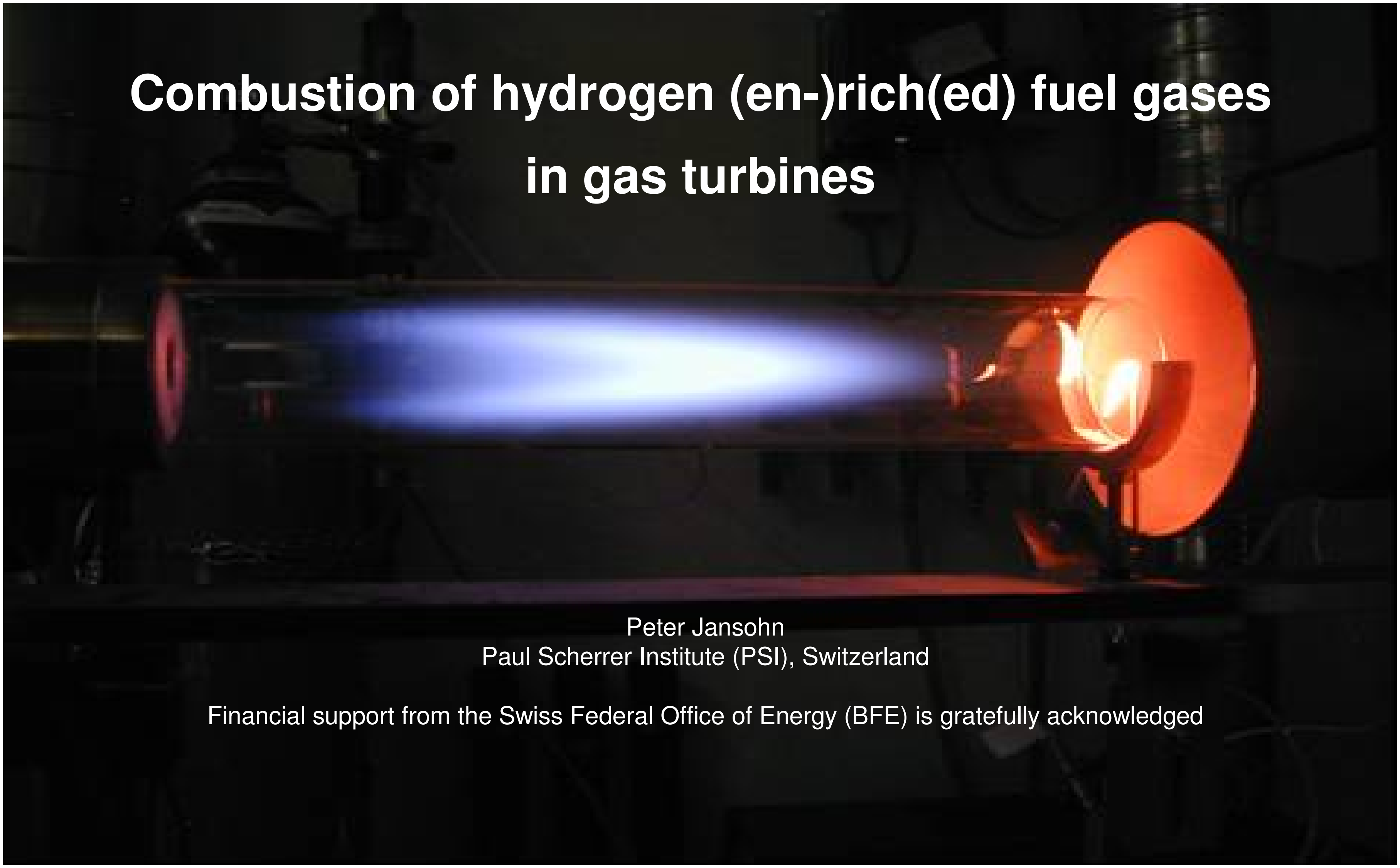
Combustion of hydrogen (en-)rich(ed) fuel gases in gas turbines



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Introduction

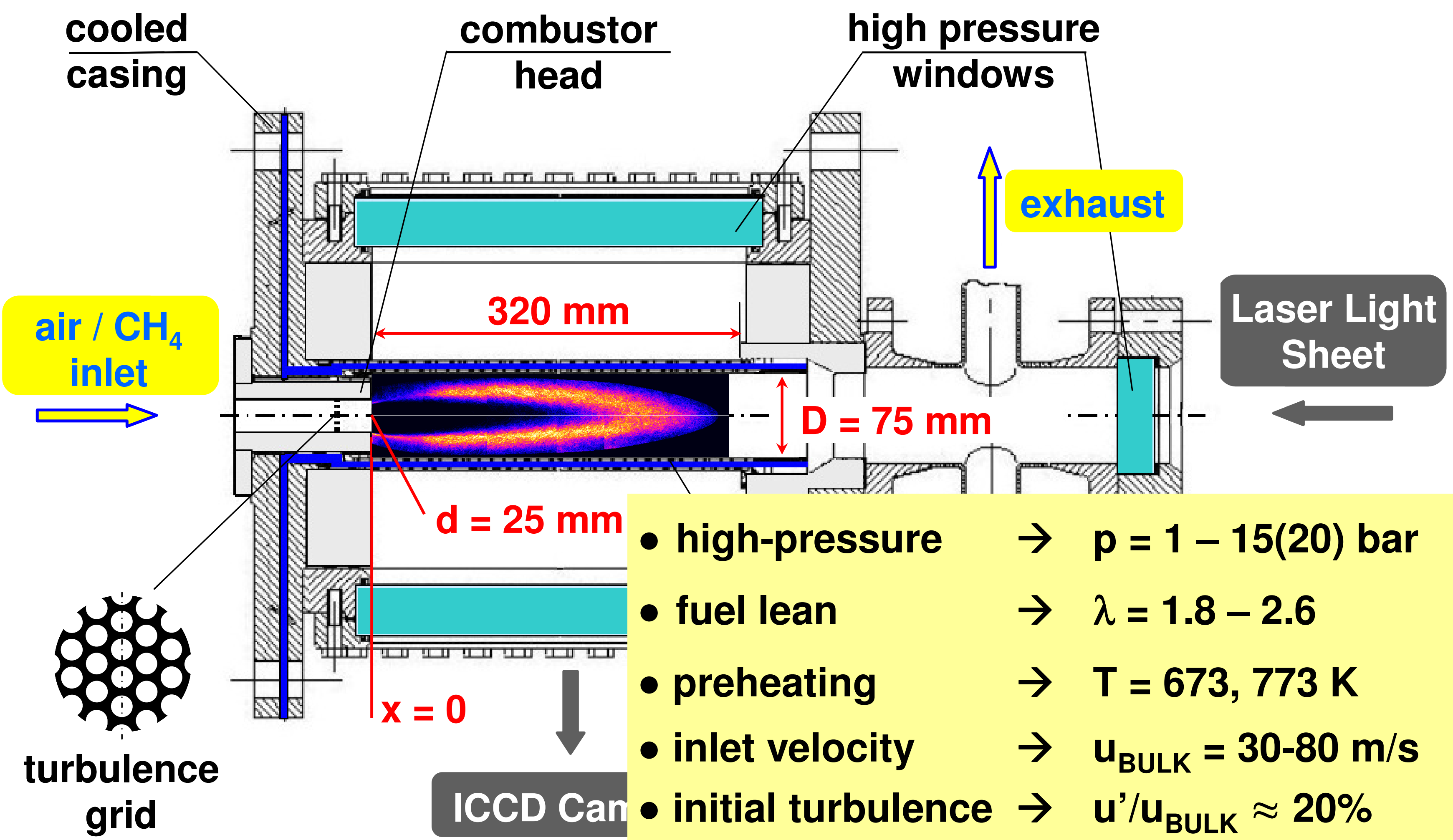
Motivation

- **improve lean premixed combustion technology for gas turbines**
  - improved flame stability (especially lean blow-out)
  - lower NO_x emissions
- **generation of experimental database for**
  - validation of numerical models
  - design rules for improved burner geometries

Objectives

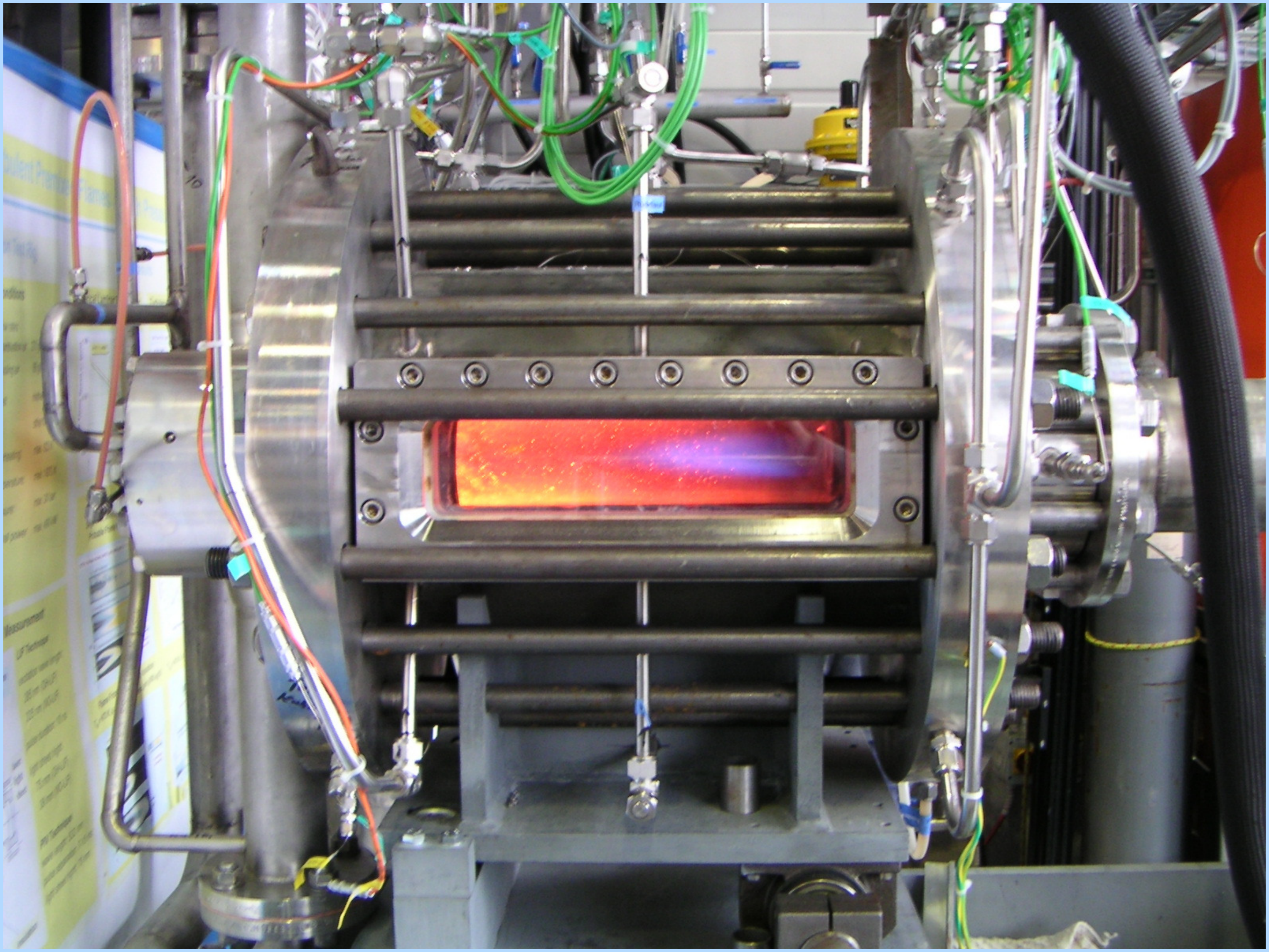
- **flame characterisation for a broad fuel spectrum (CH_4, CH_4/H_2, CH_4/C_3H_8, CO/H_2 (syngas), H_2 (>80%Vol.)) at gas turbine conditions (p: up to 20bar; $\Phi \approx 0.5$)**
  - influences of operating conditions and turbulence on flame structure (position, flame brush thickness, turbulent flame speed)
  - stability limits: Lean blowout (LBO), flashback
  - emissions: CO, NO_x

Experimental Set-up

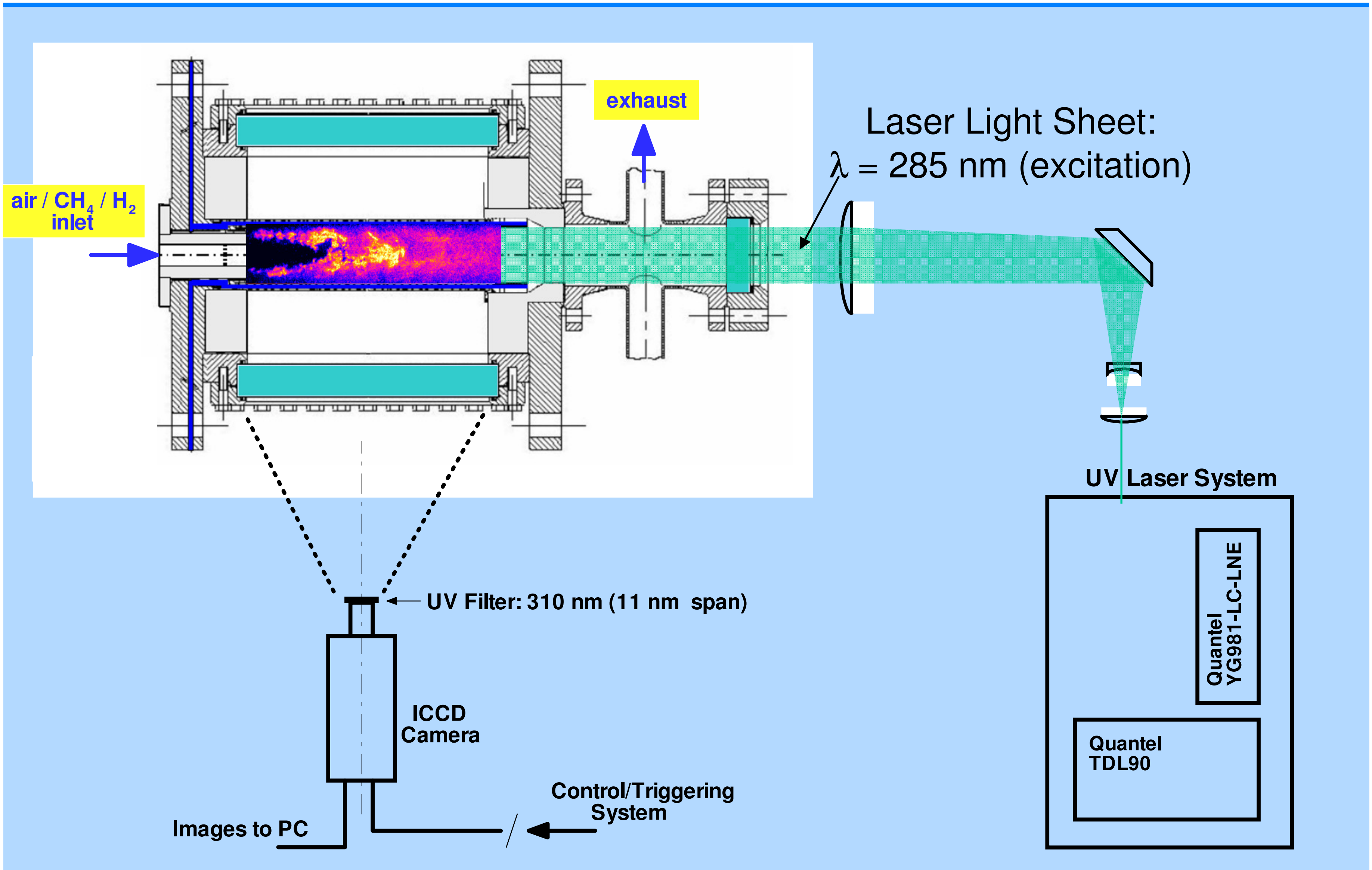


- high-pressure → p = 1 – 15(20) bar
- fuel lean → λ = 1.8 – 2.6
- preheating → T = 673, 773 K
- inlet velocity → u_{BULK} = 30-80 m/s
- initial turbulence → $u'/u_{BULK} \approx 20\%$
- fuels → CH_4, C_3H_8, CO, H_2

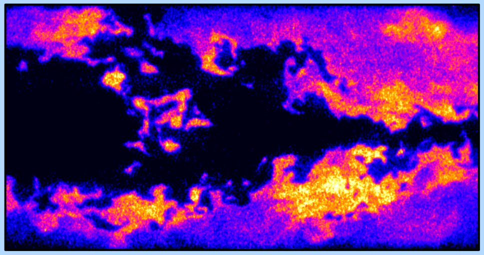
High pressure test rig



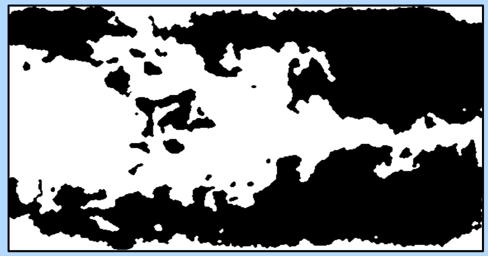
Experimental Setup: OH-PLIF



Flame Front Detection



Single shot OH-PLIF

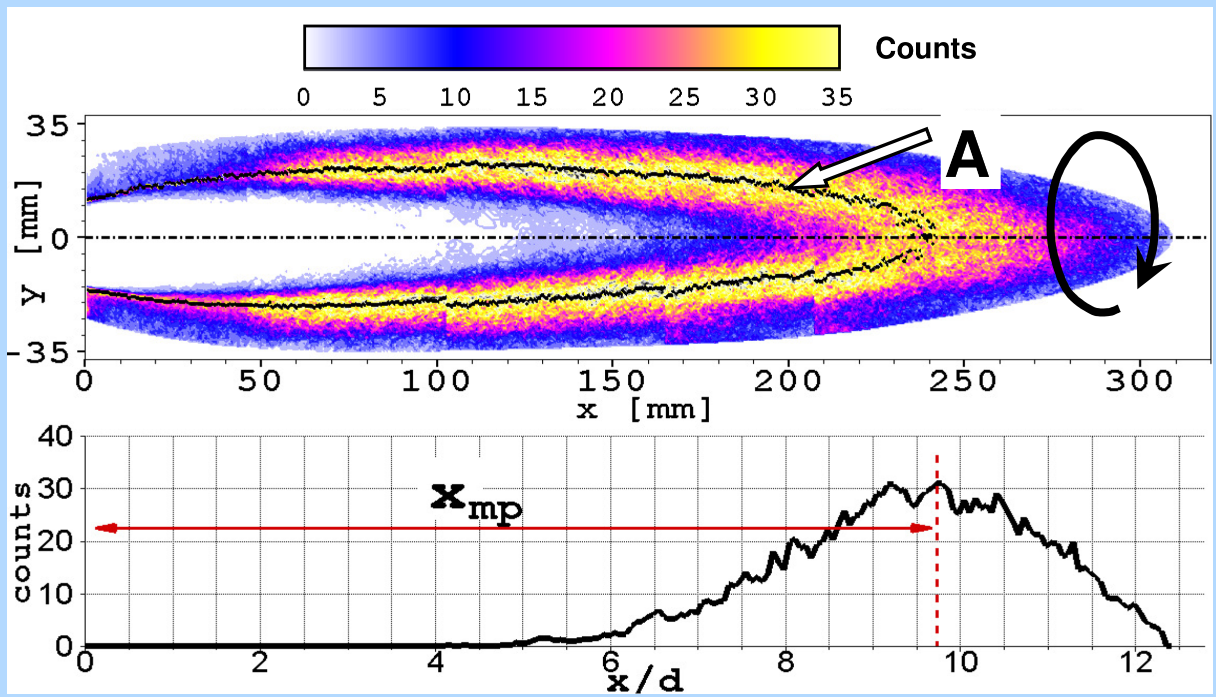


Binary image

Flame front contour

Turbulent flame speed:

$$S_T = u_{bulk} \cdot A_{inlet}/A$$



Statistical analysis (800 single shots) → most probable flame front position x_{mp}

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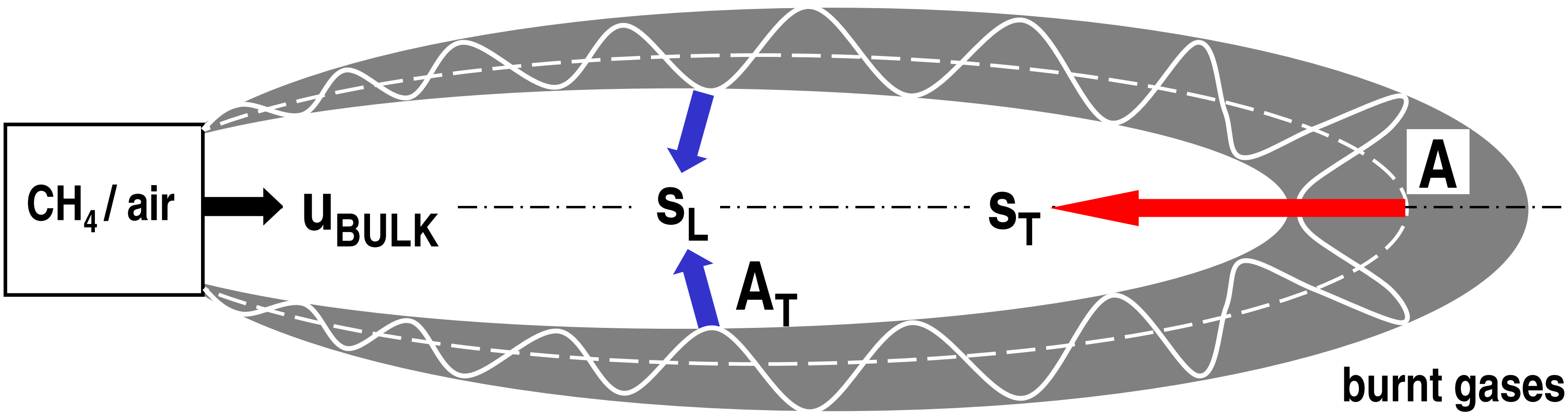
Turbulent Flame Speed



definition of s_T based on mass continuity with constant density assumption

$$\rho_0 u_{BULK} A_0 = \rho_u s_T A = \rho s_L A_T$$

$$s_T = u_{BULK} \frac{A_0}{A}$$

$$\frac{s_T}{s_L} = \frac{A_T}{A}$$

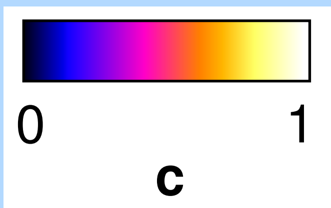
Turbulent Flame Speed S_T

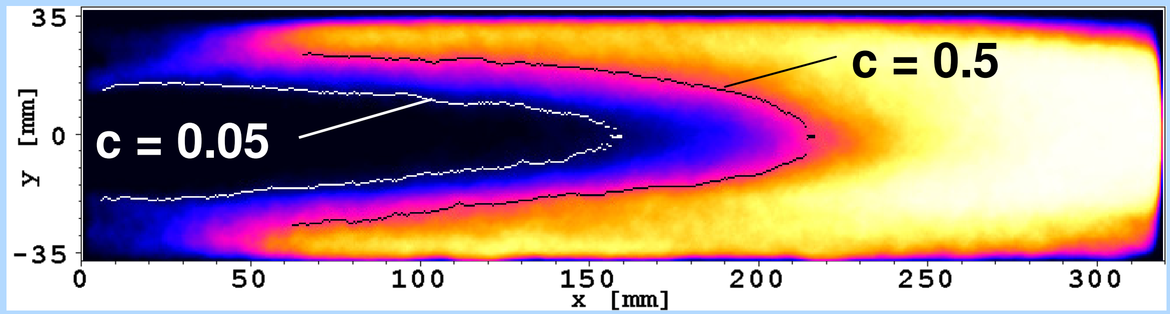
Progress Variable Approach

progress variable definition:

(e. g. normalised temperature, mass fractions, here OH-PLIF Signal); u = unburnt, b = burnt

$$c = \frac{T(z) - T^u(z)}{T^b(z) - T^u(z)}$$

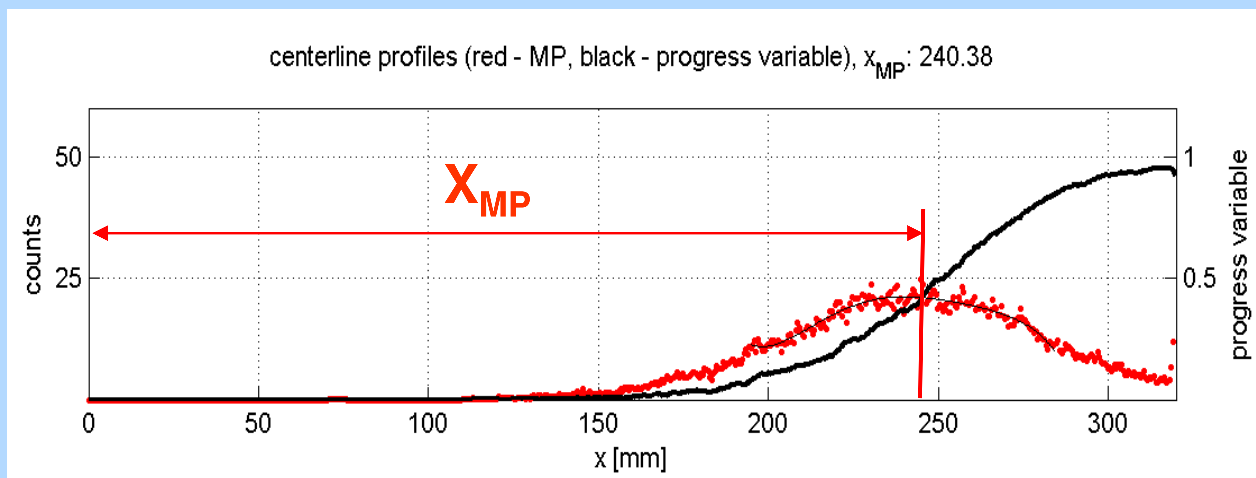




Turbulent flame speed:

$$S_T = u_{bulk} \cdot A_{inlet}/A$$

A calculated based on c=0.05



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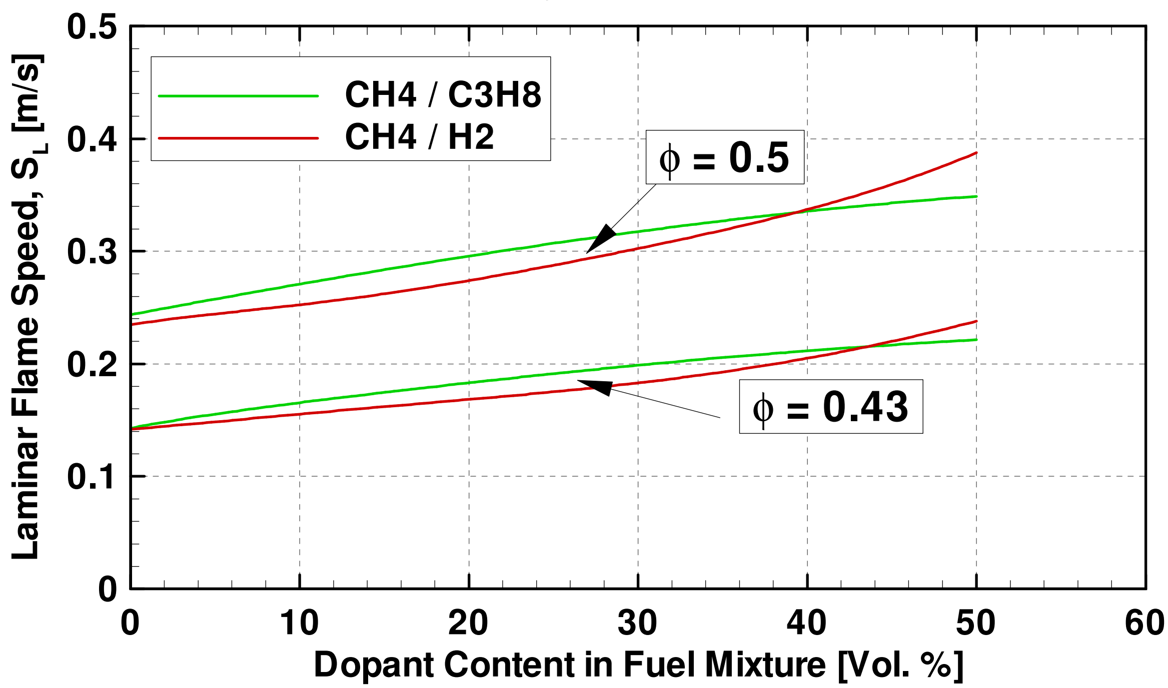
Focus

Enhanced Flame Stability

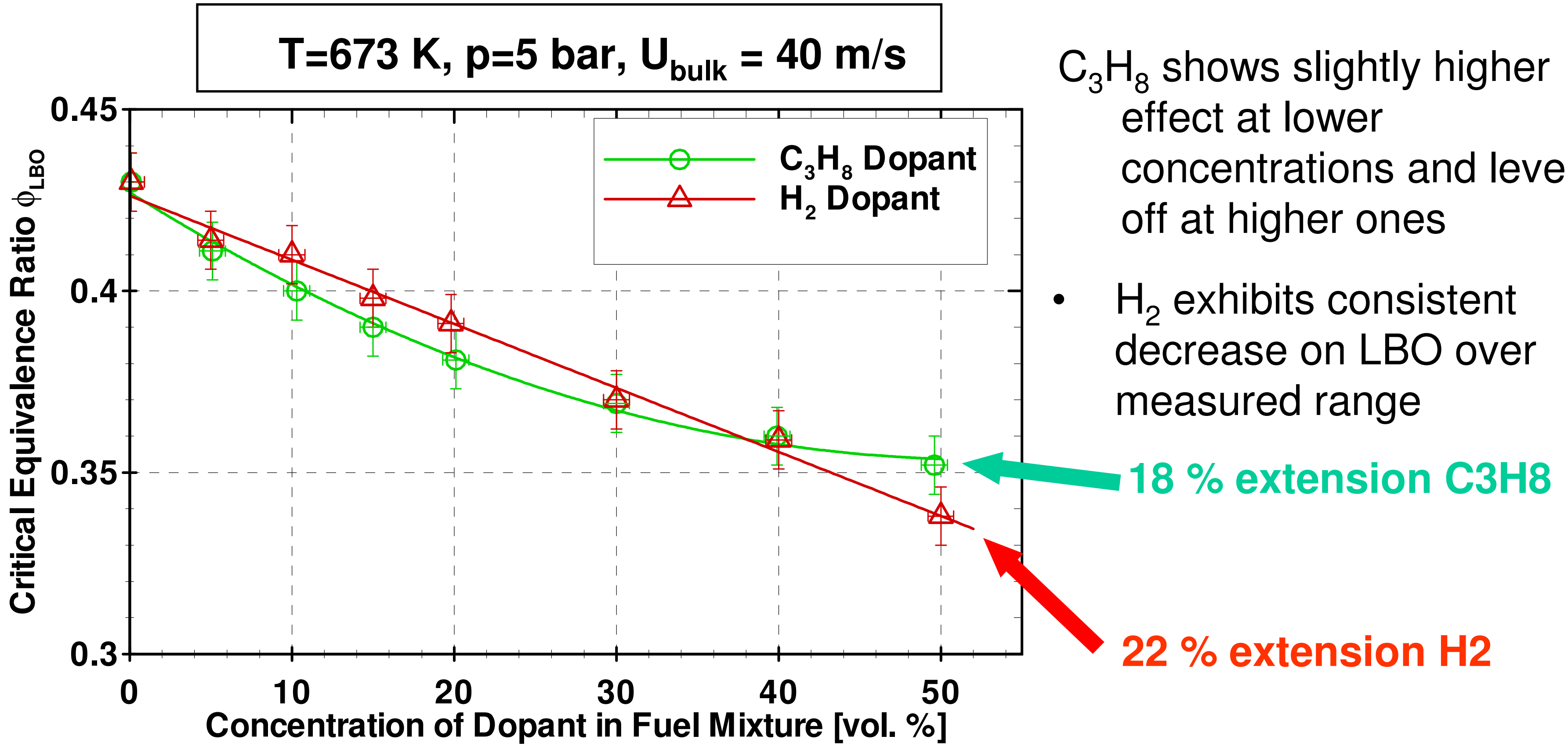
(H_2-CH_4/air flames)

- Base Fuel is methane (CH_4) → main constituent of natural gas
- hydrogen (H_2) is added to enhance lean flame stability
  1. Highly reactive – high laminar flame speed
  2. Extremely light and diffusive
- higher hydrocarbons C_2+ represented by propane (C_3H_8)
  1. More reactive than methane - higher laminar flame speed
  2. Heavier molecule: lower diffusivity



GRI-mech 3.0

Lean Blowout Limits (LBO): Influence of Fuel Blend

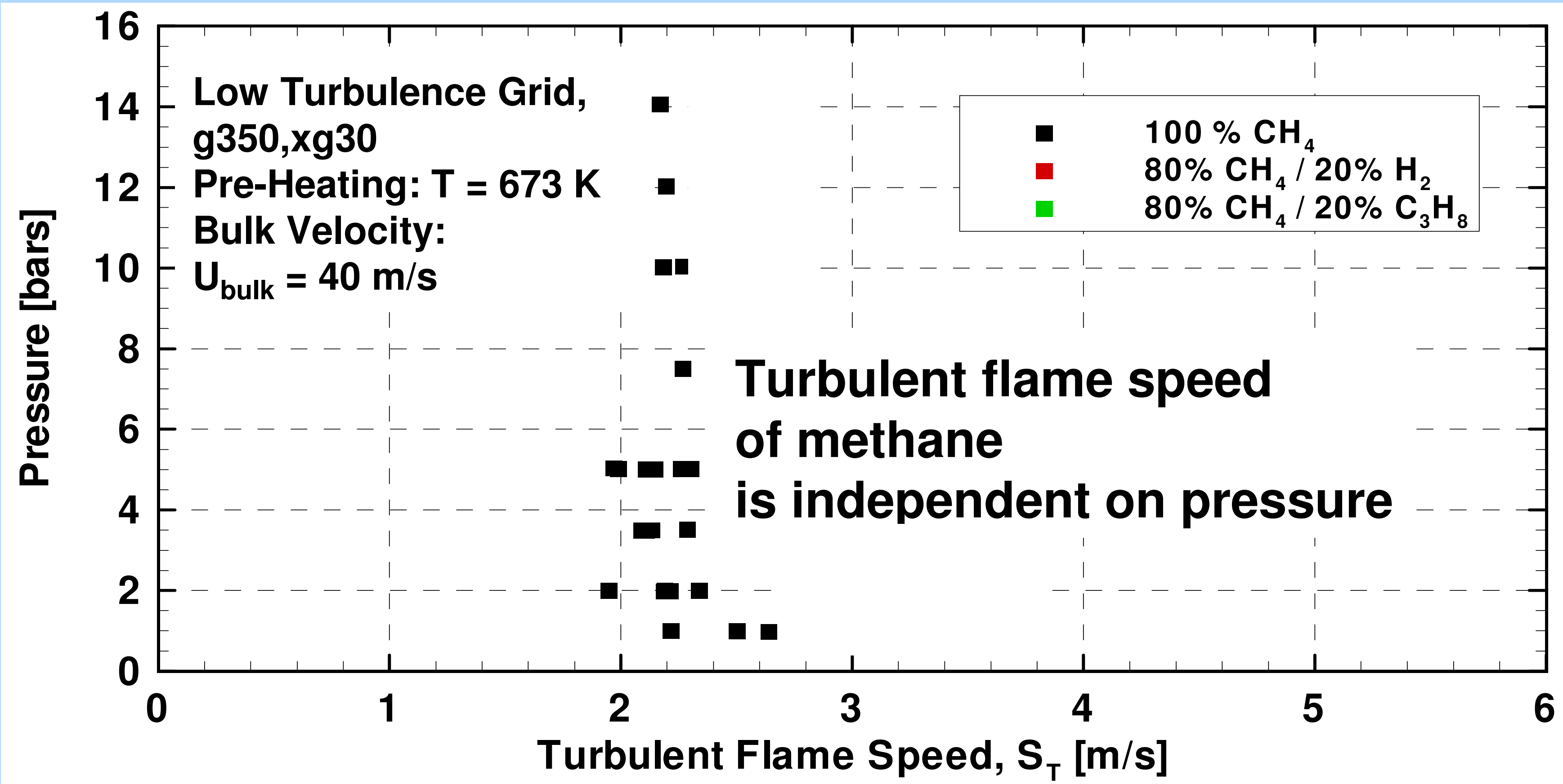


- C_3H_8 shows slightly higher effect at lower concentrations and levels off at higher ones
- H_2 exhibits consistent decrease on LBO over measured range

- Hydrogen results agree well with a study in a swirl stabilized combustor [1] which showed ~23 % extension at 50 % H_2 (Pressures 1, 4, 8 atm).

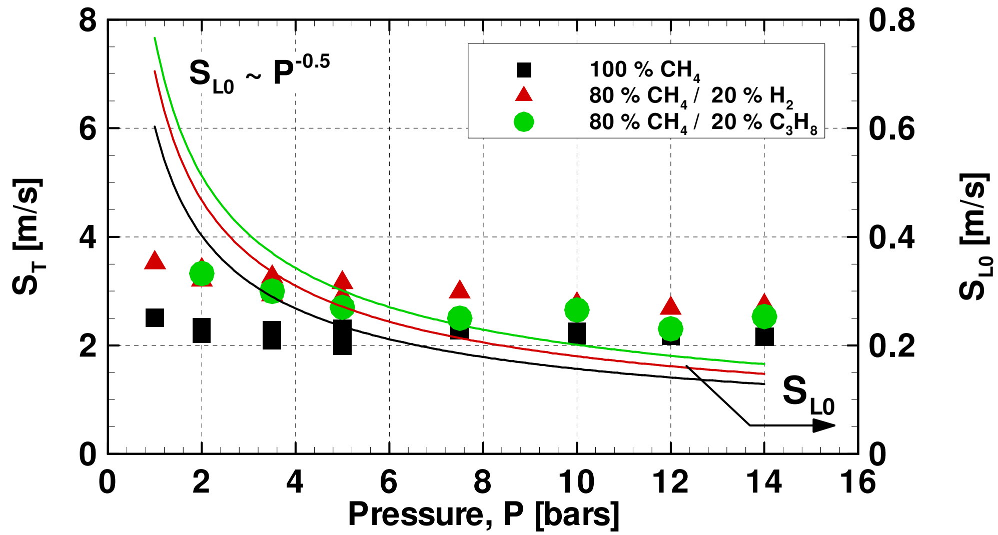
[1] Strakey, P., Sidwell, T., Ontko, J. *Investigation of the effects of hydrogen addition on lean extinction in a swirl stabilized combustor*, *Proceedings of the Combustion Institute*, 31(2), 3173-3180, (2007).

Turbulent Flame Speed



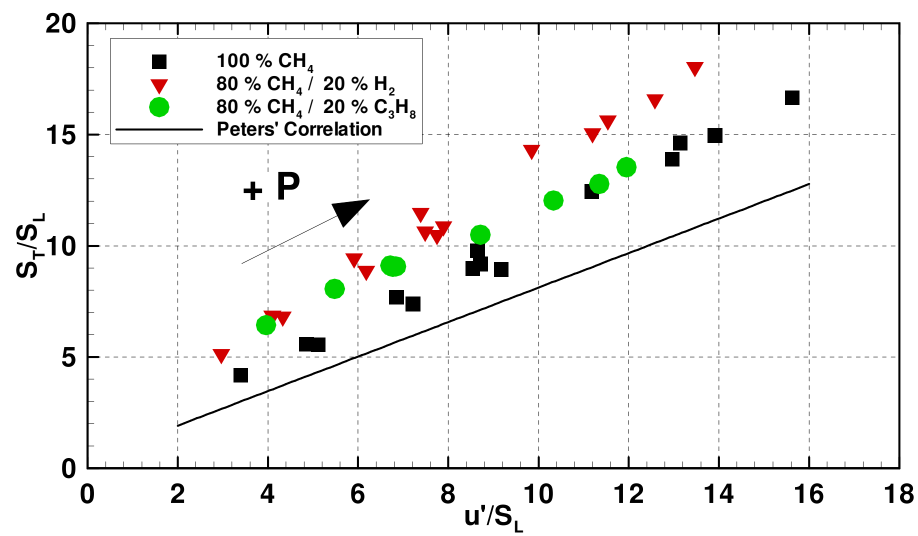
**Turbulent flame speed of methane mixtures (with C_3H_8, H_2)
is dependent on pressure
(even though the effect is very small above 10 bar)**

Turbulent Flame Speed: Influence of Pressure



- Laminar flame speed is heavily dependent on pressure
- Turbulent flame speed is nearly independent of pressure for the three mixtures
- The increase in Re_T by increasing the pressure decreases the size of the smallest turbulent eddies

- The resulting increase in turbulent flame surface counteracts the decrease of laminar flame speed
- Confirms results of prior PhD work (P. Siewert) on pure methane/air flames



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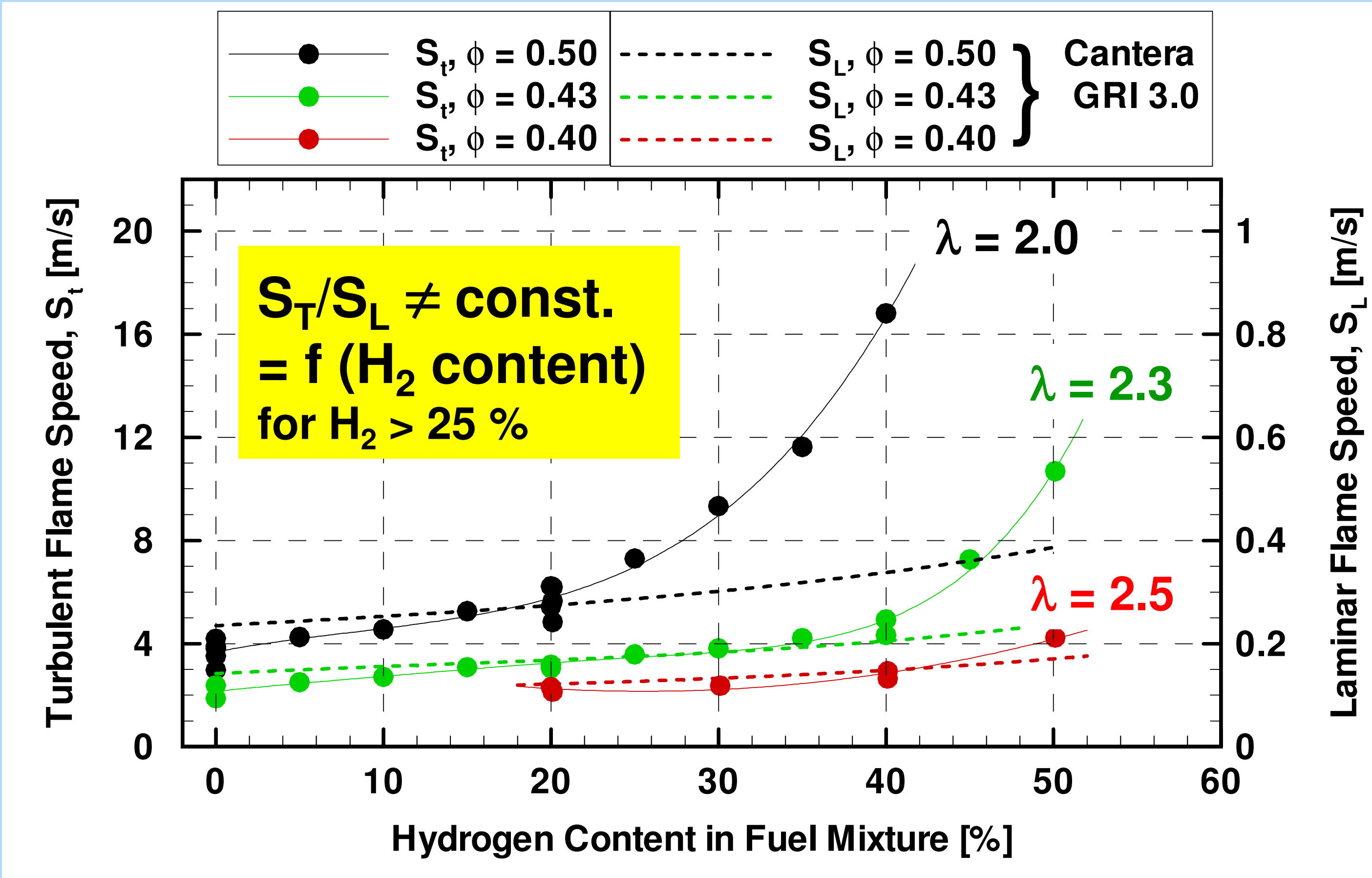
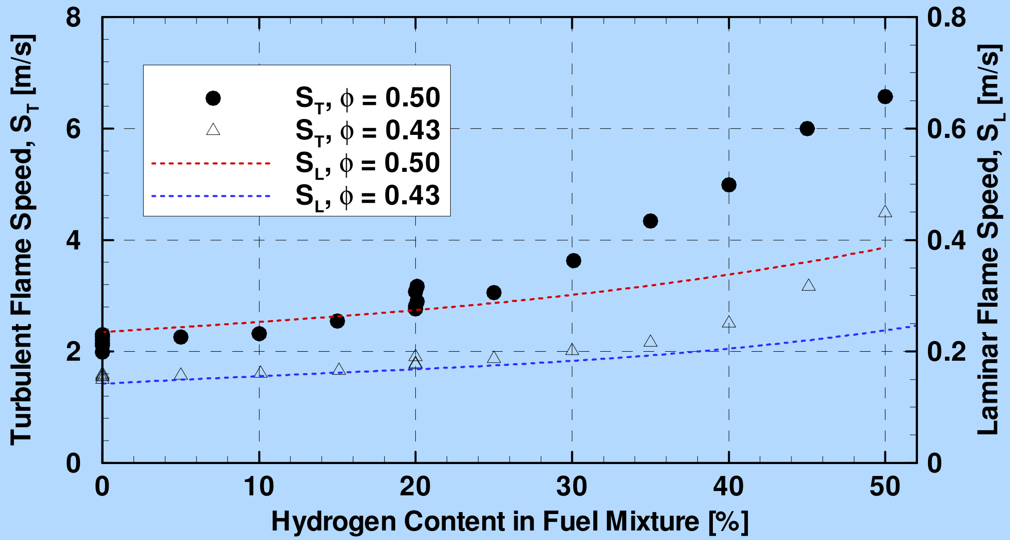
Turbulent Flame Speed

673 K, 5 bar, 40 m/s, grid g365,xg10



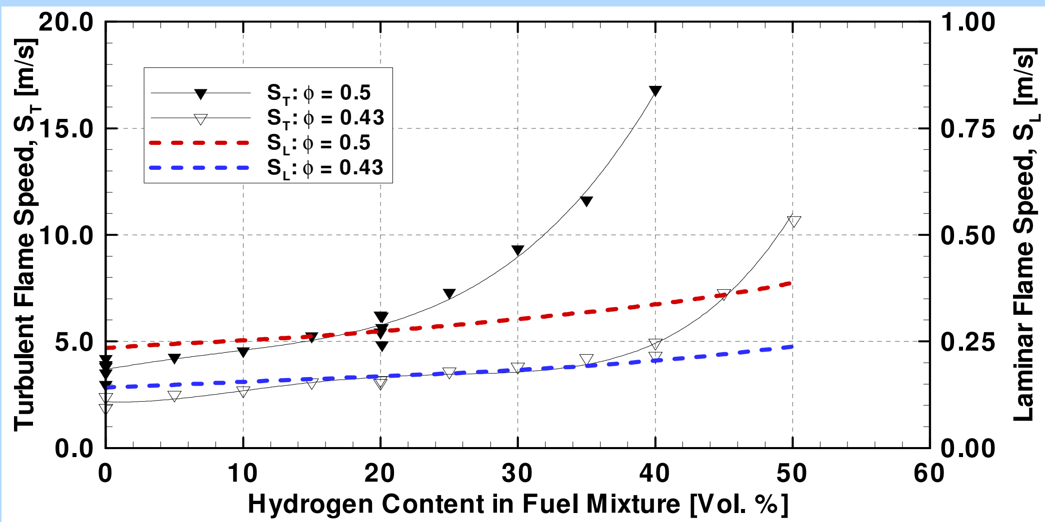
Up to approx. 25 % Vol. H_2: chemical kinetics dominate (S_T/S_L const.)
H_2 > 25 % Vol.: additional effects (preferrential diffusion, stretch)

Turbulent Flame Speed



Low Turbulence **Grid,**
g350,xg30
Pre-Heating: T = 673 K
Bulk Velocity: U_{bulk} = 40 m/s
Pressure = 5 bars

$S_T/S_L \neq$ const.
= f (H_2 content)
for H_2 > 25 %



High Turbulence **Grid,**
g350,xg30
Pre-Heating: T = 673 K
Bulk Velocity: U_{bulk} = 40 m/s
Pressure = 5 bars

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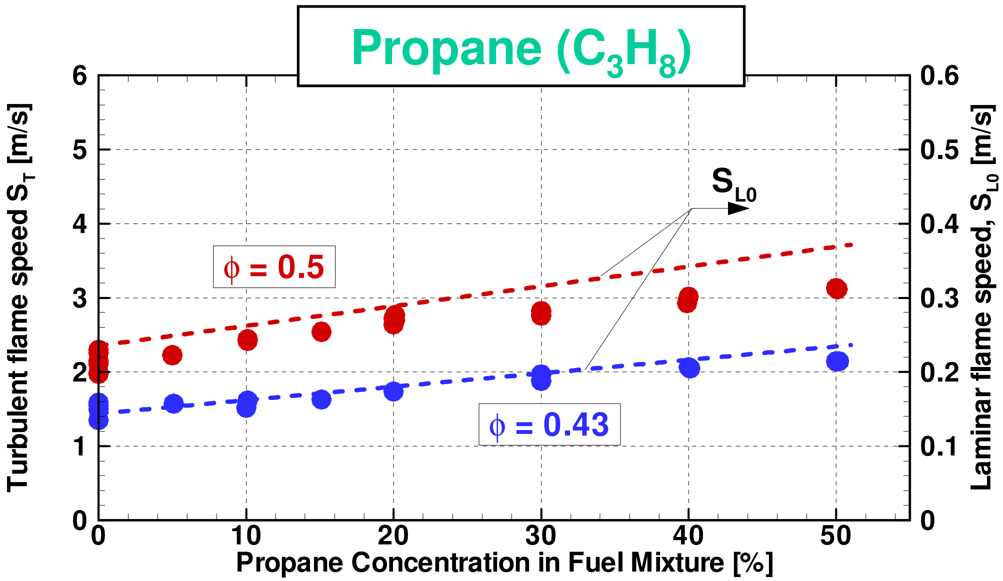
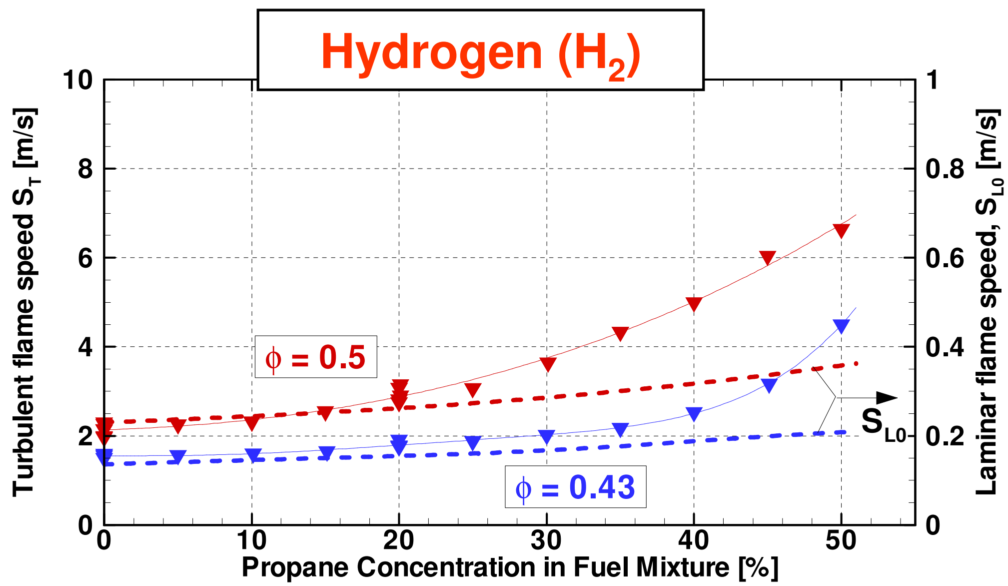
Turbulent Flame Speeds: Influence of Fuel Blend



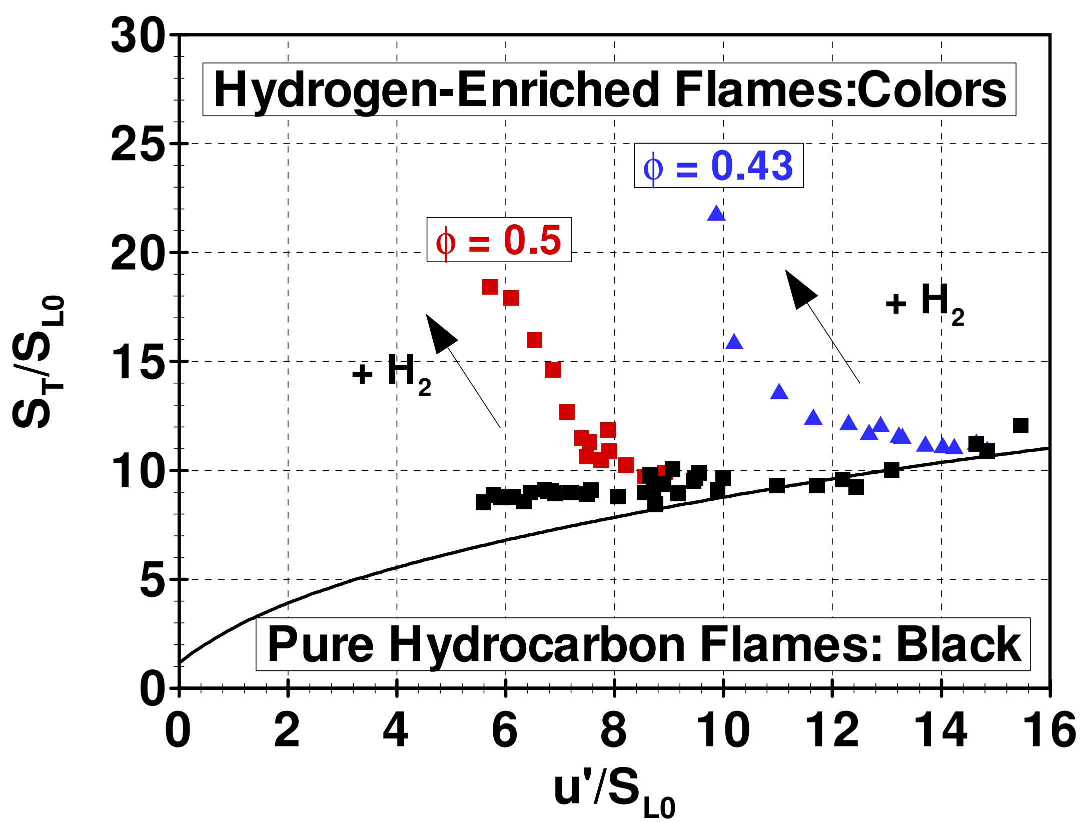
- Effect of C_3H_8 addition:
  1. Trend is consistent for both f
  2. Turbulent flame speed trend seems to be dominated by chemistry
  3. Constant $S_T/S_L \approx 10$ in the measured range (100 % CH_4 – 50 %C_3H_8)

- Effect of H_2 addition:
  1. S_T deviates greatly from S_L trend, especially at higher hydrogen content. i.e. more than just chemical effect
  2. Effect is less pronounced for leaner mixtures.



Turbulent Flame Speeds

- Effect of turbulence intensity:
  1. Generally, increasing turbulence level (u'/SL) increases the enhancement of flame speed (S_T/S_L) but reaches asymptotic maximum (onset of quenching)
  2. Hydrocarbon flames (methane and propane) fit well with this trend
  3. Hydrogen enrichment exhibits a fundamentally different behavior – significant influence of stretch effects on laminar flame speed require correction terms



Unexpected Result: Decreasing Turbulence Level increases $S_T/S_{L,0}$

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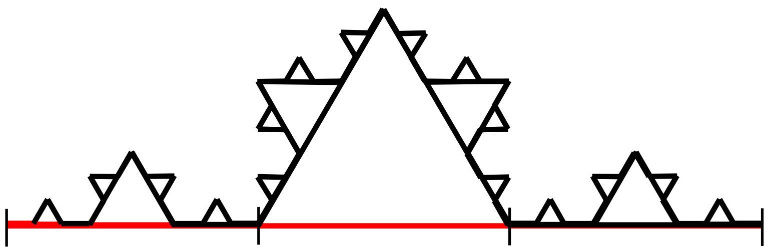
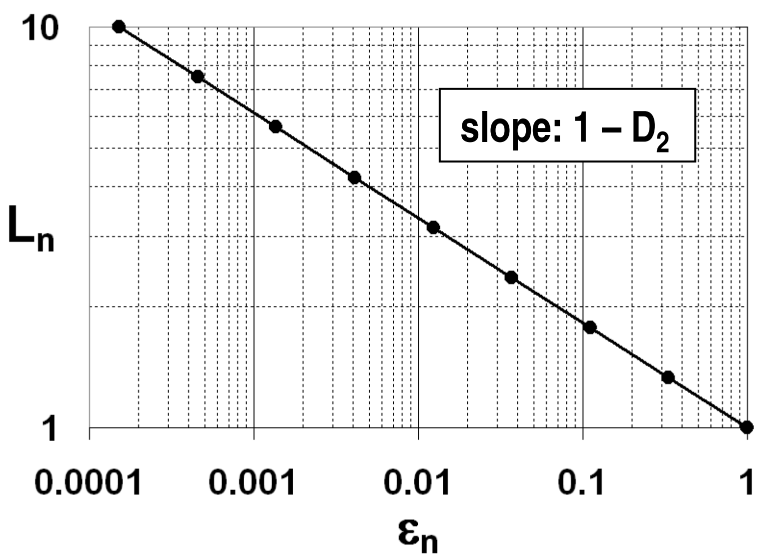
Fractals

self-similar geometry → fractal



ε_n – length scale L_n – length of a curve



relation between scale (ε_n) and length (L_n)

$$L_n \sim \varepsilon_n^{(1-D_2)}$$

D_2 - fractal dimension of a curve

D_2 is a measure of corrugation

Smooth curve:	$D_2 = 1$
Koch curve:	$D_2 = 1.26$

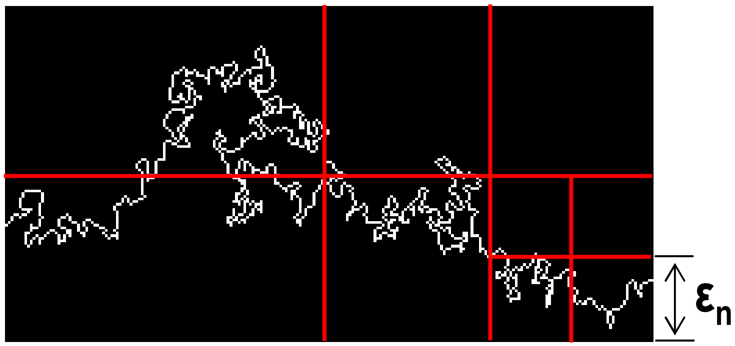
length L_n and surface A_n relation

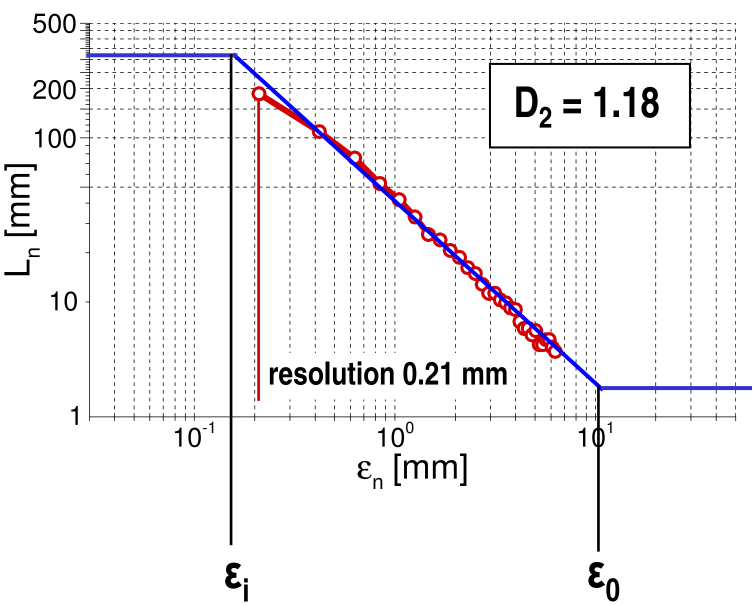
$$A_n \sim \varepsilon_n^{(1-D_3)}$$

$$D_3 = D_2 + 1$$

Fractal Nature of the Flame Front

fractal dimension of a flame front





inner and outer cut-off scales

outer cut-off scale (ε_0)

the largest scale → Integral Length Scale (L_T)

inner cut-off scale (ε_i)

the smallest scale able to wrinkle the flame front

turbulent flame speed (s_T) – fractal approach

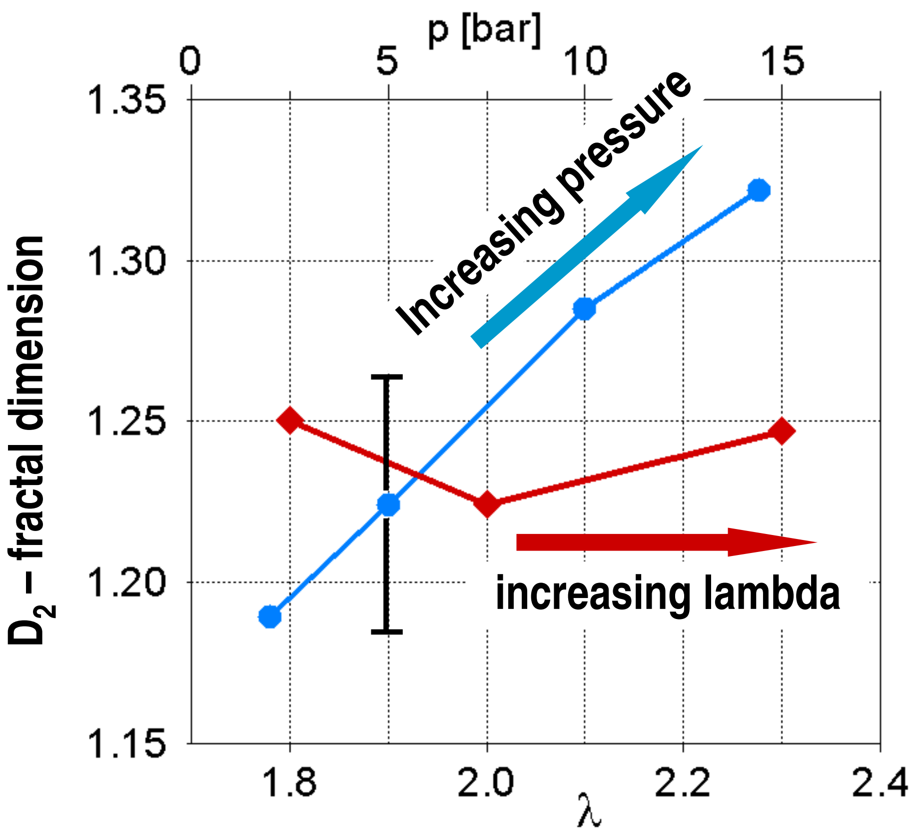
$$\frac{s_T}{s_L} = \frac{A_T}{A} = C \cdot \left(\frac{\varepsilon_0}{\varepsilon_i}\right)^{D_3 - 2} = \left(\frac{L_T}{\eta}\right)^{D_2 - 1}$$

Assumption:

inner cut-off scale is equal to Kolmogorov scale

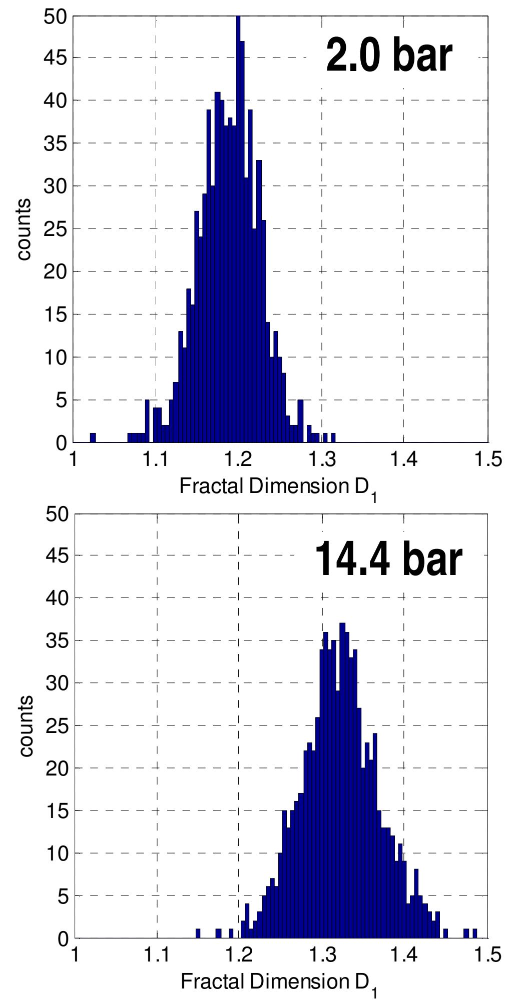
$$L_T / \eta \sim Re_T^{\,3/4} \sim p^{\,3/4}$$

Fractals Dimension D = f(p, λ)

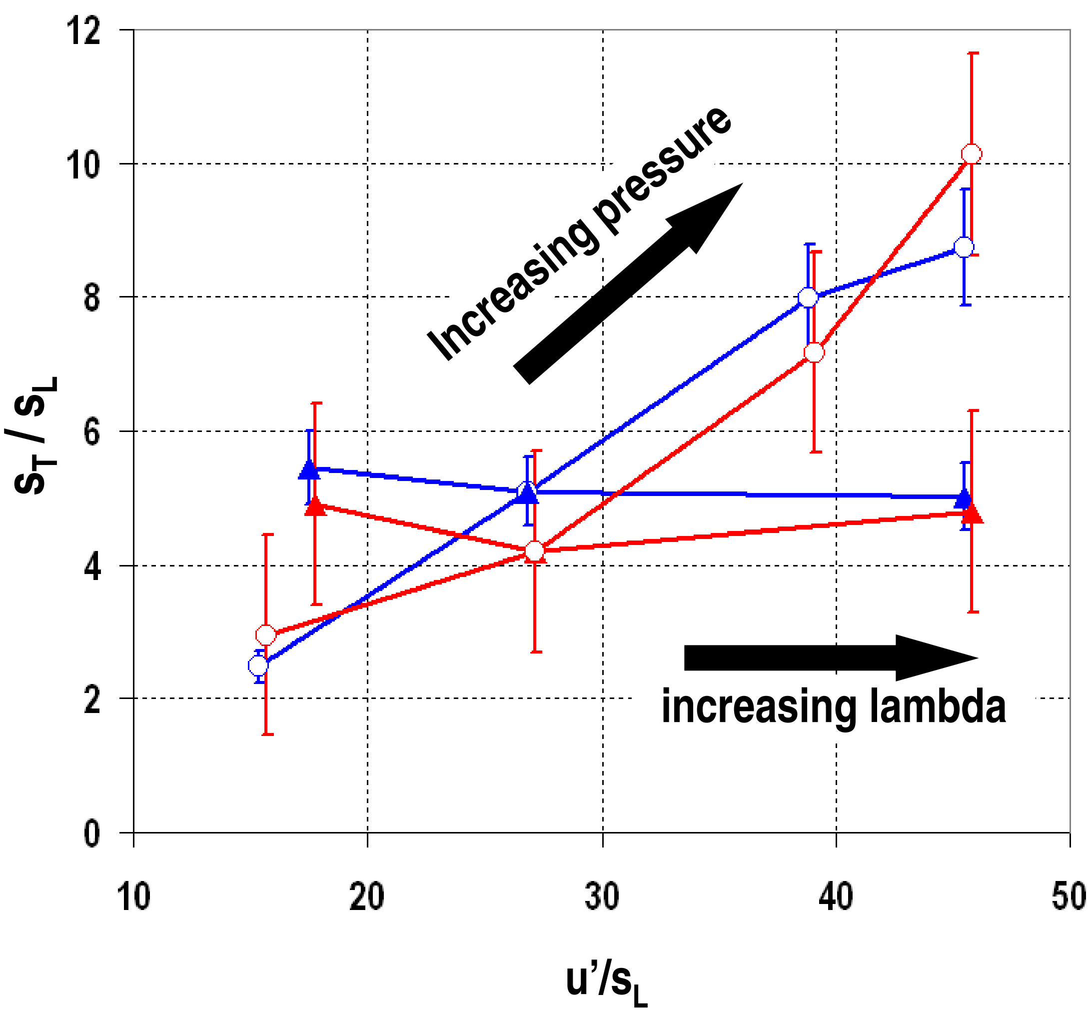


flame front corrugation (D_2)
- increases with pressure
- is independent of lambda

D_2 based on 800 single shots



s_T / s_L – Fractals Approach



fractal analysis confirms trends and values of s_T/s_L

fractal approach based on the instantaneous flame front surface

classical approach based on the average flame front surface

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Outlook

1. **Flame characterisation for a broad fuel spectrum at GT conditions (high-pressure test rig):**

- **H_2- CH_4/air flames (ongoing work)**

  determine fundamental reasons for specific characteristics
  (turbulent flame speed at high H_2 content)

  <u>approach:</u>
  apply fractal analysis; derive stretch effects
  (evaluate correction factor: Markstein length)

$$\boxed{\frac{S_L}{S_{L,0}} = 1 - Ma \cdot Ka}$$

- **Syngas (H_2/CO/inerts) combustion**

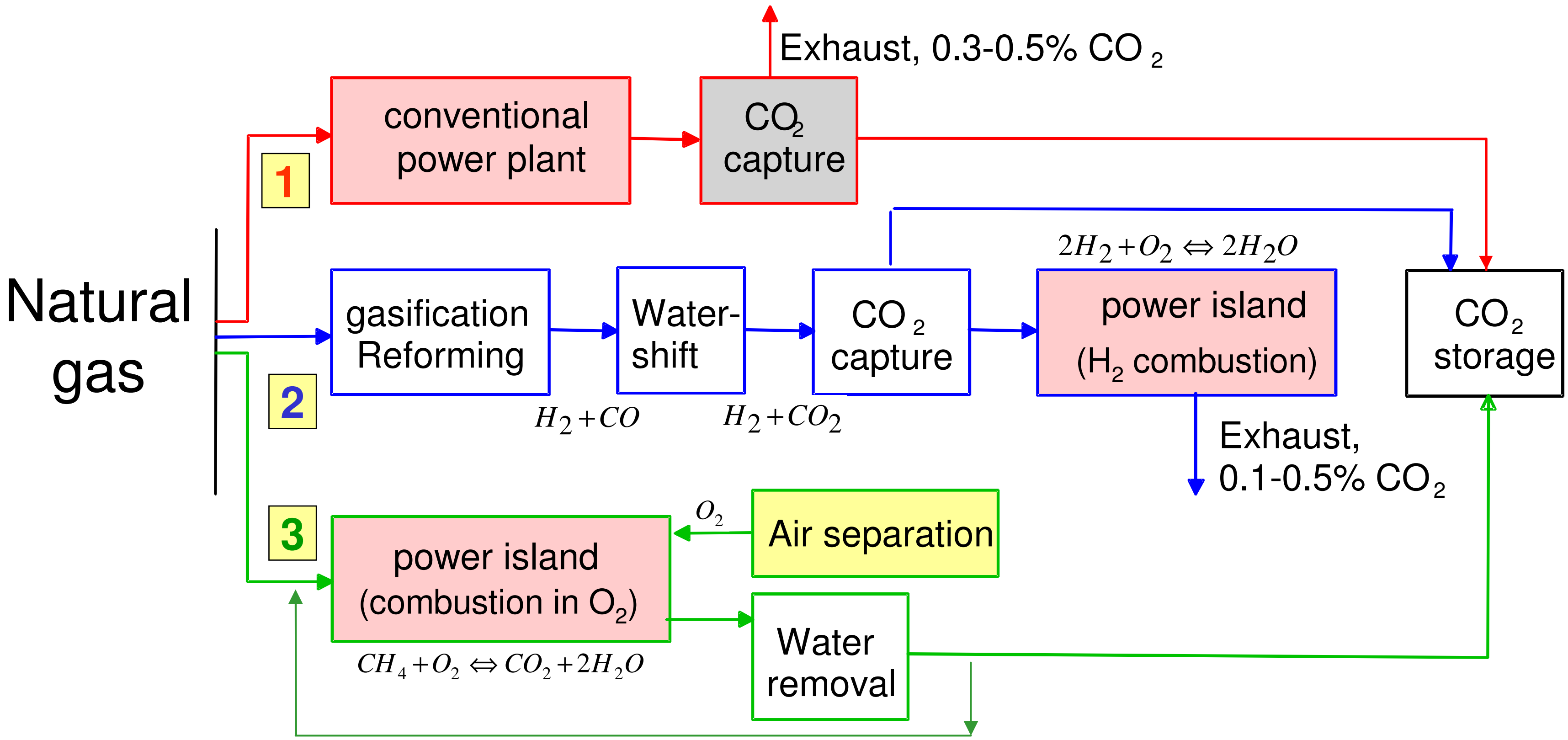
  study flame characteristics (LBO/flashback, NOx emission, flame speed)

  <u>motivation:</u> demonstrate & understand safe, low-emission combustion of fuel gases derived from gasification of solid fuels (biomass, coal, …)

- **combustion of hydrogen rich fuel mixtures (> 80%Vol. H_2; rest: CO, inerts)**

  study flame characteristics of fule mixtures derived from pre-combustion decarbonization process schemes

Gasturbine Technologies for CO_2-free power generation



1: Tail End Measure

2: Front End Measure

3: Integrated Measure: Oxy-fuel (λ=1; combustion in O_2)

Fuel Decarbonization