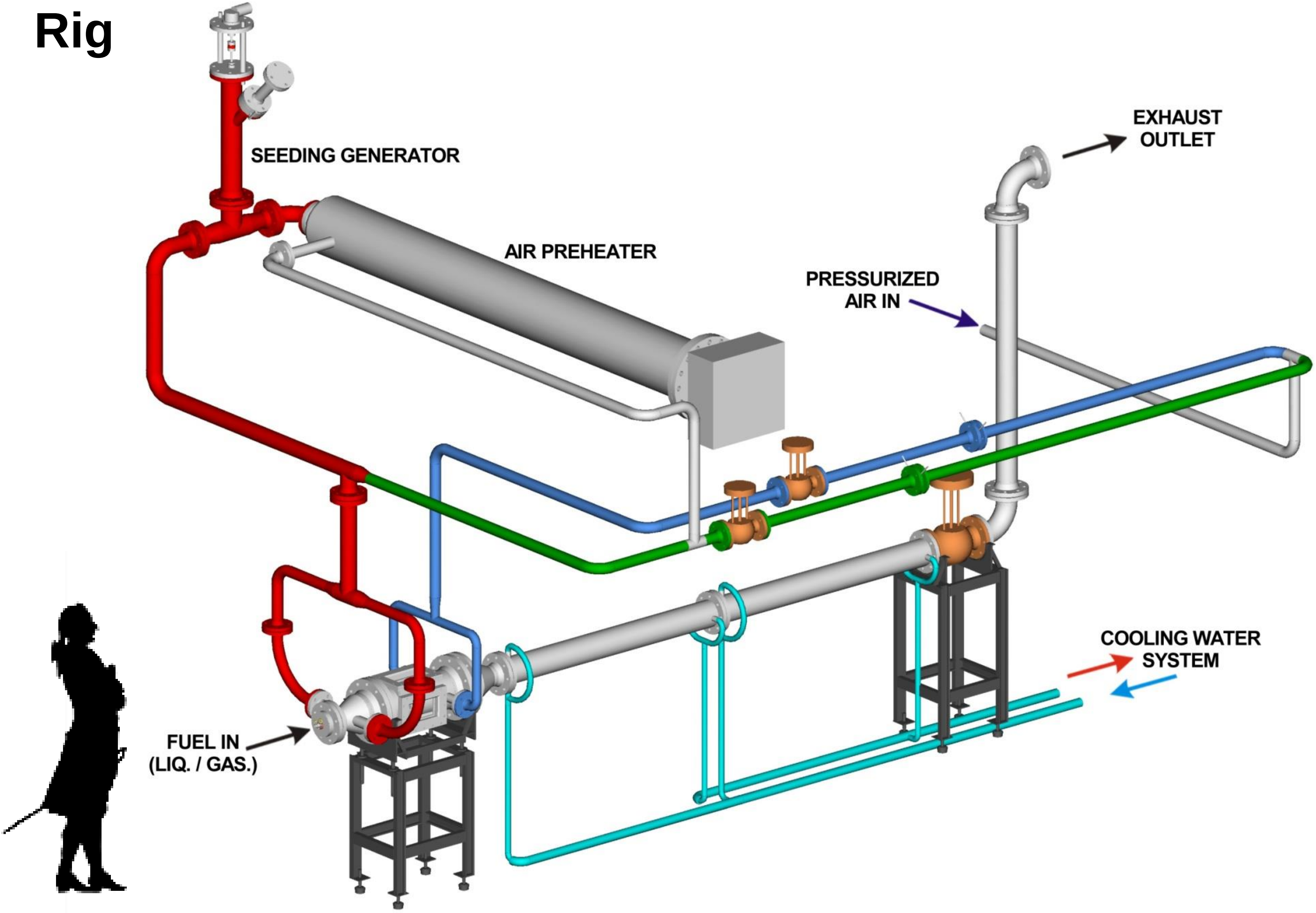
- **Example 3: enclosed pressurized flames**
  - Non-premixed natural gas flames or spray flames and lean premixed flames
  - Mimicking performance of real combustors but only single nozzle (for example circumferential modes in annular combustors not accessible)

Enclosed pressurized flames

- **Modular setup**
  - Pressure housing
  - Optically accessible flame tube
  - Complex infrastructure
    - Pressurized air supply
    - Electrical heating of combustion air to mimic inlet conditions of GT-combustor
    - Pressurized fuel supply
      (natural gas compressor, for liquid fuels high pressure pump and large storage capacity)
    - Exhaust gas treatment (cooling)
    - Safety equipment (sensors and explosion protection)

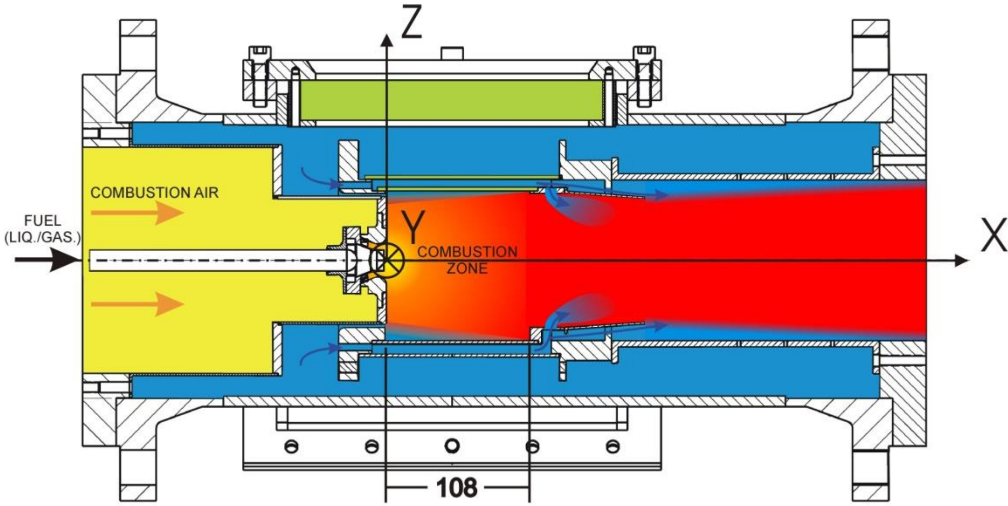
Enclosed pressurized flames

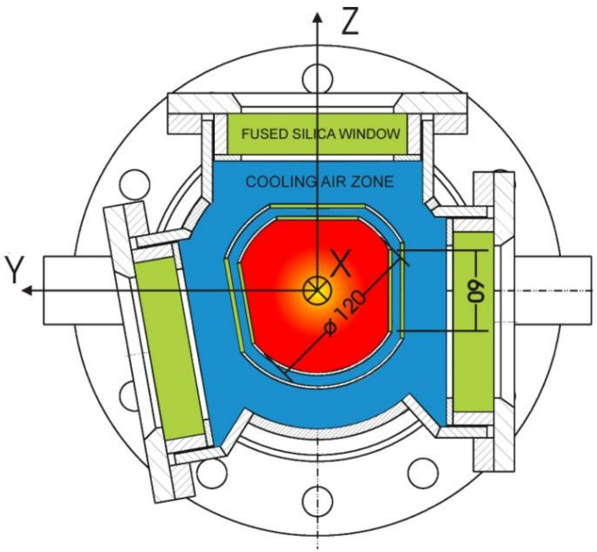
- **Rig**

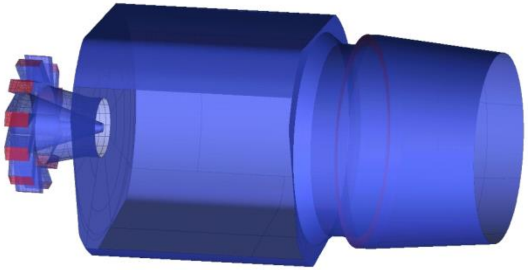


Enclosed pressurized flames

- **Optically accessible combustor**
- “Can-combustor-concept”
- P_{max}=10bar, T_{max}=773K
- Modular to adapt different geometries/ combustion concepts
- Optical access from three sides for LDA/PDA, PIV, LIF, CARS, etc.
- No disturbance of primary reaction zone by cooling air
- CAD-design for computational meshes



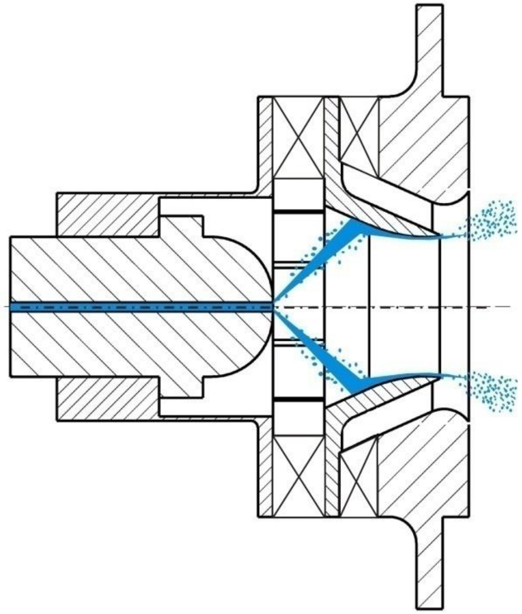


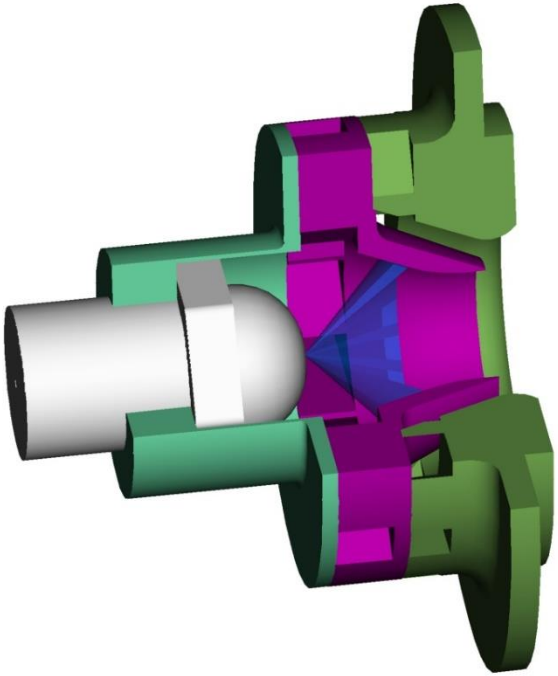


Hage et int. Dreizler. ASME Turbo Expo, GT2010-23378

Enclosed pressurized flames

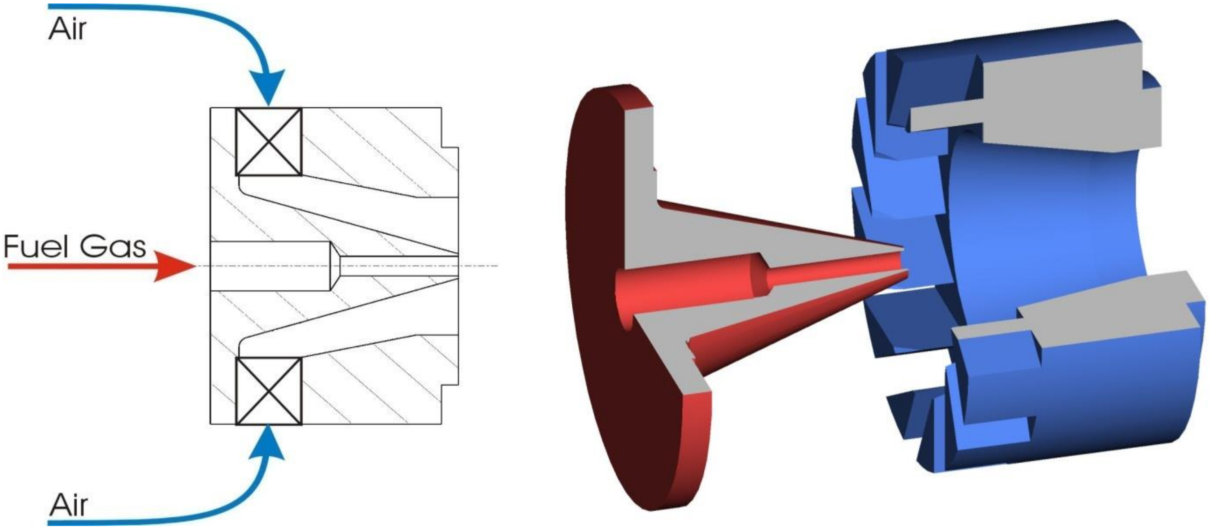
- **Nozzles**
  - Spray flames: n-heptane / air
  - Surrogate n-heptane advantageous compared to kerosene due to chemical kinetics modeling and spectroscopic properties





Enclosed pressurized flames

- **Nozzles**
  - Non-premixed gaseous flame: Natural gas / air



- Simple, generic design
- Non-reactive conditions: Mixture of helium and air to match density
- Swirl number from geometry S=1

Janus, Dreizler, Janicka. Proc. Combust. Inst. (2007) 31:3091 – 3098

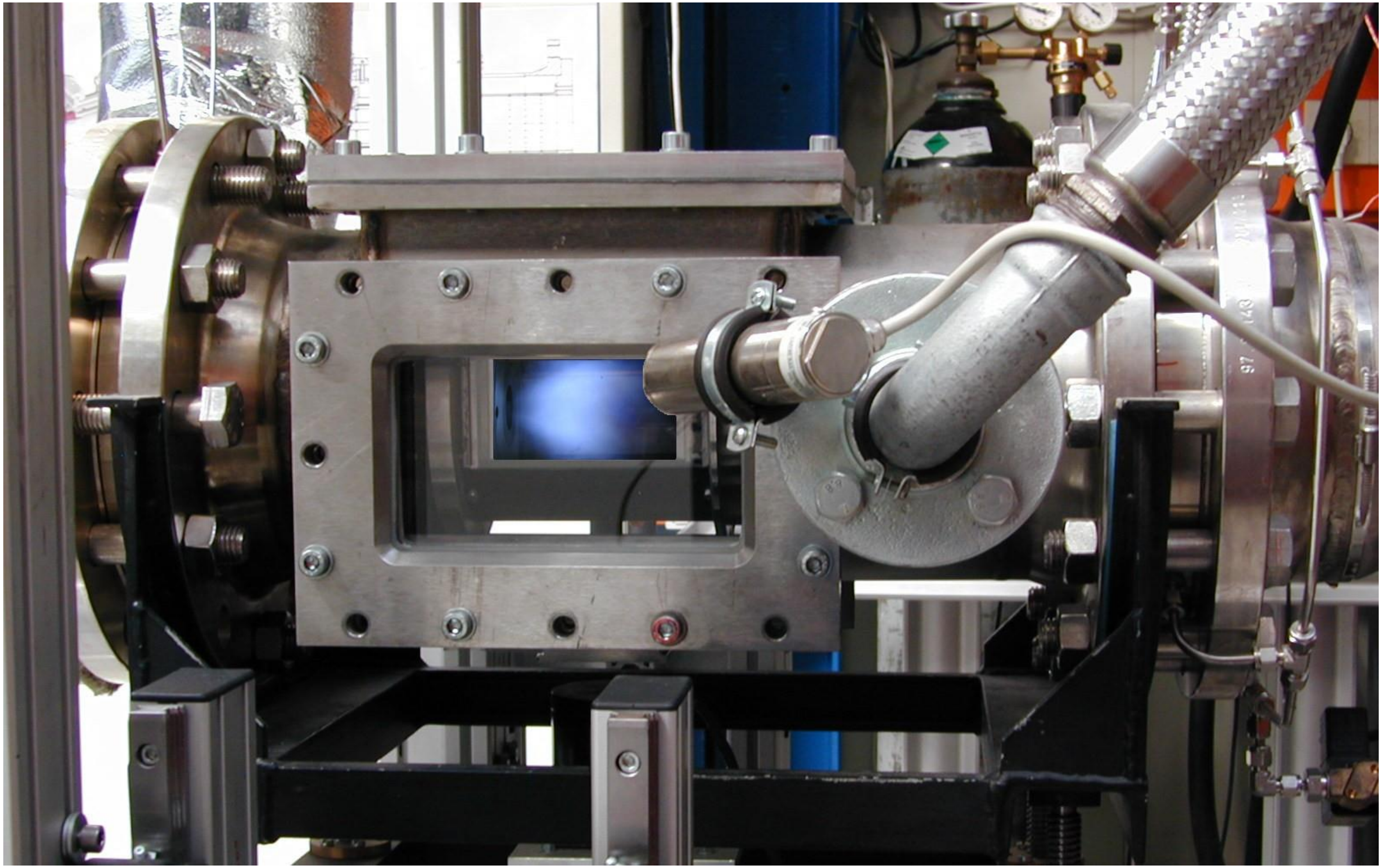
Enclosed pressurized flames

- **Operational conditions**

Pressure	2bar	4bar	6bar
Combustion air temperature	623K	623K	623K
Fuel temperature	373K	373K	373K
Combustion air mass flow	30g/s	60g/s	90g/s
Re_{Air}	46000	92000	138000
Re_{Fuel}	33000	67000	100000

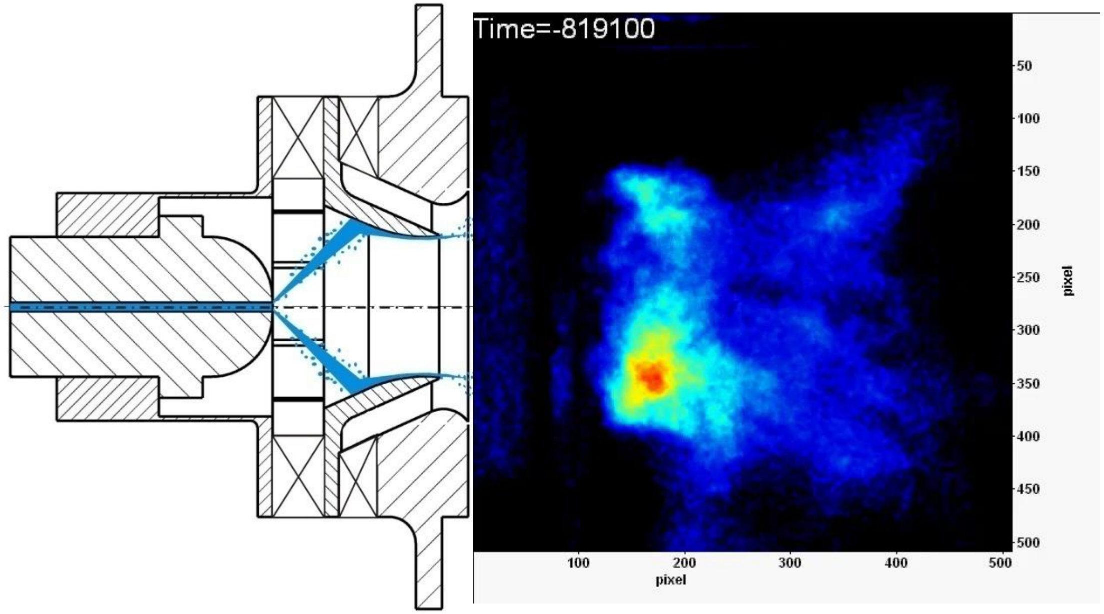
Enclosed pressurized flames

- **Visual impression**



Enclosed pressurized flames

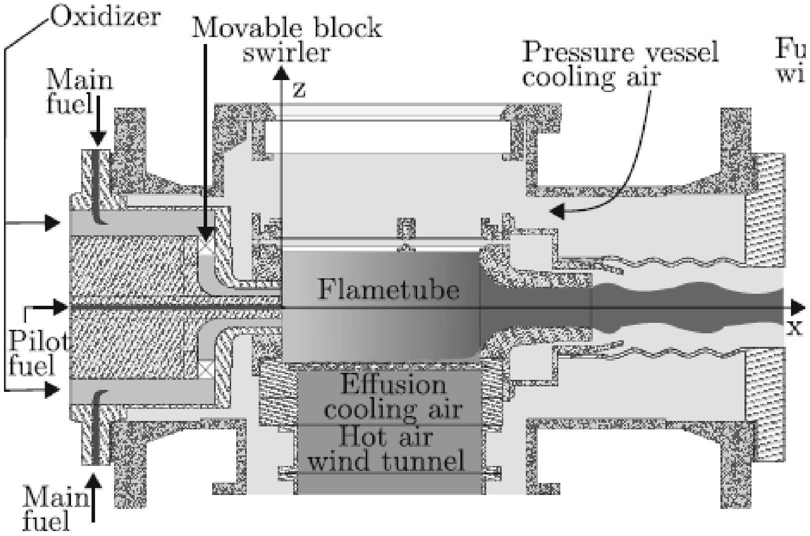
- **Visual impression – chemoluminescence of spray flame**

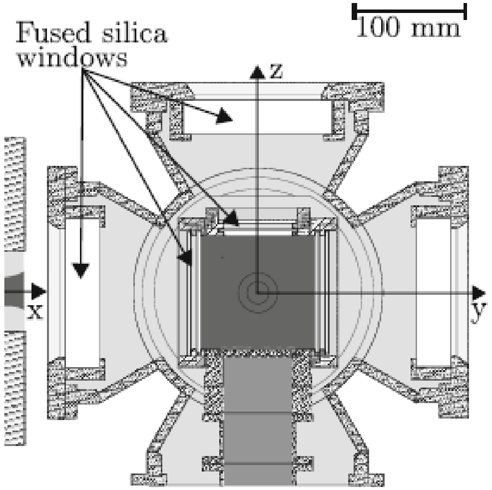


Enclosed pressurized flames

Optically accessible combustor

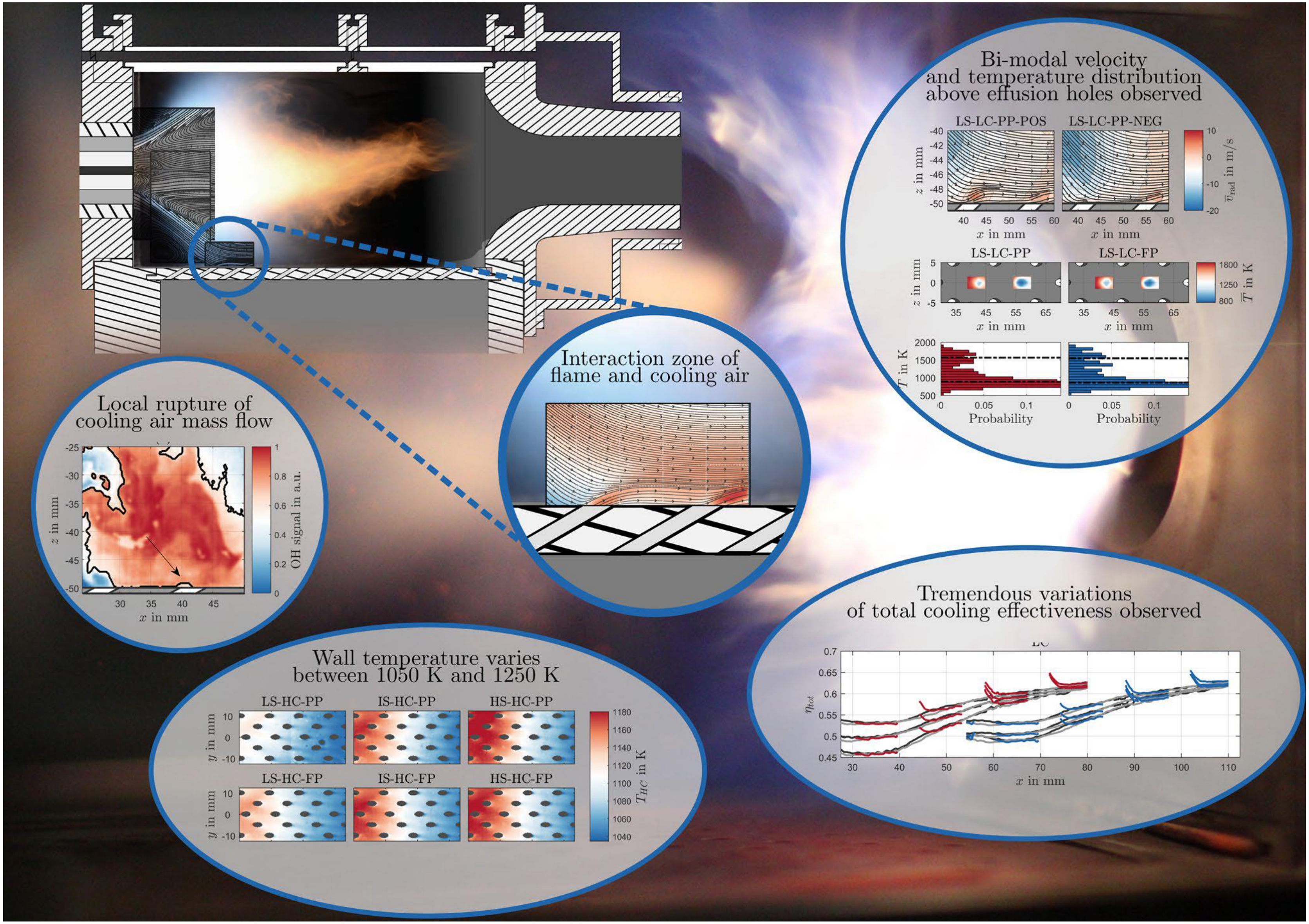
- For investigation of effusion cooling





Greifenstein et int. Dreizler. Experiments in Fluids (2019) 60 (1):10

Pressurized flames: effusion cooling



Bi-modal velocity and temperature distribution above effusion holes observed

Interaction zone of flame and cooling air

Local rupture of cooling air mass flow

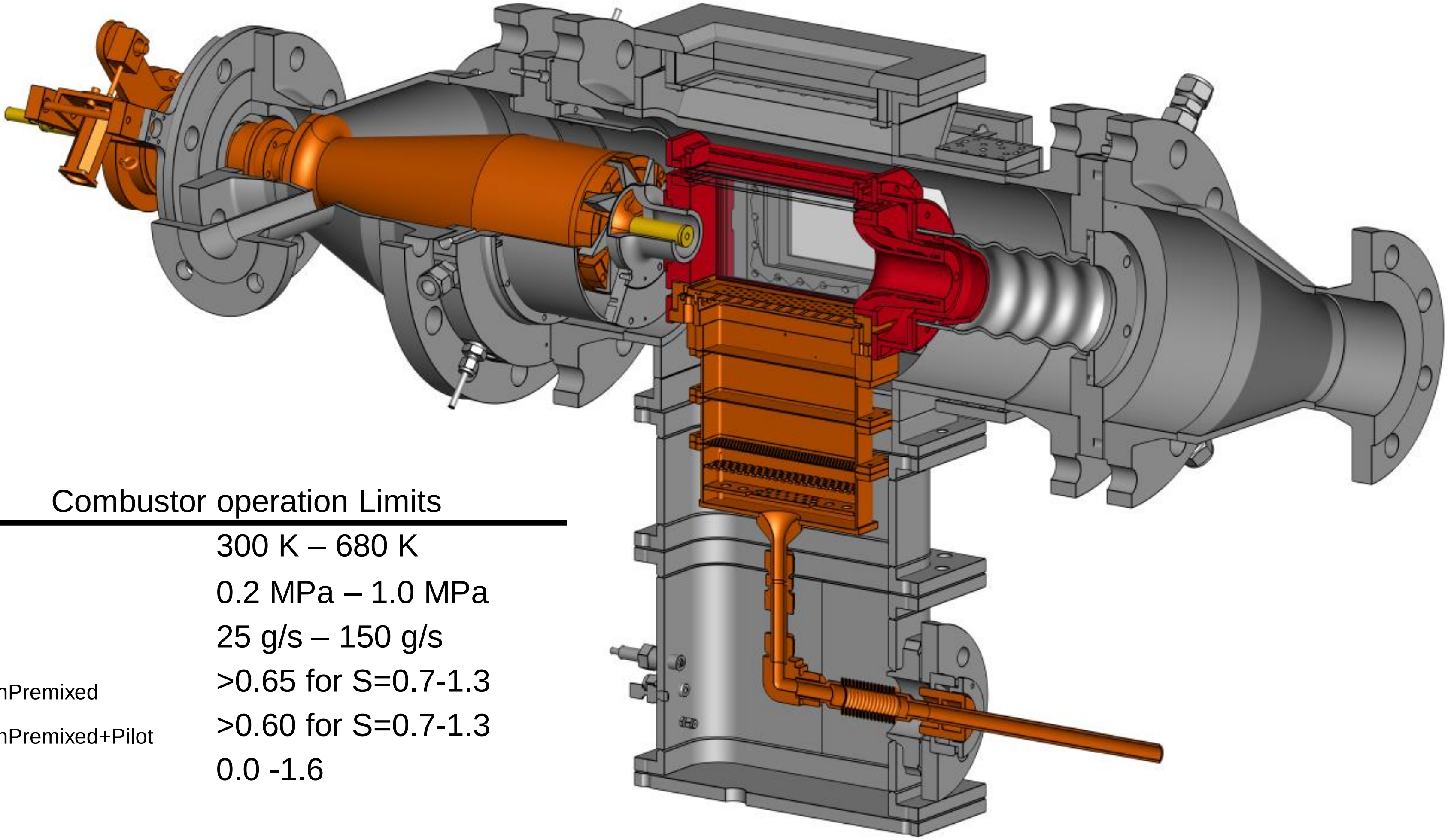
Wall temperature varies between 1050 K and 1250 K

Tremendous variations of total cooling effectiveness observed

Greifenstein et int. Dreizler. Experiments in Fluids (2019) 60 (1):10

Enclosed pressurized flames

- **Present research: Effusion cooling**



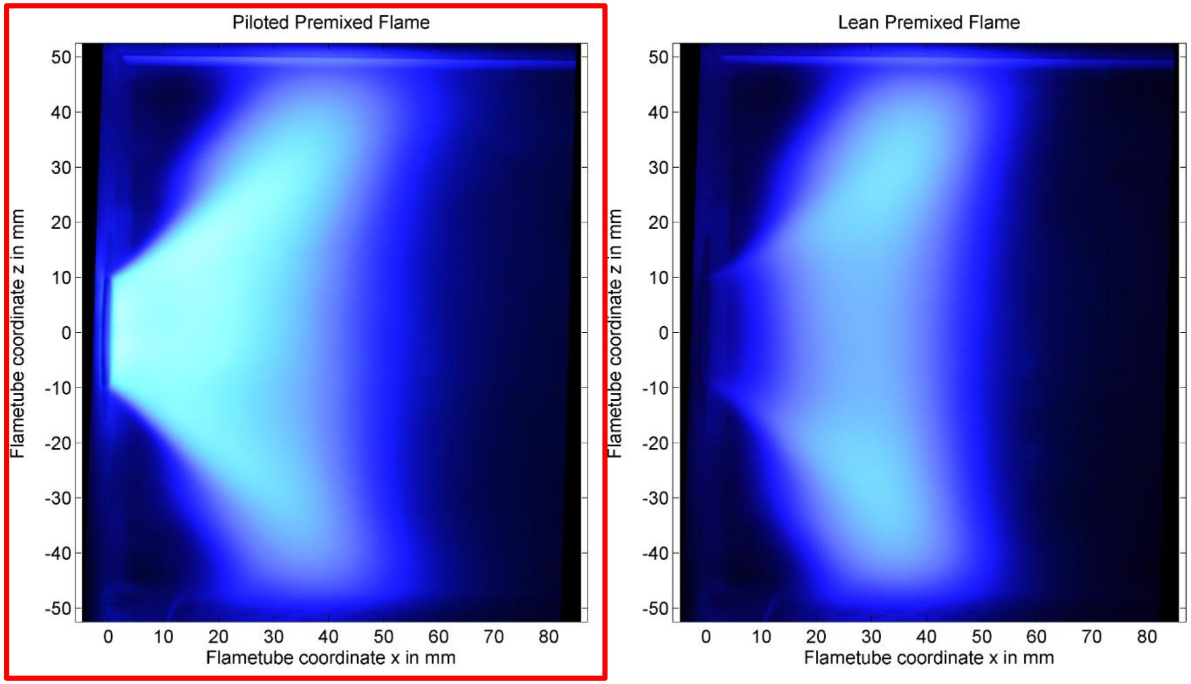
Combustor operation Limits	
T_3	300 K – 680 K
P_3	0.2 MPa – 1.0 MPa
m_3	25 g/s – 150 g/s
$\varphi_{LeanPremixed}$	>0.65 for S=0.7-1.3
$\varphi_{LeanPremixed+Pilot}$	>0.60 for S=0.7-1.3
S	0.0 -1.6

Herrmann et int. Dreizler. Flow Turb. Combust. (2019) https://doi.org/10.1007/s10494-018-9999-y

Enclosed pressurized flames

- **Present research: Effusion cooling**

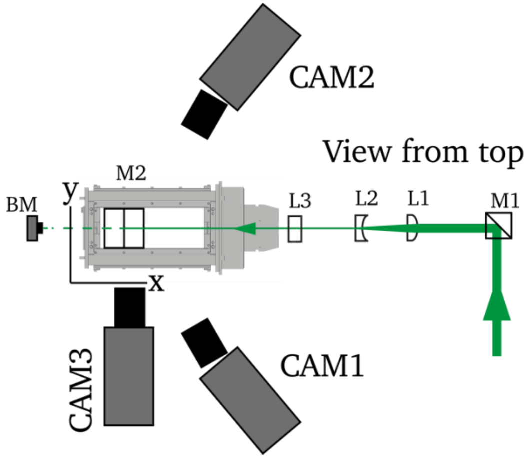
Operation conditions	
T_3	623K
P_3	0.25 MPa
$\dot{m}_3$	0.030kg/s
$\Phi_{LeanPremixed}$	0.65/0% Pilot
$\Phi_{LeanPremixed+Pilot}$	0.65/10% Pilot
S	0.7
$\dot{m}_5$	0.0125 kg/s
T_5	623 K

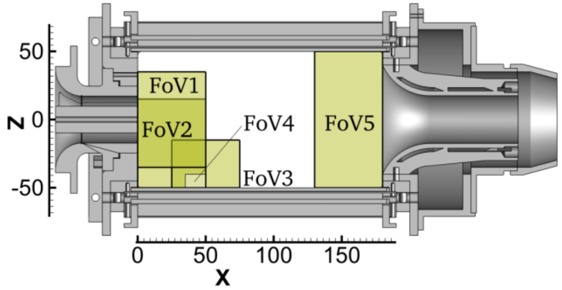


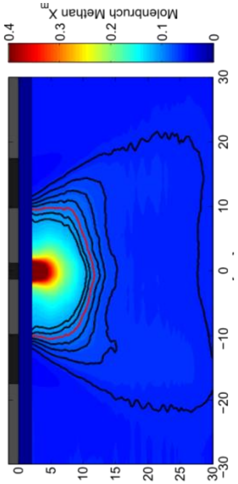
Low-pass (490nm) filtered Chemiluminescence images from piloted and premixed flames

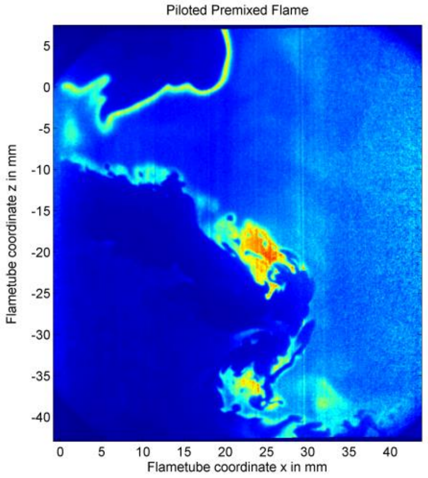
Enclosed pressurized flames

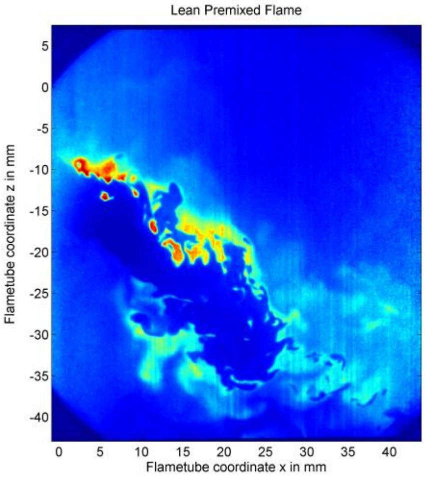
- **Present research: Effusion cooling**
  - Flow field: 2C and 3C PIV
  - Flame brush: OH-PLIF
  - Mixing fields: Acetone PLIF
  - Gas temp: CARS
  - Surface temp: phosphor thermometry







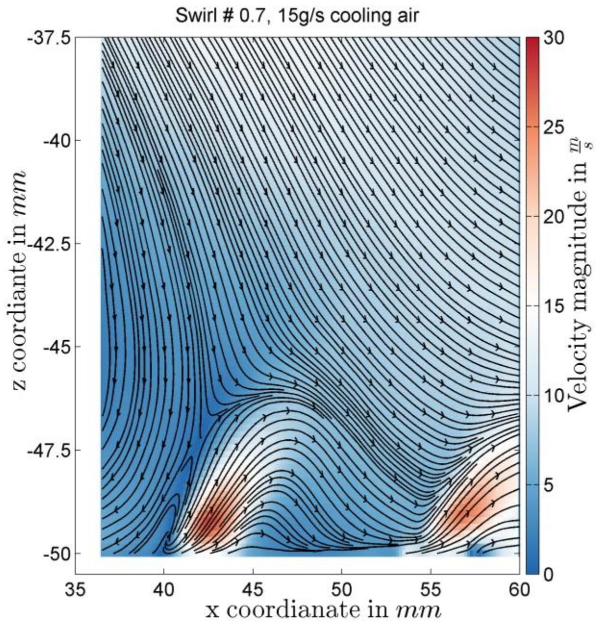




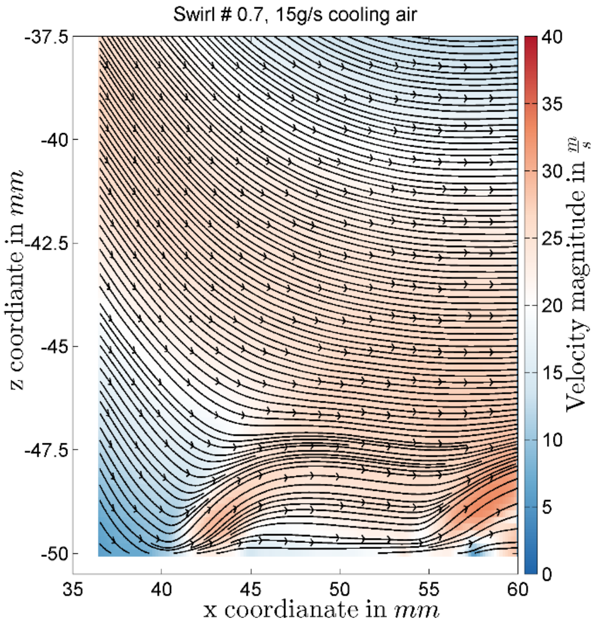
Enclosed pressurized flames

- **Present research: Effusion cooling**
- **Particle Image Velocimetry - PIV**

without pilot



with pilot

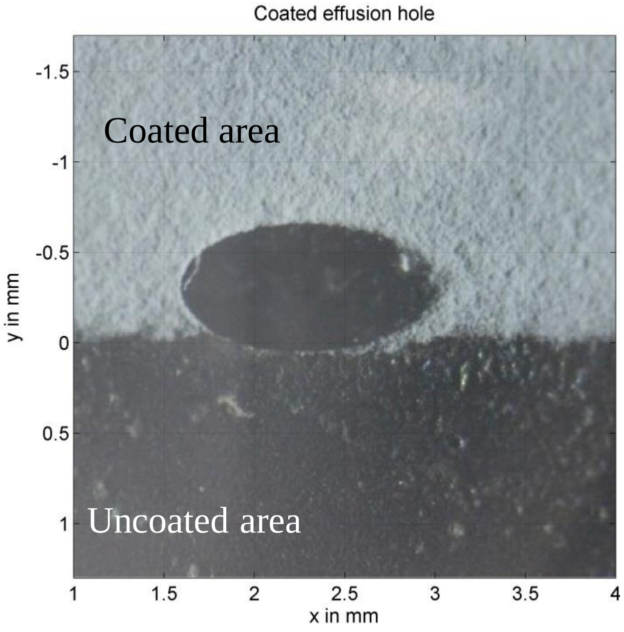


Enclosed pressurized flames

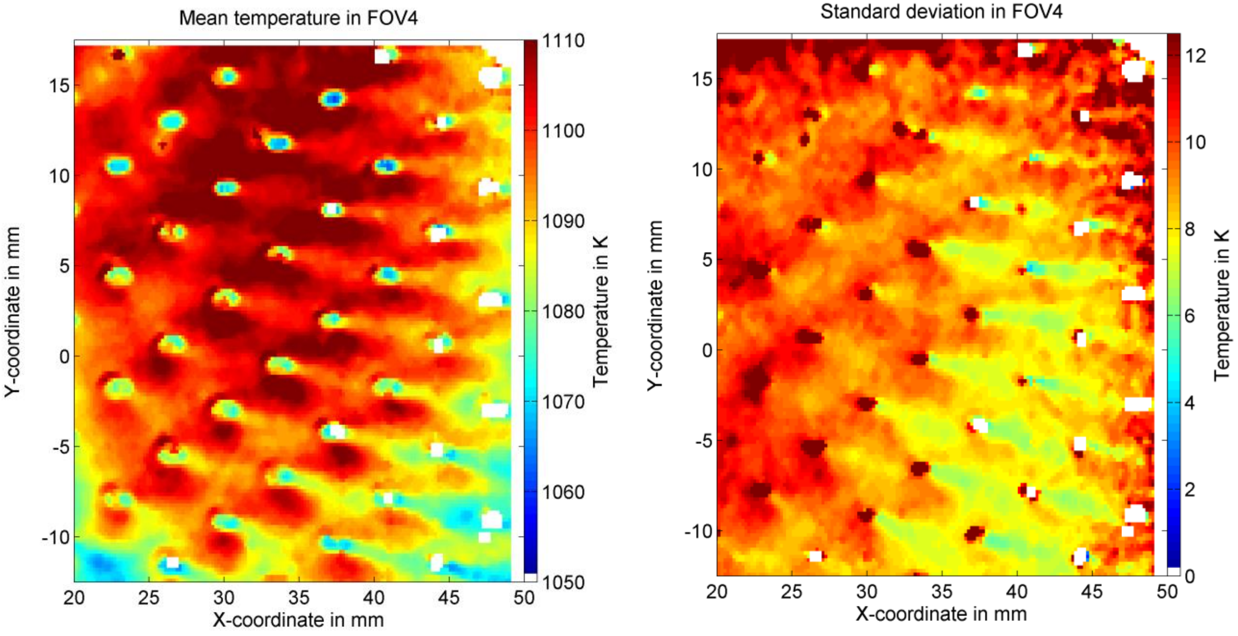
- **2D wall temperature**

Magnified view of the coated liner.

Coating thickness t 10um <t <50um



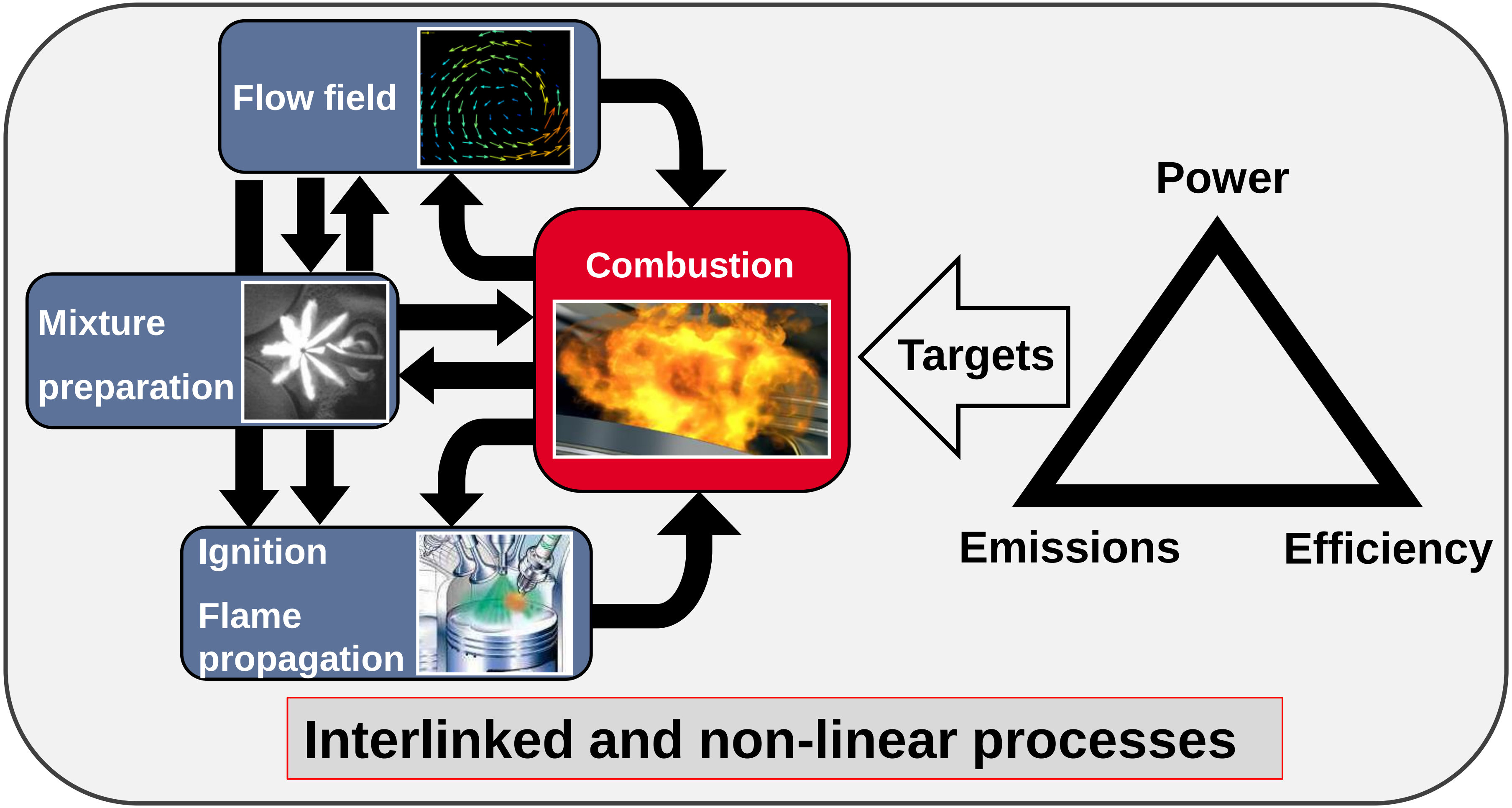
Mean and standard deviation from 500 single shots at the liner surface



- Temperature measurement in flame wall contact zone at 20mm < x < 45mm
- Influence of cooling film visible in wakes behind single holes

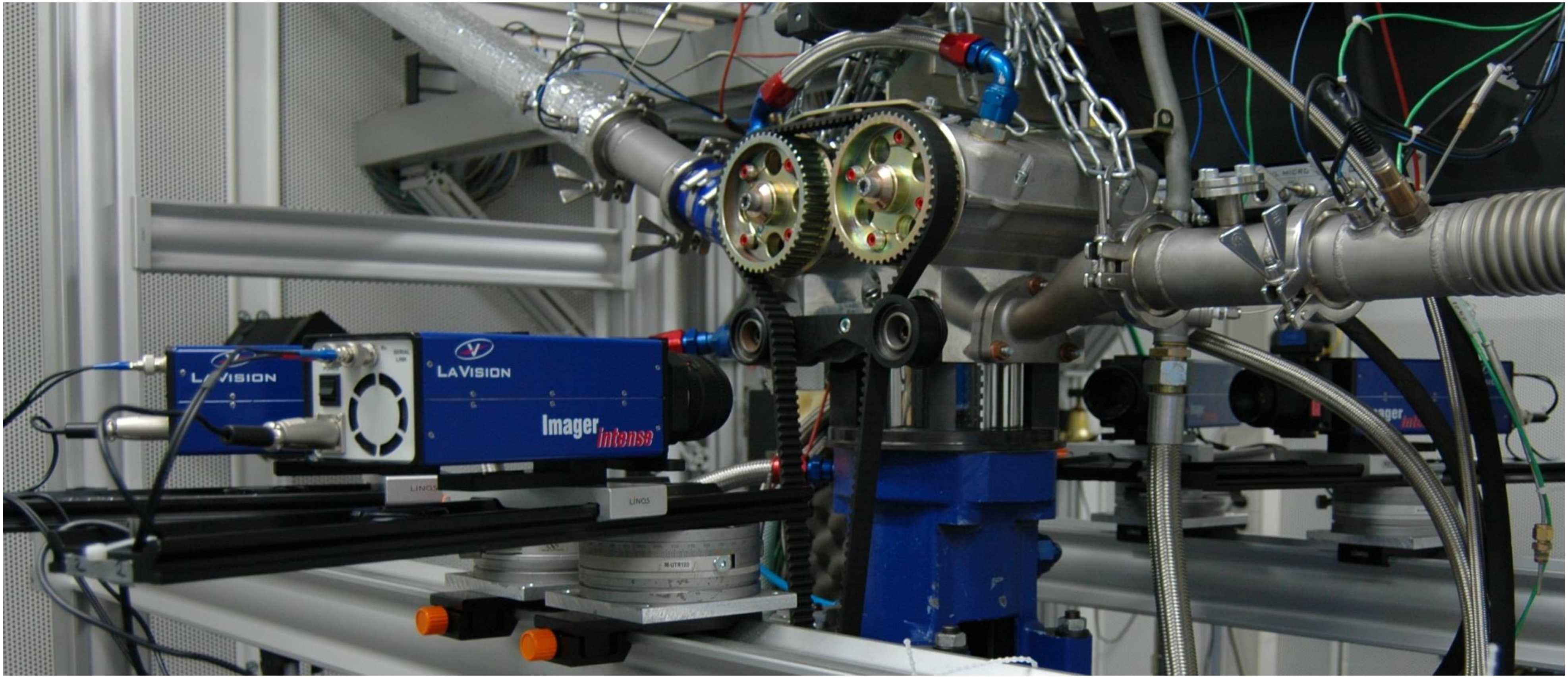
Generic bench mark configurations

- **Example 4: Optically accessible IC-engine**
  - Different to GT-combustion there does not exist a simplified generic configuration where important and relevant effects can be studied!



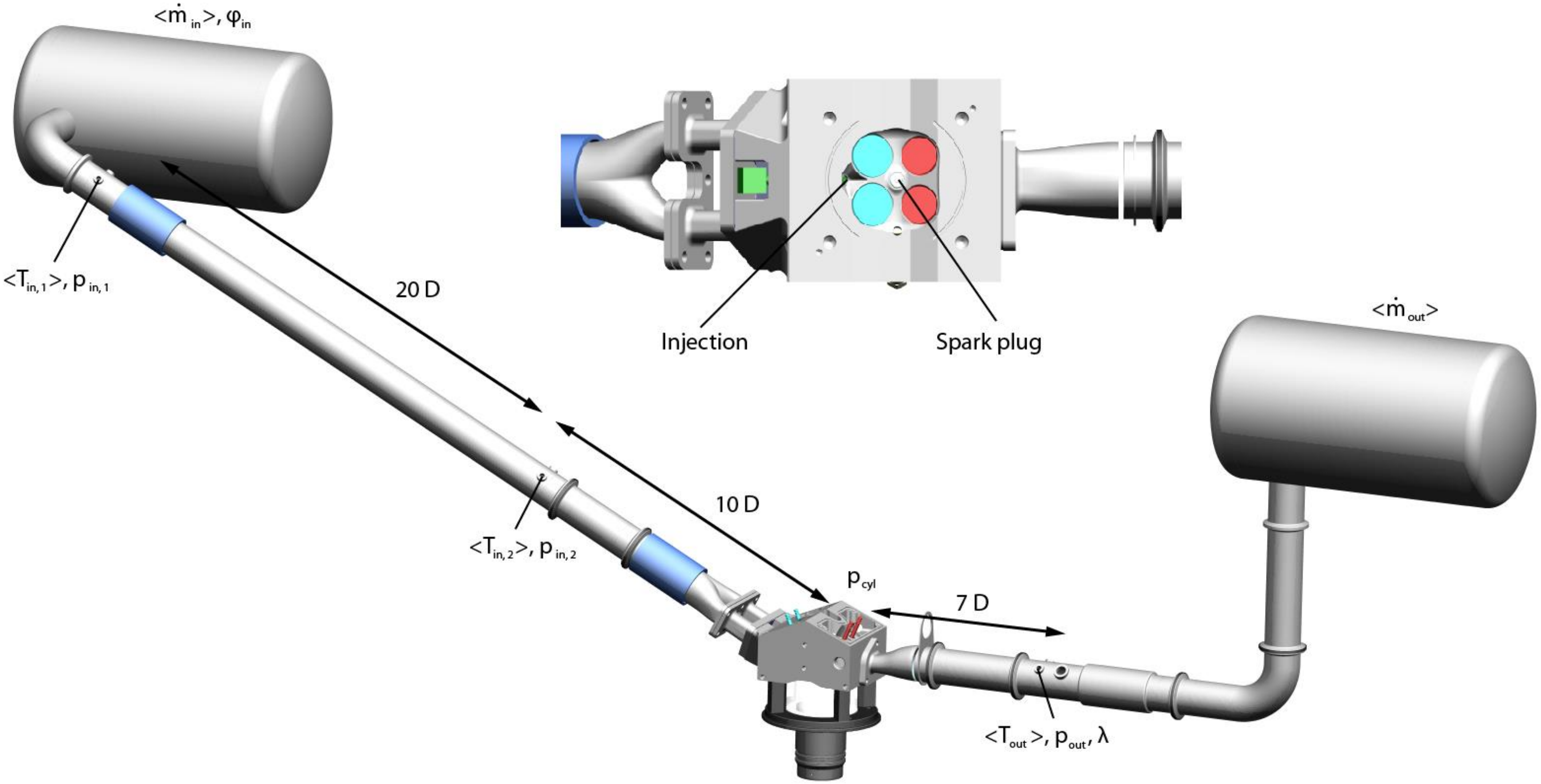
Interlinked and non-linear processes

Transparent DISI engine



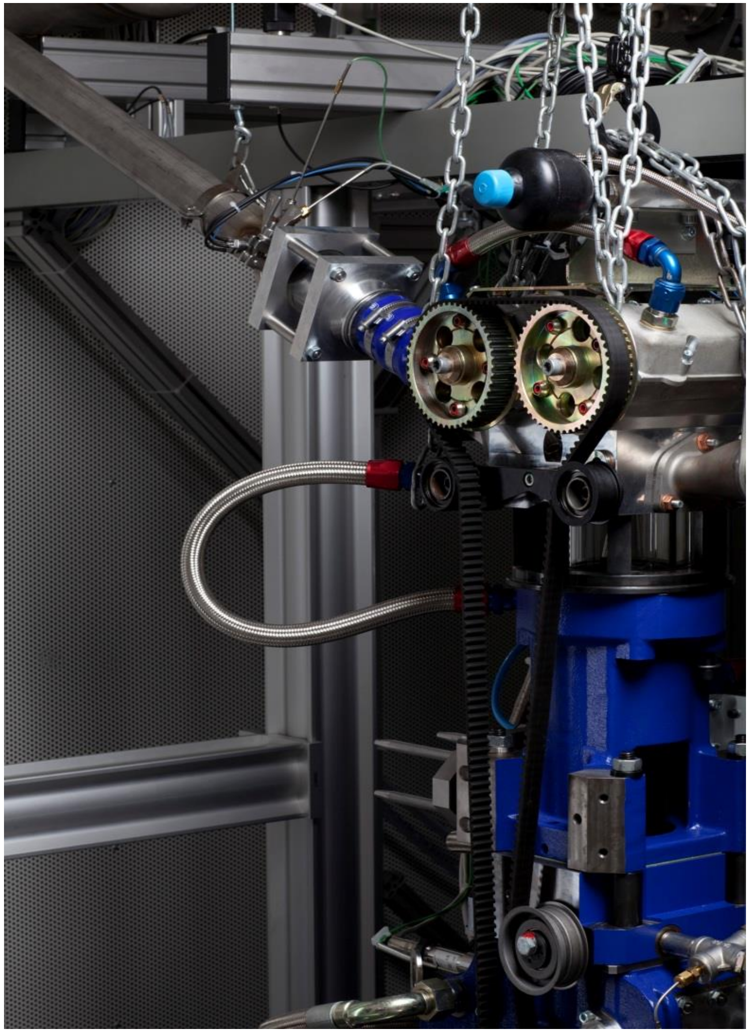
Baum et int. Dreizler. Flow Turbulence and Combustion (2014) 92:269 – 297

Boundary conditions



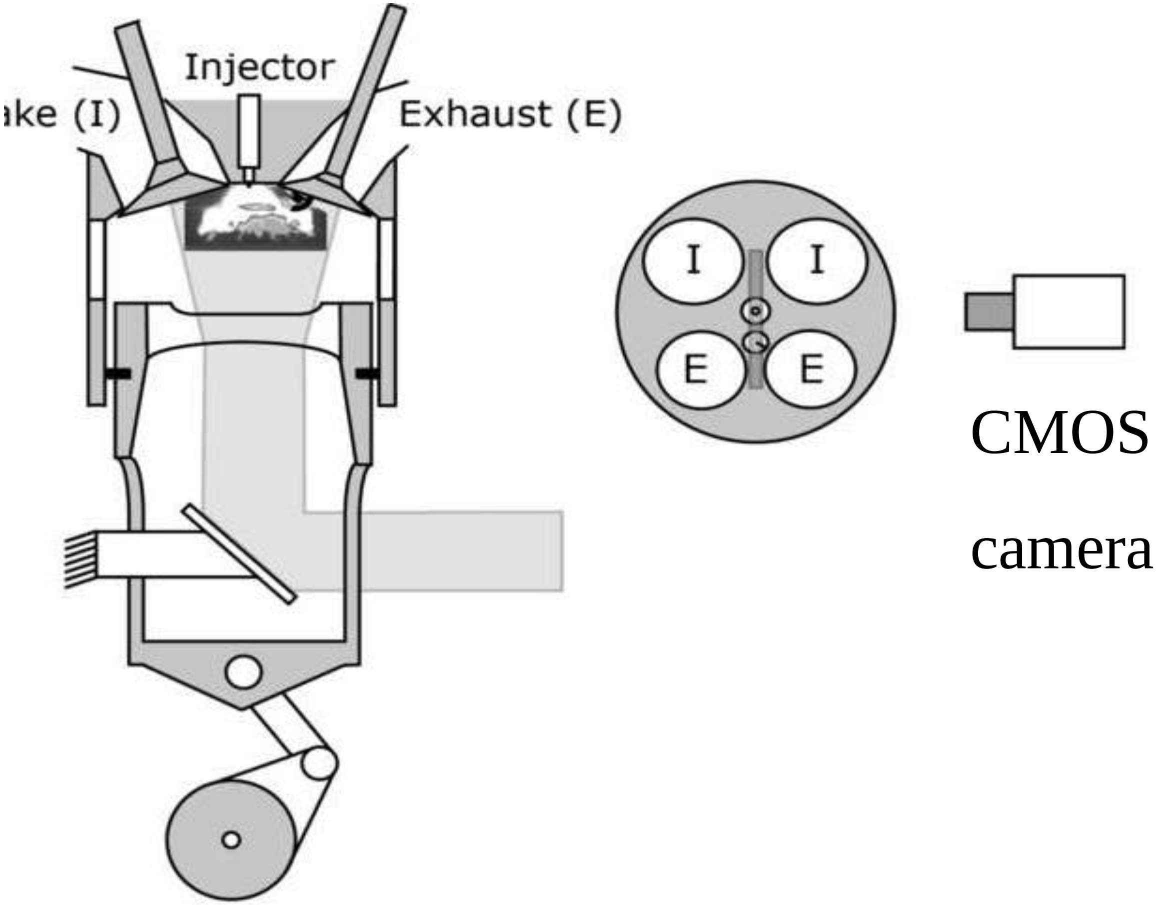
Specifications

- **Optical accessible IC Engine**
  - Capacity: 499 ccm
  - Bore: 86 mm
  - Stroke: 86 mm
  - Compression ratio: 8.5
  - Optically accessible liner: 55 mm
- **Motored or fired operation:**
  - ≤ 3000 rpm
  - Manifold pressure: variable
- **Seeding**
  - Silicon oil (~1µm) or BN-particles



In-cylinder flow field measurements – 2C PIV

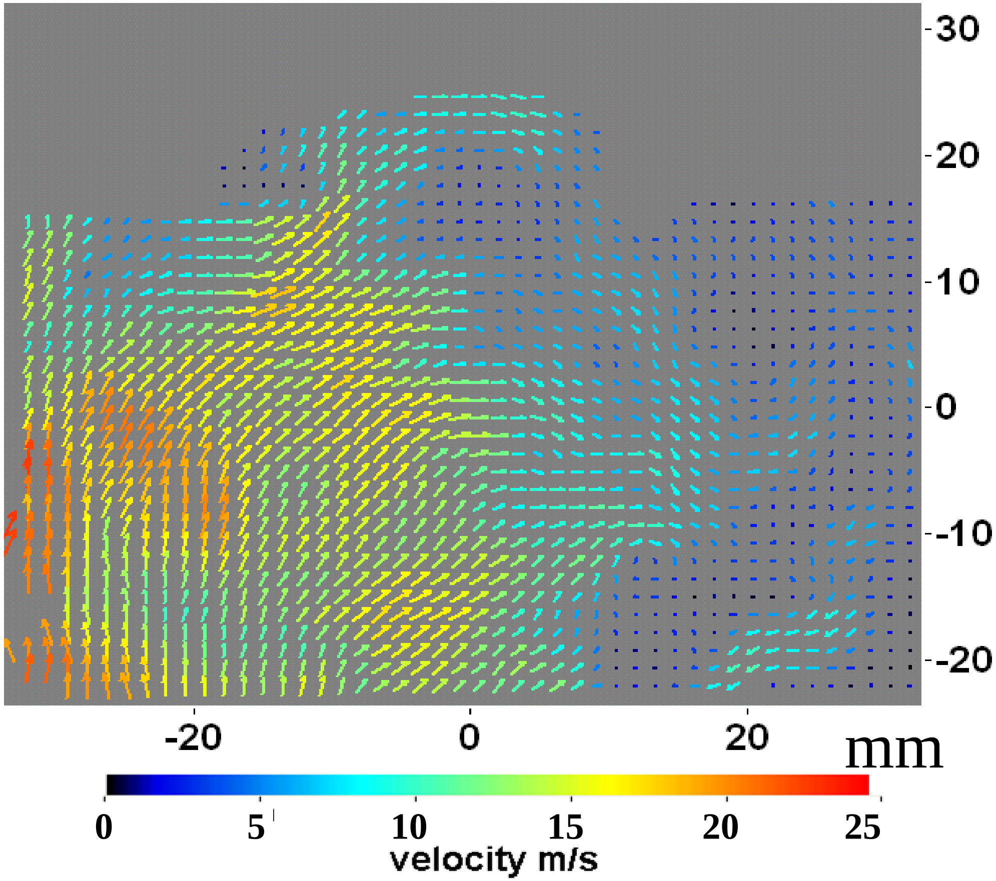
- **Particle Image Velocimetry (PIV)**
  - @ 16 kHz
  - 100 – 0 °bTDC
  - ~40x30mm²
  - 768x592px²
  - 273 cycles/run
- **<u>Challenges:</u>**
- **Scattered light off surfaces**
- **Contamination optical accesses**
- **Suitable PIV-seeding particles**
- **Optimized interval between laser illumination**



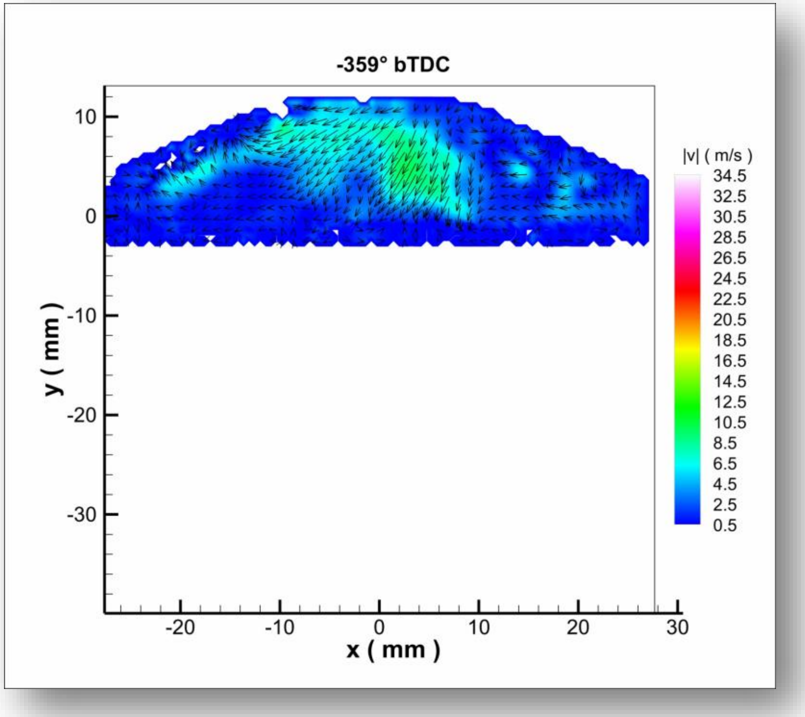
Stiehl et int. Dreizler. Flow Turbulence and Combustion (2013) 91:431 – 450

In-cylinder flow field measurements – 2C PIV

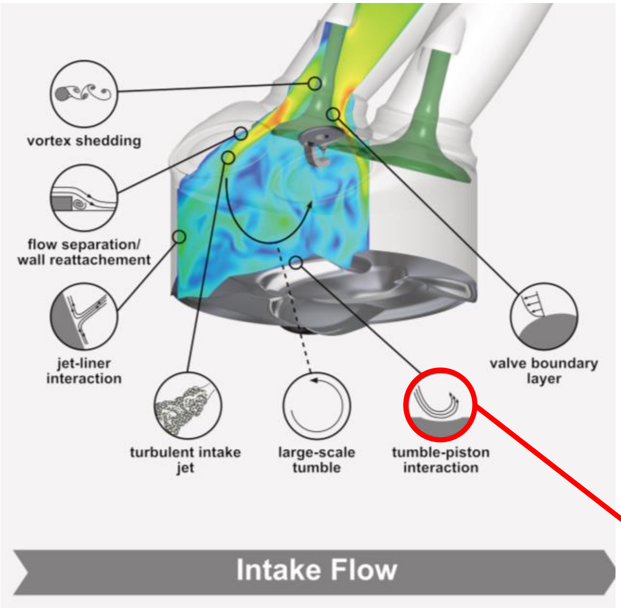
- **Particle Image Velocimetry (PIV)**
  - Up to 16 kHz
  - Different field of views
- **Challenges:**
- **Scattered light off surfaces**
- **Contamination optical accesses**
- **Suitable PIV-seeding particles**
- **Optimized interval between laser illumination**

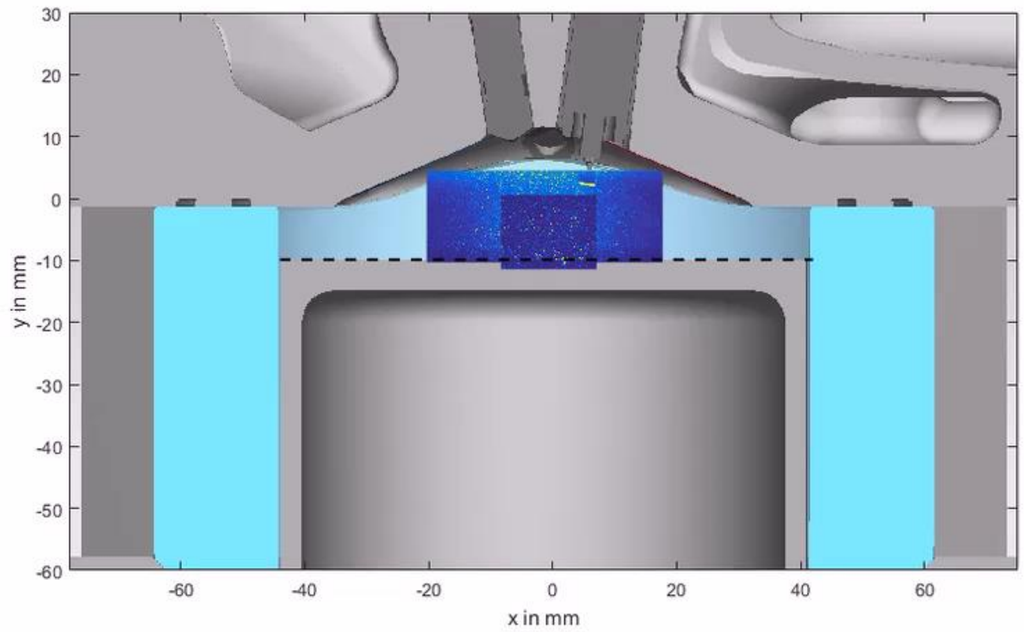


In-cylinder flow field measurements – 2C PIV, full cycle

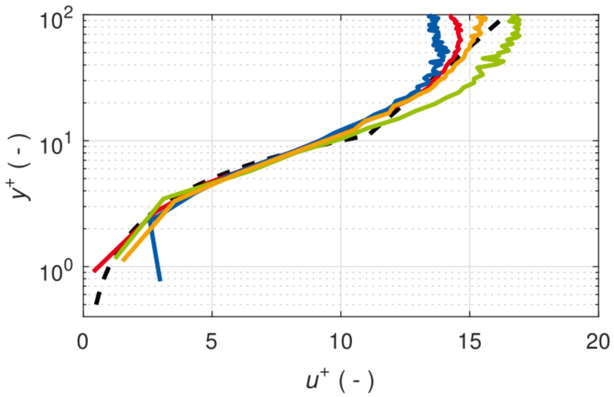


In-cylinder flow field measurements – 2C PIV





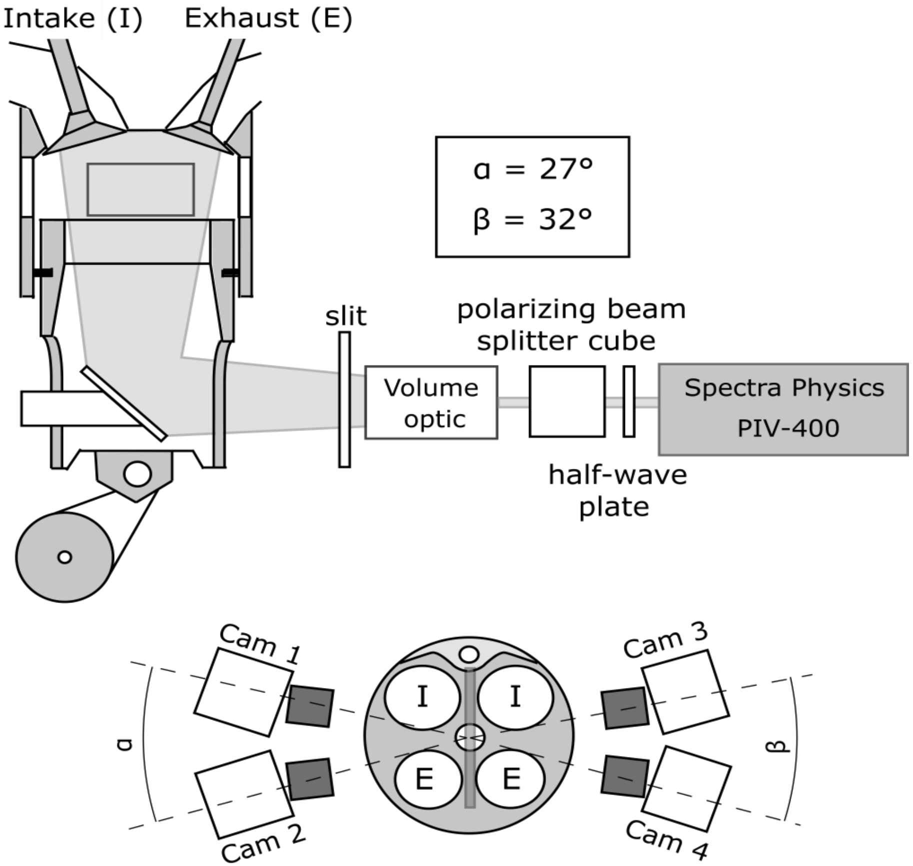
- Flow field measurements near walls
- Support model developement



Renaud et int. Dreizler, Böhm. International Journal of Heat and Fluid Flow 71, 366-377

Towards volumetric imaging: example TomoPIV

- **Illumination**
  - Dual-cavity laser (PIV400, Spectra Physics)
  - Avg. 375 mJ per single pulse
  - Phase-locked acquisition during intake and compression (<5 Hz)
  - Volume of: 48 x 35 x 4/8 mm
- **Detection**
  - Interline transfer CCD (ImagerIntense, LaVision, 1376x1040 pixels)
  - Nikon 50 mm, 1.4 (f# 16)
  - Limitation of Camera angles due to cylinder head bolts



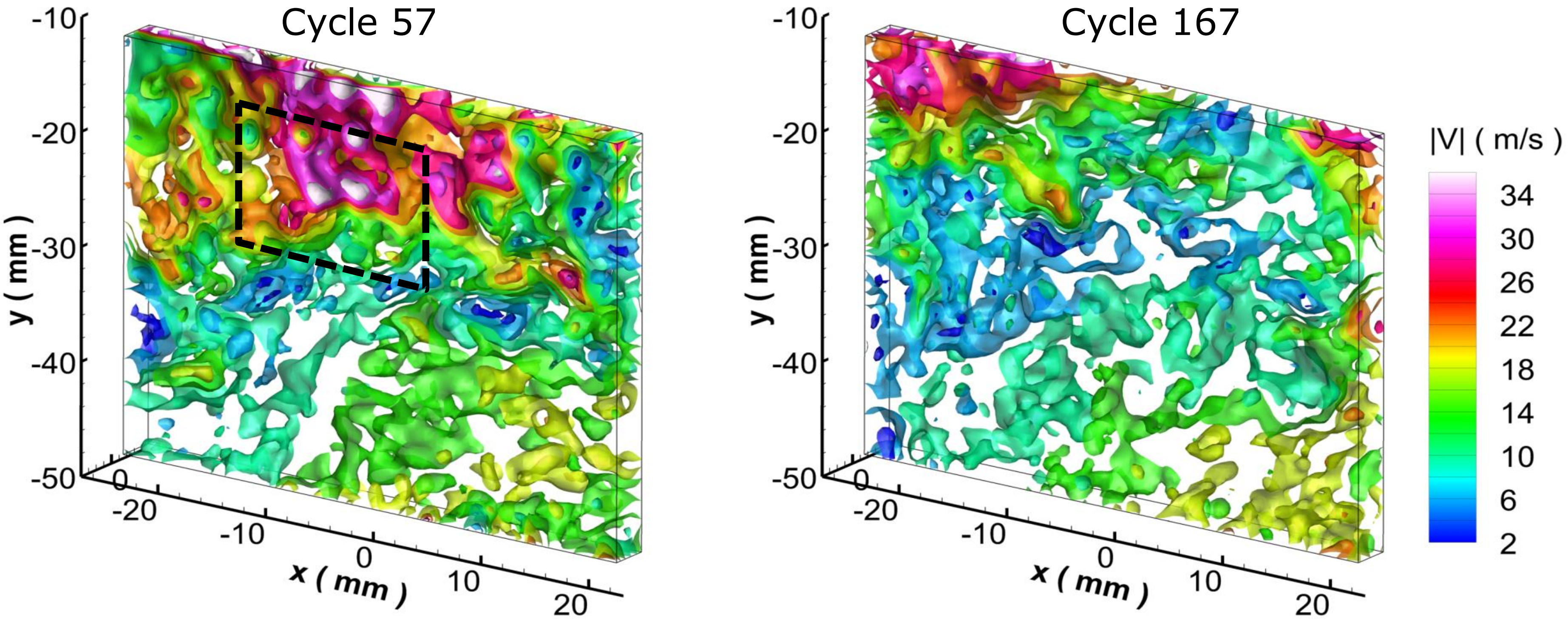
Baum et int. Dreizler. Proc. Combust. Inst. (2013) 34:2903 – 2910

Instantaneous Results

- **Iso-surfaces of instantaneous velocity magnitudes**

Intake stroke (270° bTDC)

Δz = 4 mm



Baum et int. Dreizler. Proc. Combust. Inst. (2013) 34:2903 – 2910

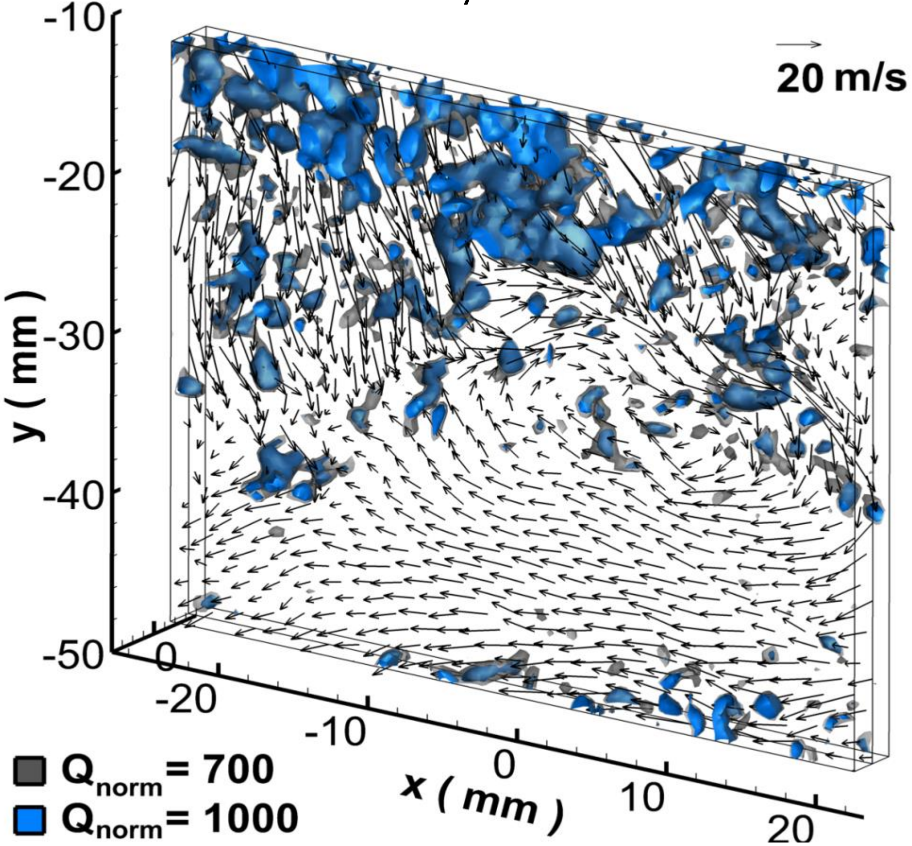
Instantaneous Results

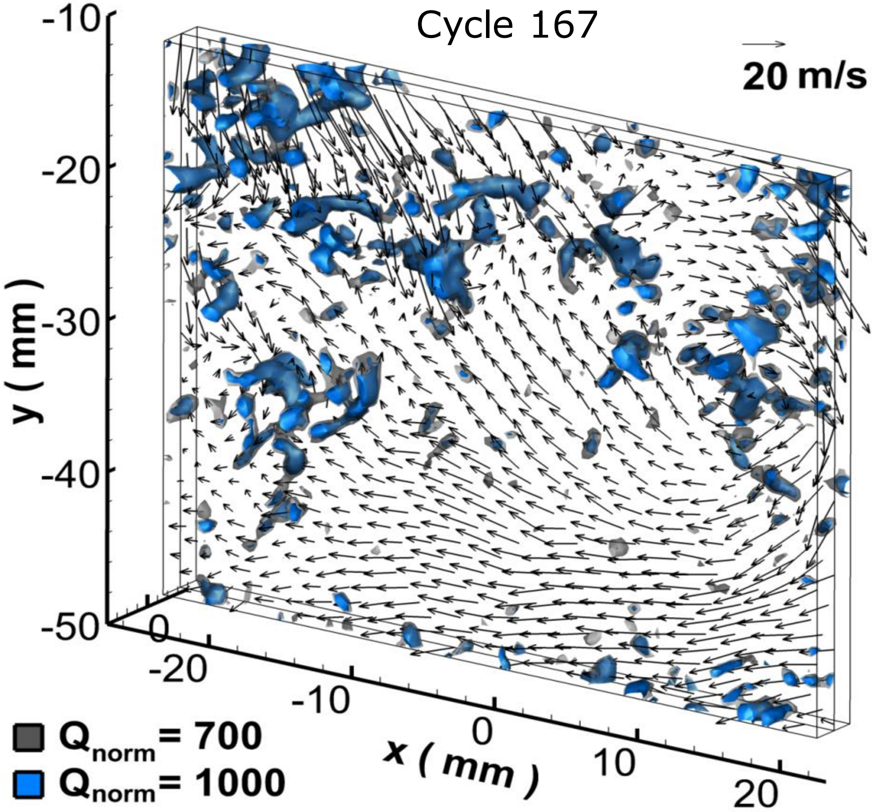
- Vortex region by second invariant of the velocity gradient tensor

Hunt et al., 1988: $$Q_{incompresible} = \frac{1}{2}\left(\left|\Omega\right|^2 - \left|S\right|^2\right) \geq 0\ ;\quad Q_{norm} = \frac{Q_{incomp.} d^2}{\left|v\right|}$$

d: bore; $|v|$:mean velocity

Cycle 59




Cycle 167

Conclusions – bench mark configurations

- Configurations of rising complexity and different geometries necessary to study different phenomena
- Optical access in atmospheric flames no problem
- Pressurized combustion (GT-combustor or IC-engine)
  - causes large investments for reliable, safe and reproducible operation
  - realization of optical access more difficult
- Improved characterization of inflow conditions needs more attention