Experimental analysis of hydrogen combustion @IMFT

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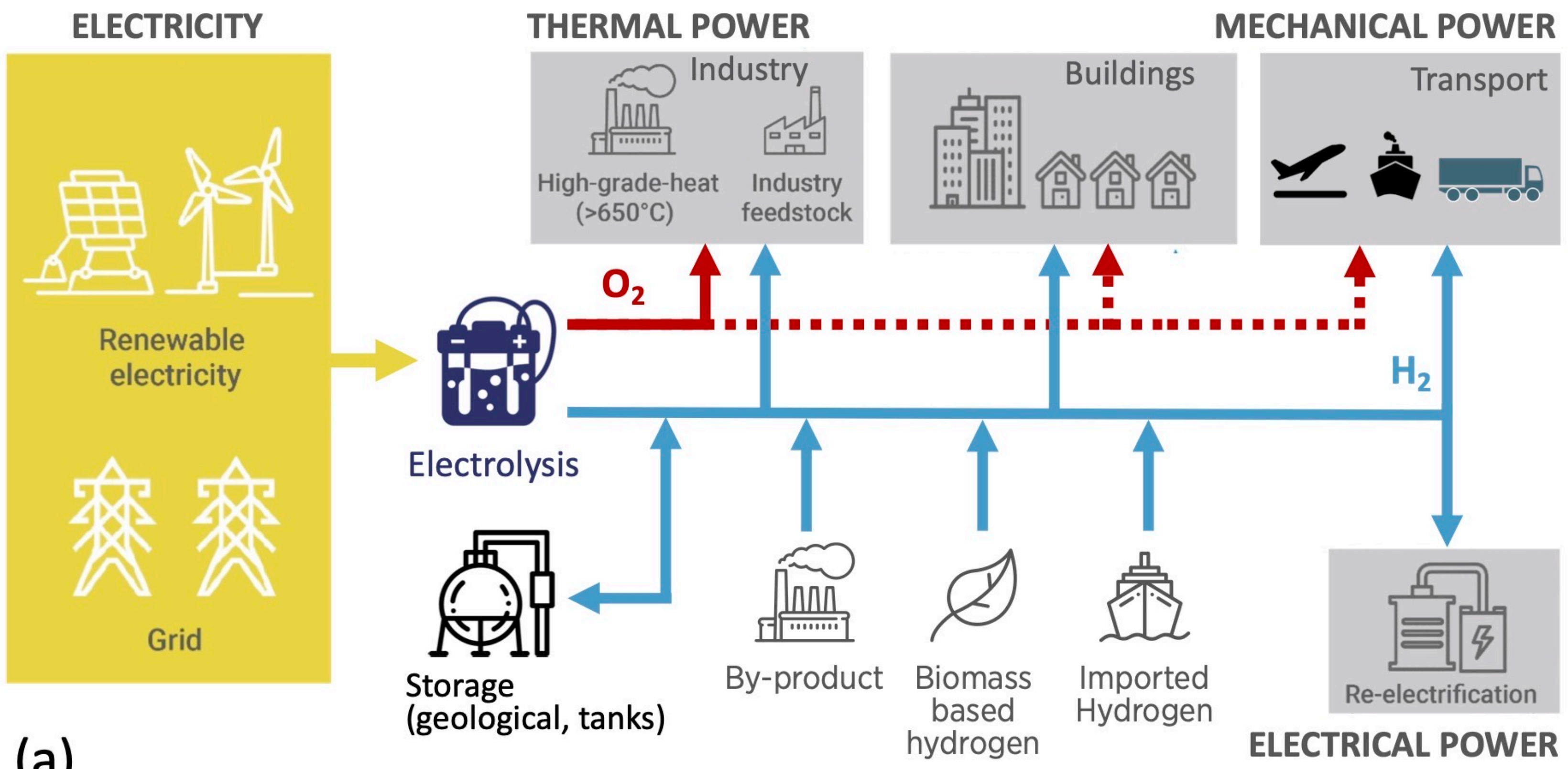
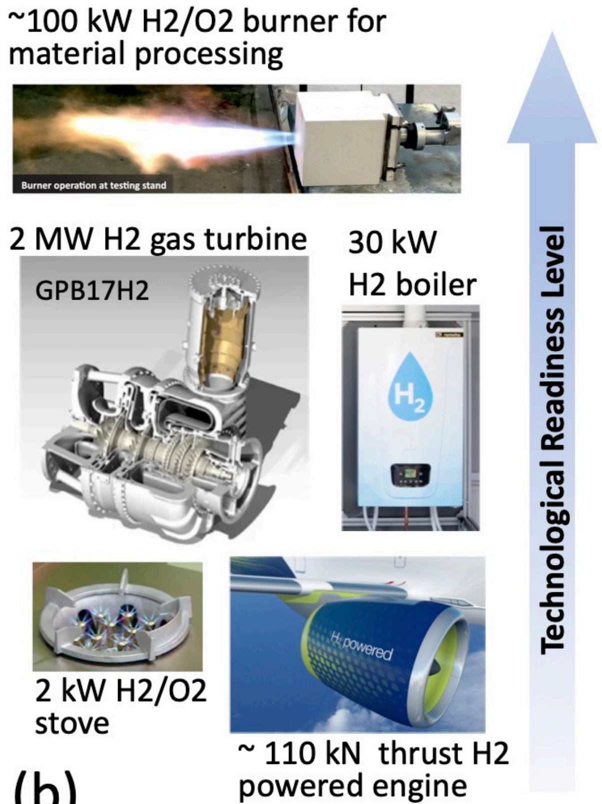
T. Guiberti, T. Poinsot, L. Selle

H2 week, IMFT, February 27, 2024

Low carbon hydrogen production and its final use



(a)



(b)

A widespread of low carbon H2 is only possible with abundant and cheap electricity

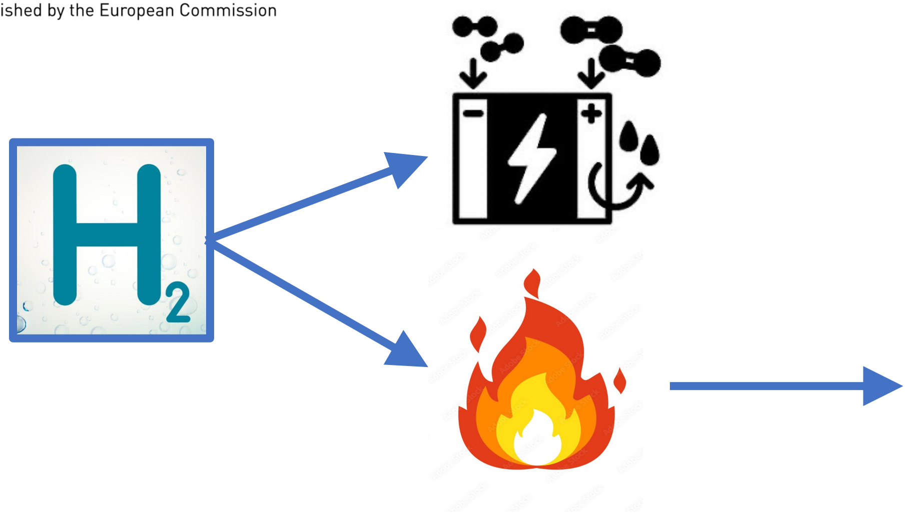
Select-H

Develop numerical tools and validate to design safe and reliable H2 power units

erc

European Research Council

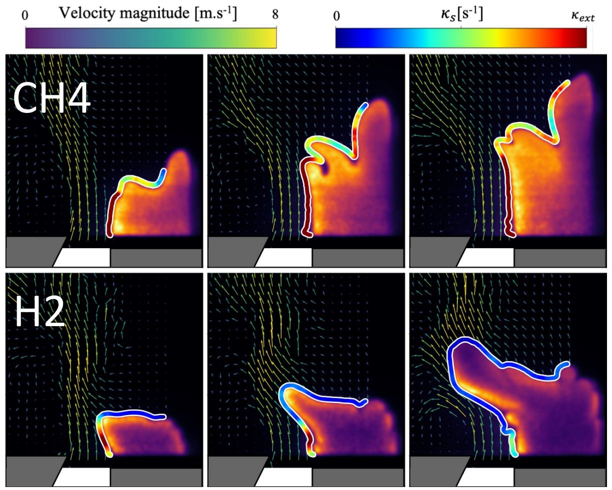
Established by the European Commission



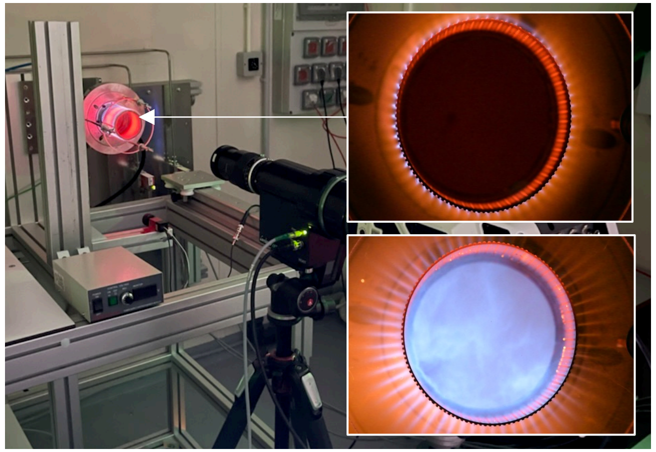
These technologies cannot be designed without **new fundamental science for H2 combustion**

H2 combustion issues studied @ IMFT

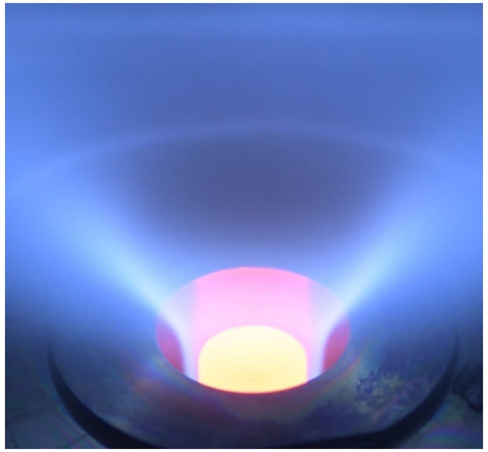
Ignition



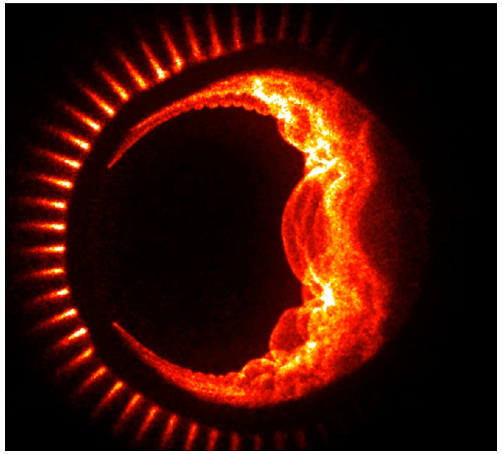
Flashback



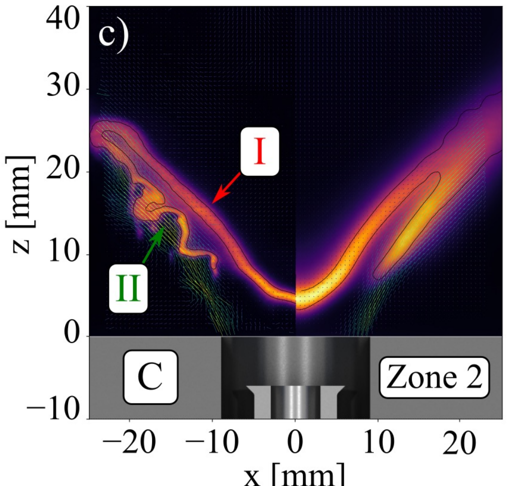
Flame wall



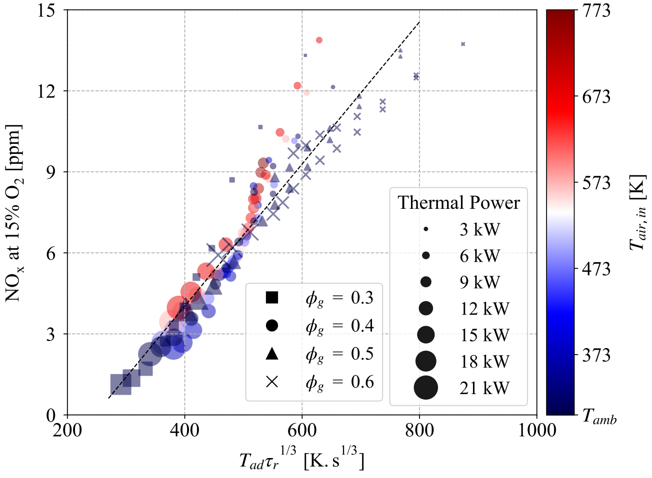
Thermodiffusive effects



Stabilization

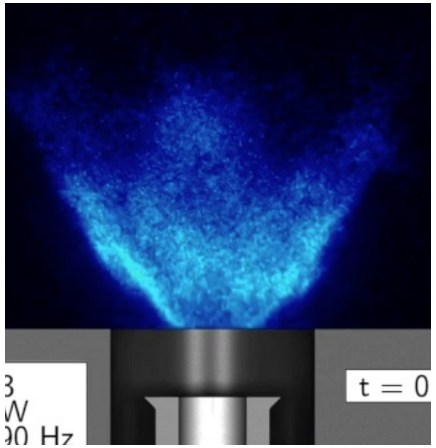


Emissions



Noise

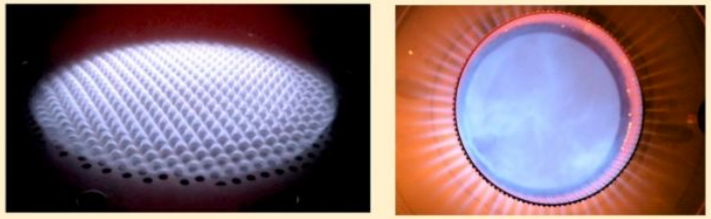
Thermoacoustics



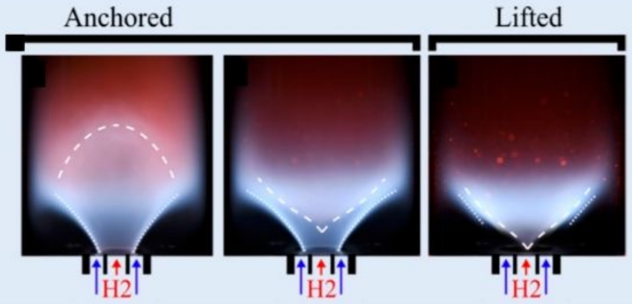
Hydrogen combustion lab

6 test benches adapted to optical diagnostics and acoustic characterization

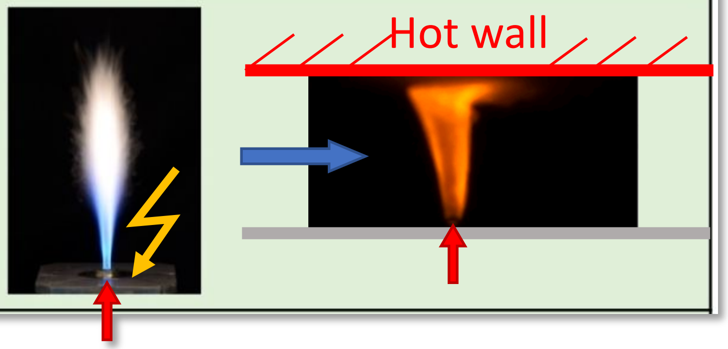
WP1: Low power premixed laminar hydrogen flames



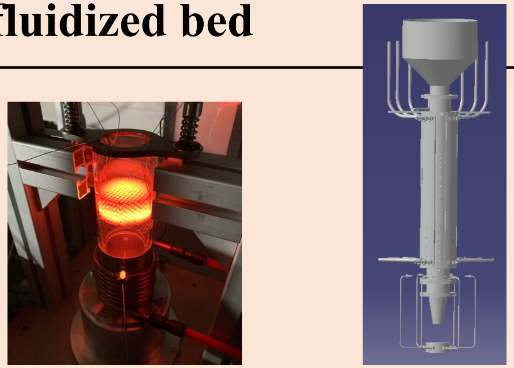
WP2: High power turbulent partially premixed hydrogen flames



WP3 : Jet flames from small gaseous hydrogen leaks



WP4 : Submerged combustion and fluidized bed



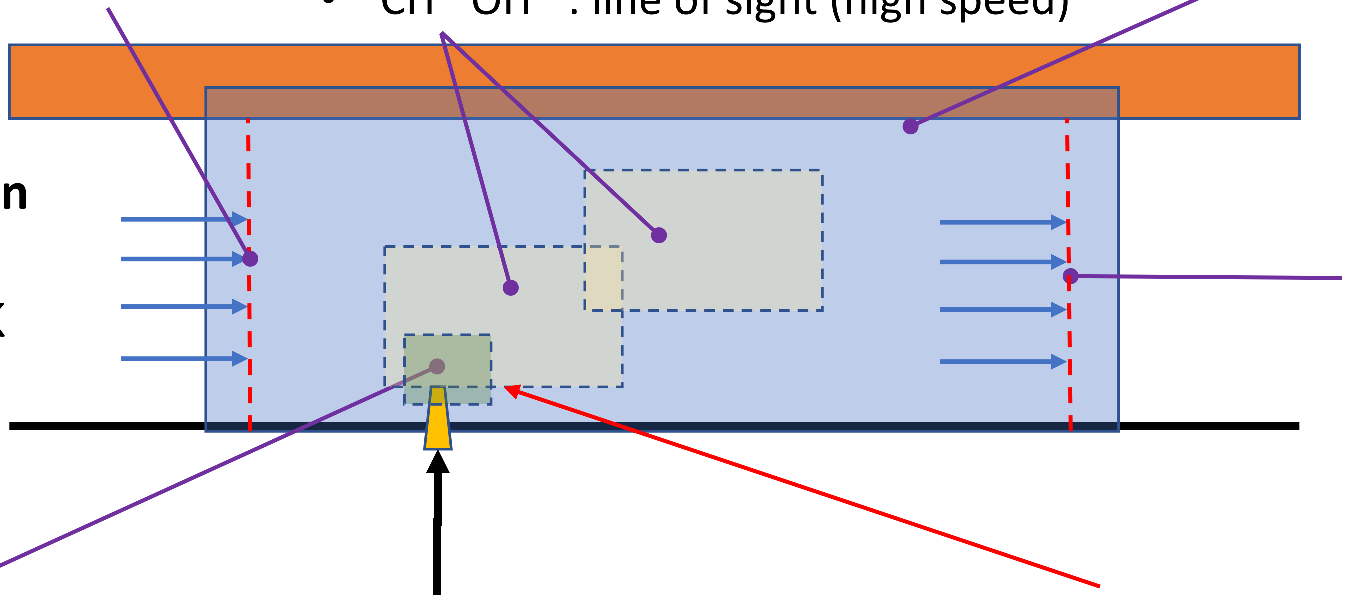
IMFT test rigs are designed and instrumented for CFD

Upstream boundary conditions
- Hotwire: mean, rms, time resolved
- Pressure drop
- Acoustic impedance
- Acoustic modulations

Flow field analysis: up to 10 cm x 10 cm
- 2D stereoscopic PIV: mean, rms, phase synchro.
- OH-PLIF : flame front, burnt gases
- CH* OH* : line of sight (high speed)

Walls:
- Temperatures: pyrometers, thermocouples, IR camera, LIP
- Heat flux

Air/N2 injection
~1 bar
Tu =300 - 700 K
250 nm^3/h



Downstream boundary conditions
- Velocity: PIV
- Temperature: radiative corrected thermocouples
- Species concentrations:

O2, CO2, CO, CH4, H2
NO, NO2
- Acoustic impedance
- Acoustic modulations

Zoomed diagnostics:
Down to 2 mm x 2 mm
- Hot wire, PIV: u, urms
- PIV – OH-PLIF: flow, flame
- Raman scattering (mixing)
- Schlieren

Fuel injection conditions
CH4, C3H8, H2
P_i = 1 - 5 bar, T_i = 300 - 700 K
80 kW

Ignition
- Spark
- Laser

1. Operability of multi perforated laminar premixed burners

Domestic boiler burners

Aniello et al. IJHE (2022) 47:33067

Nominal operation with Natural Gas

$$1.15 \leq \lambda \leq 1.55$$

$$0.65 \leq \phi \leq 0.85$$

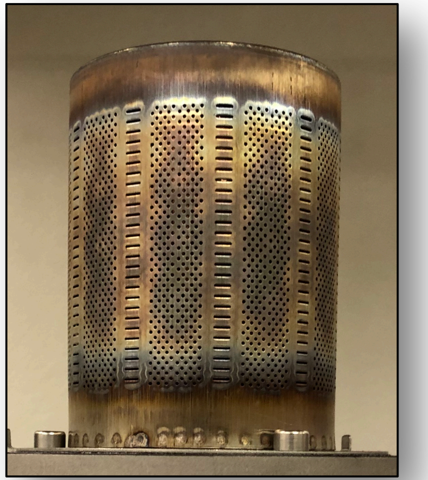
Turndown ratio : 3 kW – 30 kW

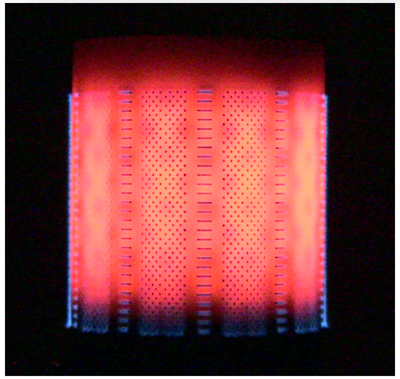
$$P = 3 \text{ kW}$$

$$\phi = 0.6$$

$$\mathcal{P}_{H_2} = 0.4$$

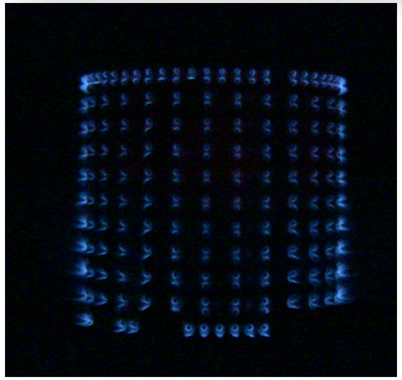
Burner 1



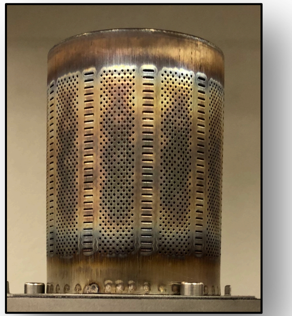


Radiant mode

Burner 2



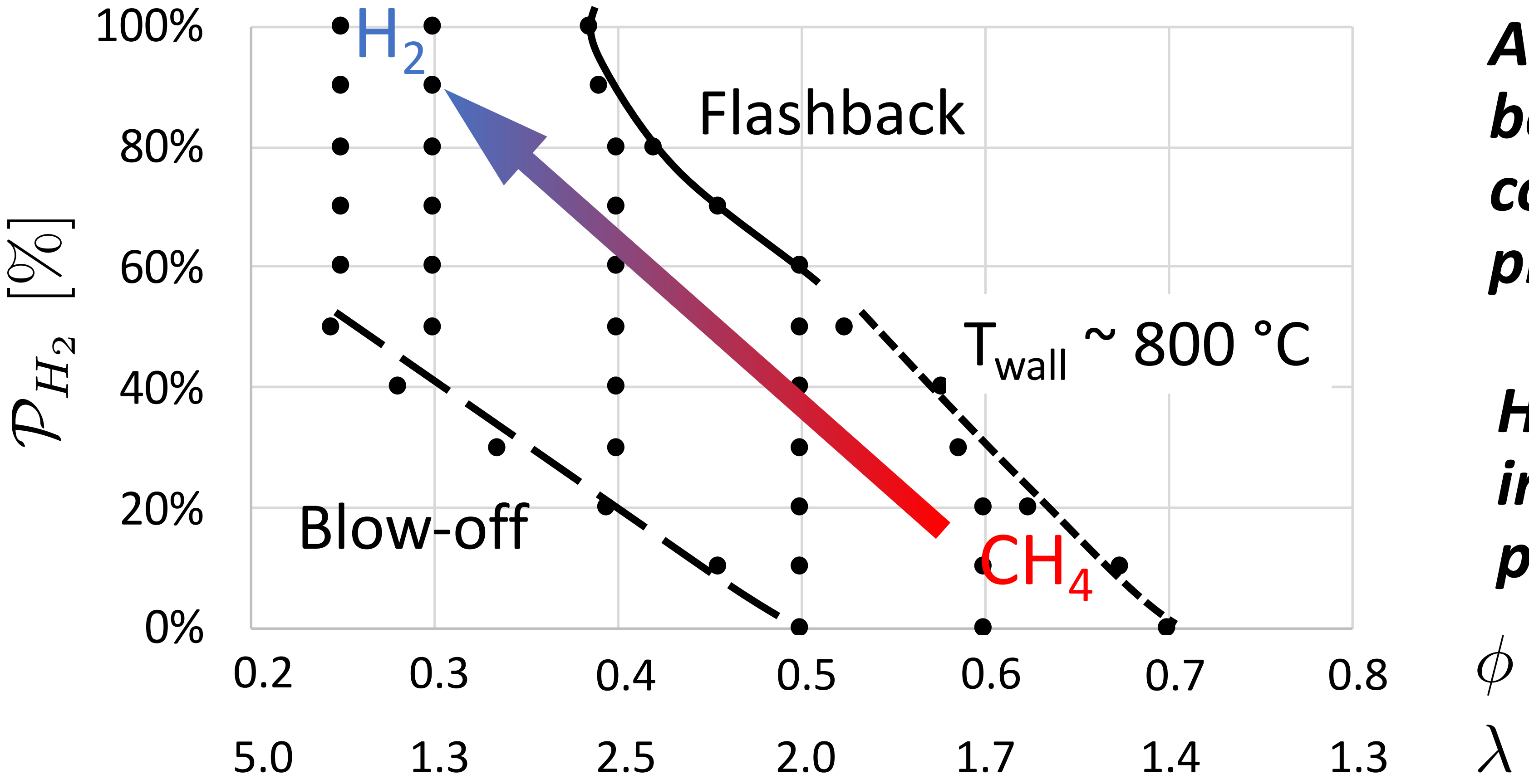
Adiabatic mode



Burner 1 operating map

Aniello et al. IJHE (2022) 47:33067

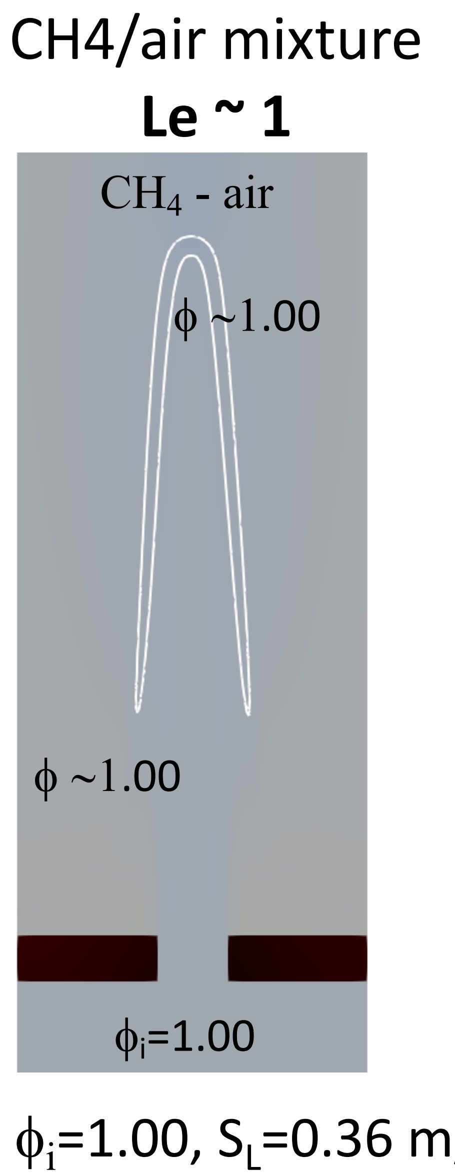
Fixed thermal power $P = 3\ \mathrm{kW}$

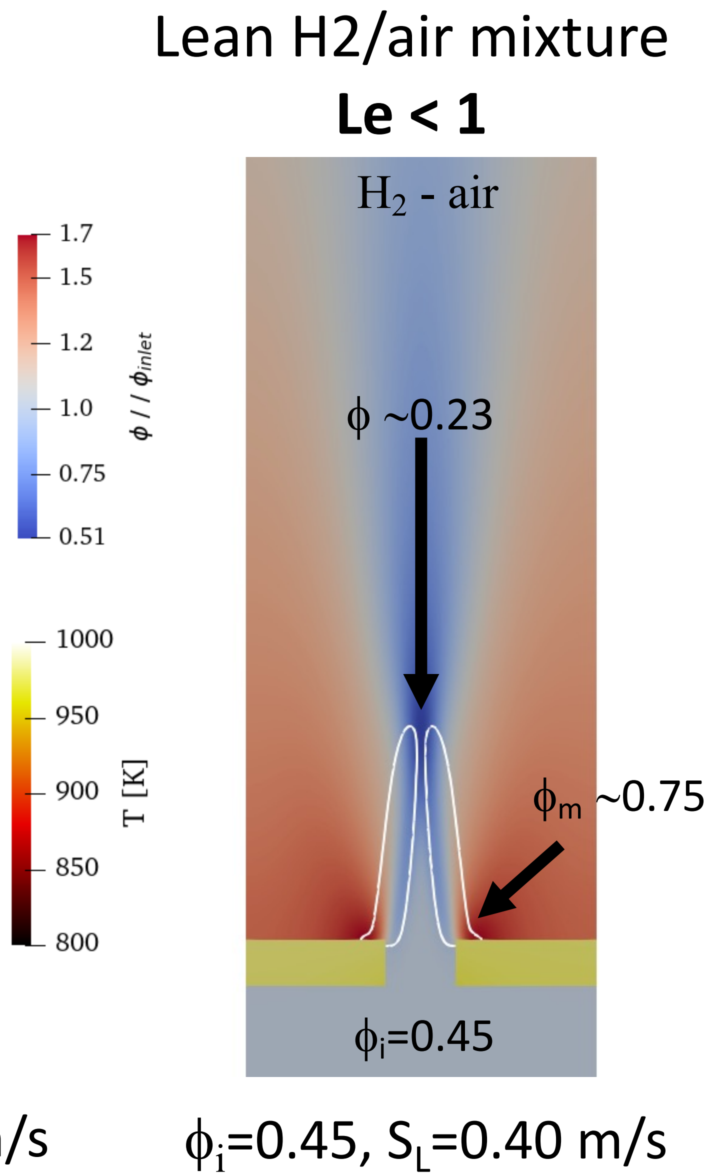


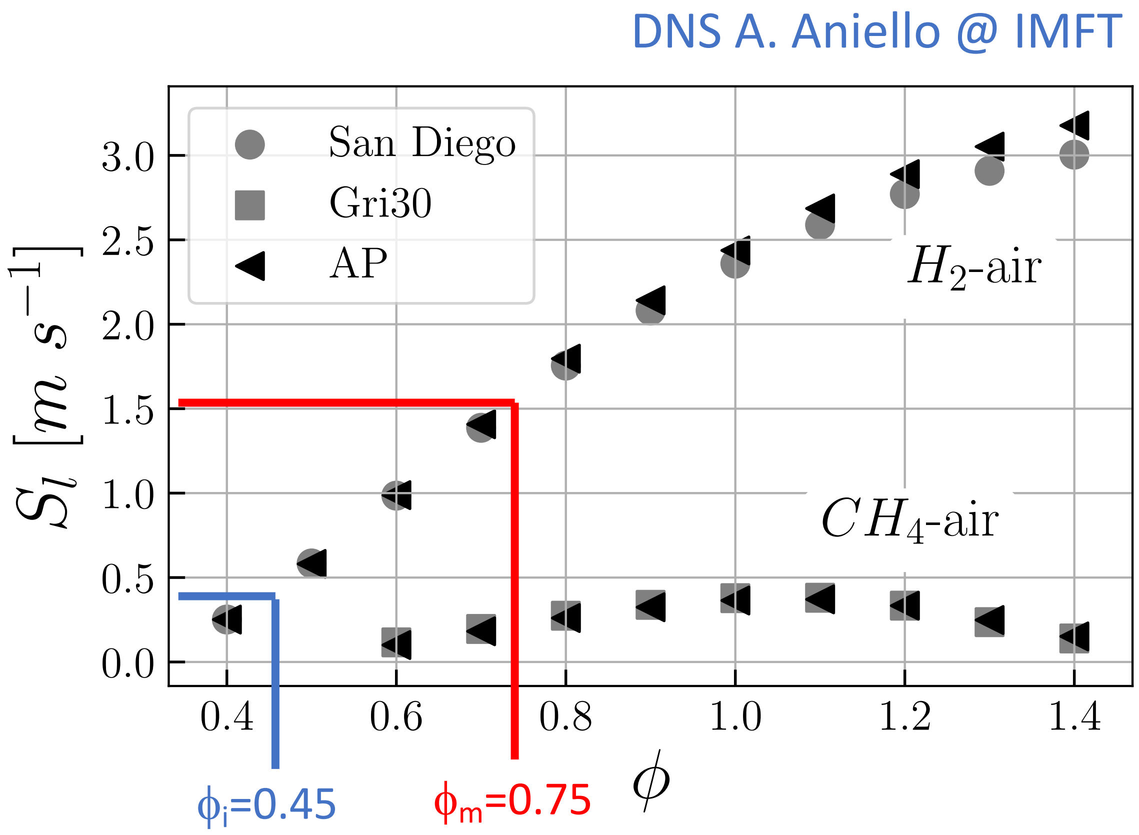
Air excess ratio needs to be increased with H2 content in the fuel (higher pressure drop)

Hydrogen injection increases flashback propensity at low power

Demixing induced by preferential diffusion



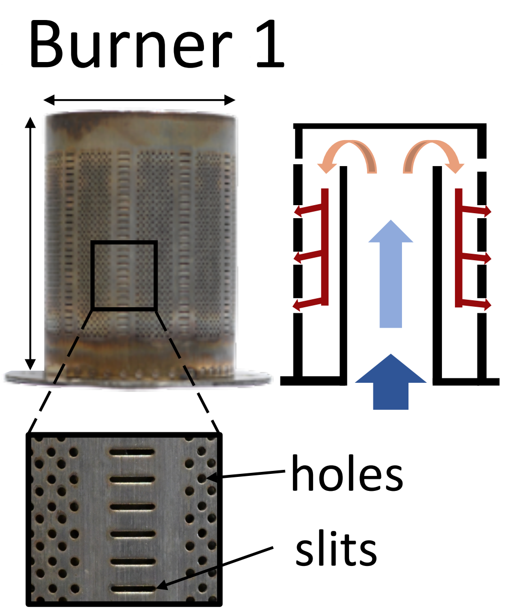


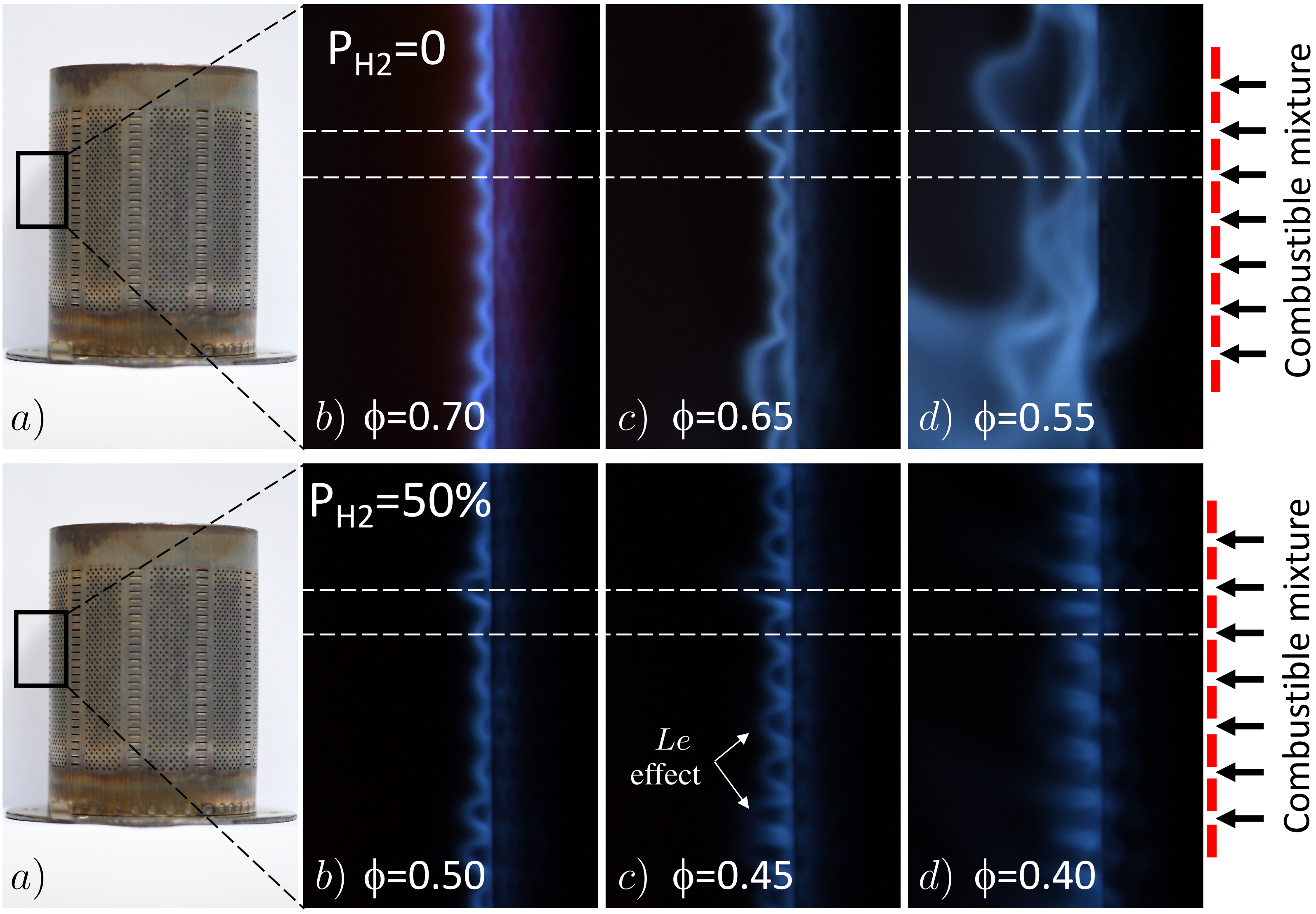


For lean H2/air mixtures Le<1, ϕ increases in the wake of the injection hole

Delayed blow off

Aniello et al. IJHE (2022) 47:33067





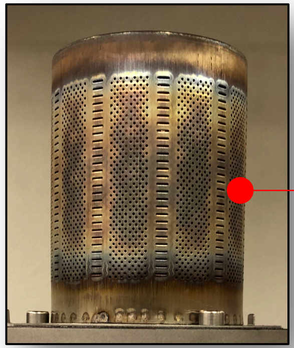
Lean H2/air premixed flames stabilize in the wake of bluff bodies

Blow off is not an issue for H2/air flames

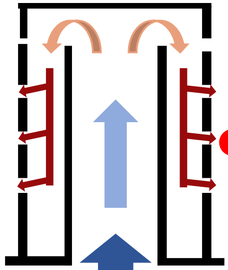
Analysis of flashback

Aniello et al. IJHE (2022) 47:33067

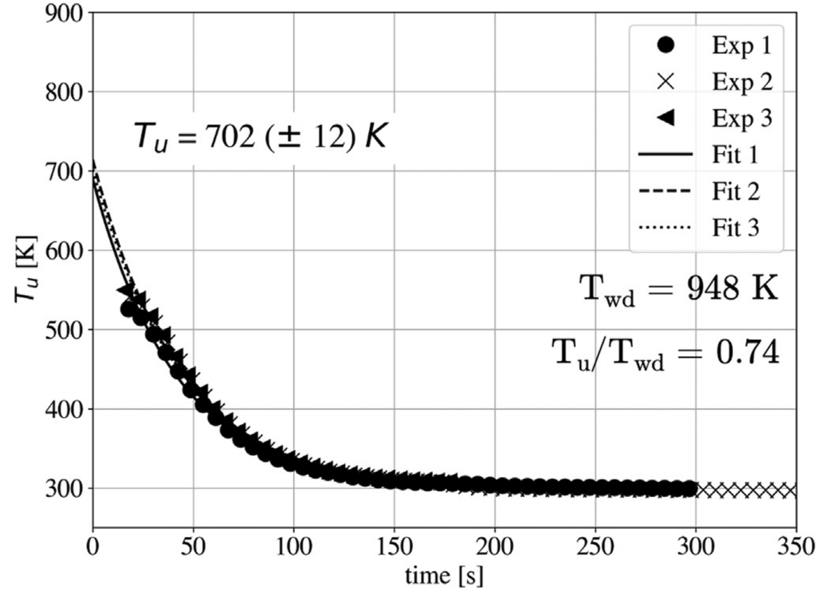
Impact of wall temperature



T_w burner wall temperature



T_u mixture temperature at burner outlet



(a) $\phi = 0.65,\ PH_2 = 60\%$

Bulk velocity U_b and burning velocity S_L at flashback limit

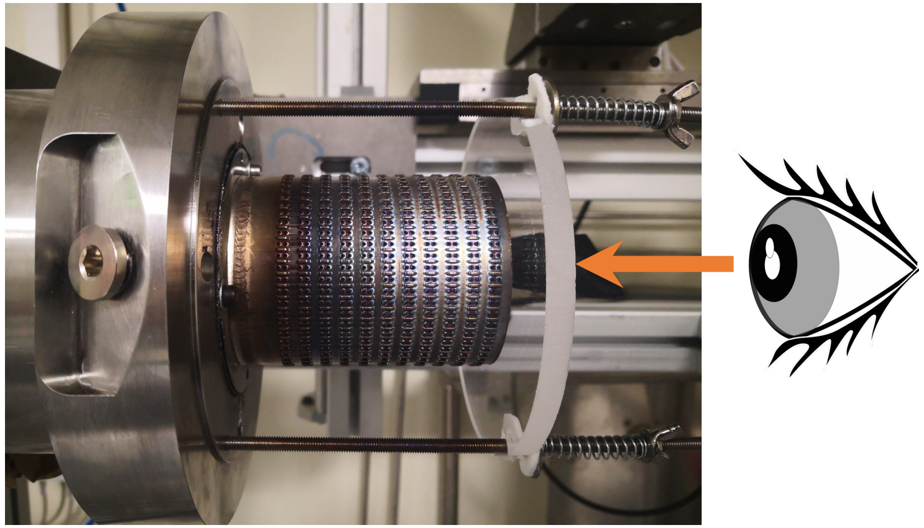
Description	ϕ_g ; P_{H_2}	T_u (K)	T_w (K)	$(U_b/S_L)_{T_u}$
Stable*	1.0 ; 0%	771 ± 4	1100 ± 3.3	1.1
Stable	0.8 ; 0%	692 ± 6	1060 ± 3.2	1.9
Flashback	0.6 ; 45%	594 ± 5	973 ± 2.9	1.8
Flashback	0.5 ; 62%	521 ± 11	863 ± 2.6	2.8
Flashback	0.45 ; 76%	499 ± 11	820 ± 2.5	3.3

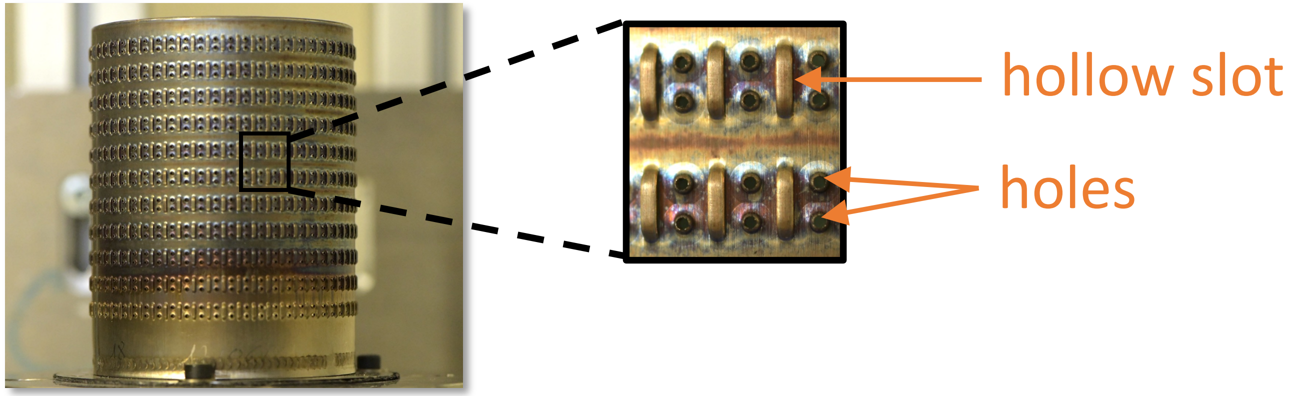
No systematic relationship between U_b/S_L and flashback limit

Flashback dynamics

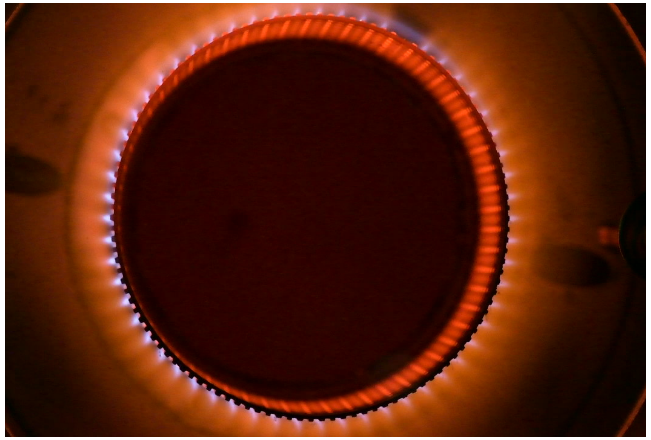
Pers et al. IJHE (2023) 48:10235

Burner 2 with optical acccess
from the top

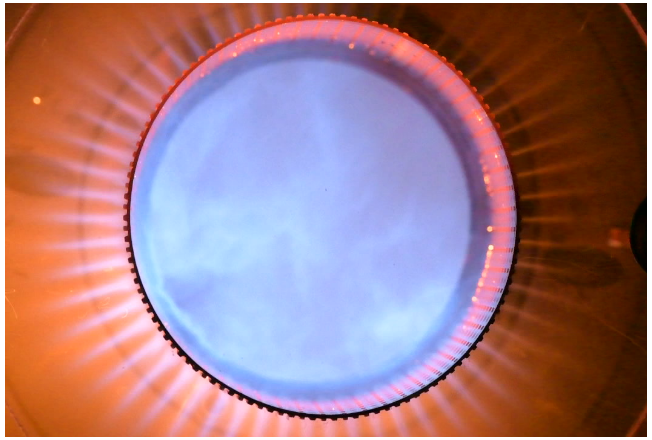




Before flashback

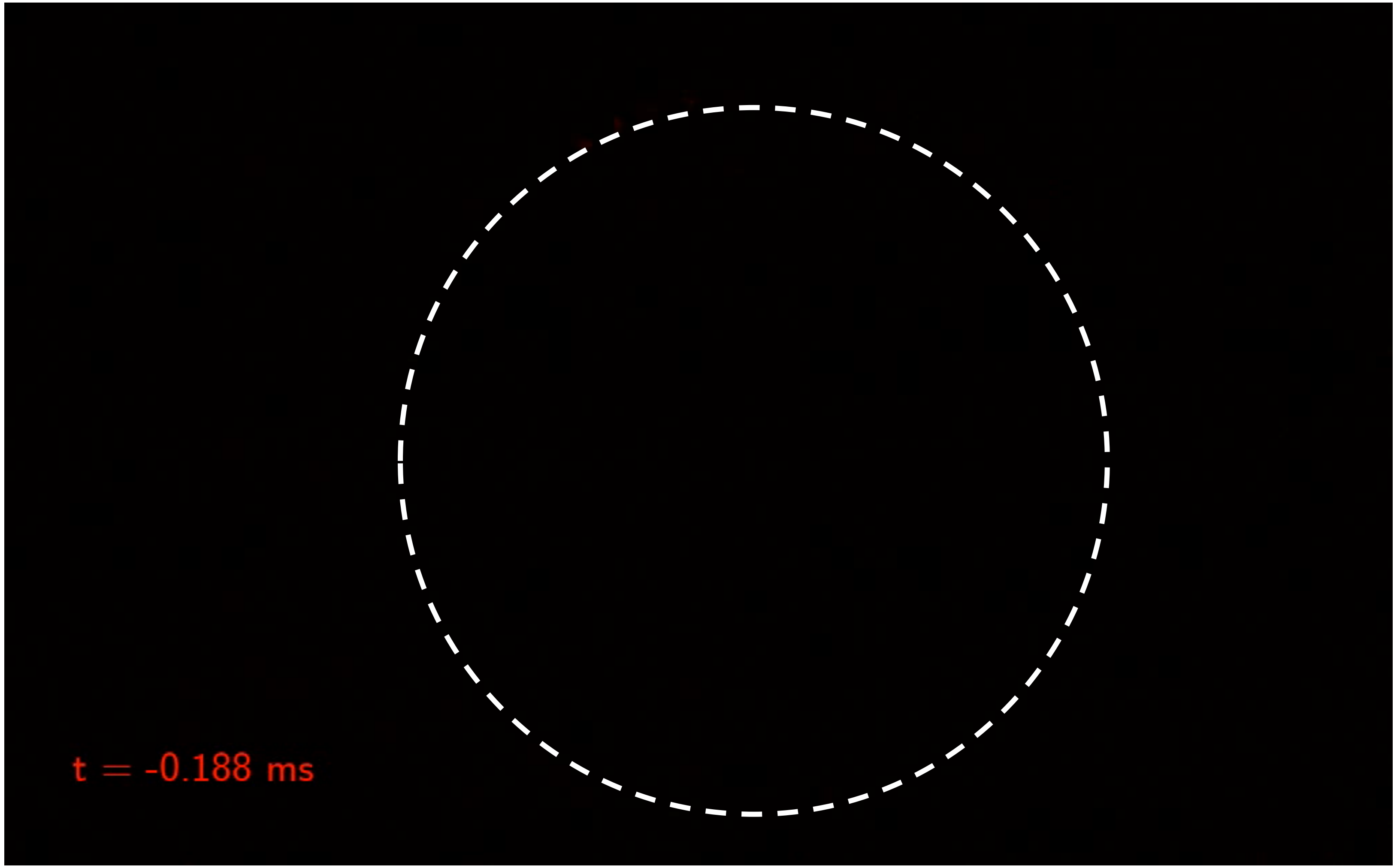


After flashback



High speed OH^* emission during flashback, ϕ=0.75, X_{H2}=0.95, T_w=1050 K 16 kHZ

Pers et al. IJHE (2023) 48:10235



(1) Hemispherical expansion

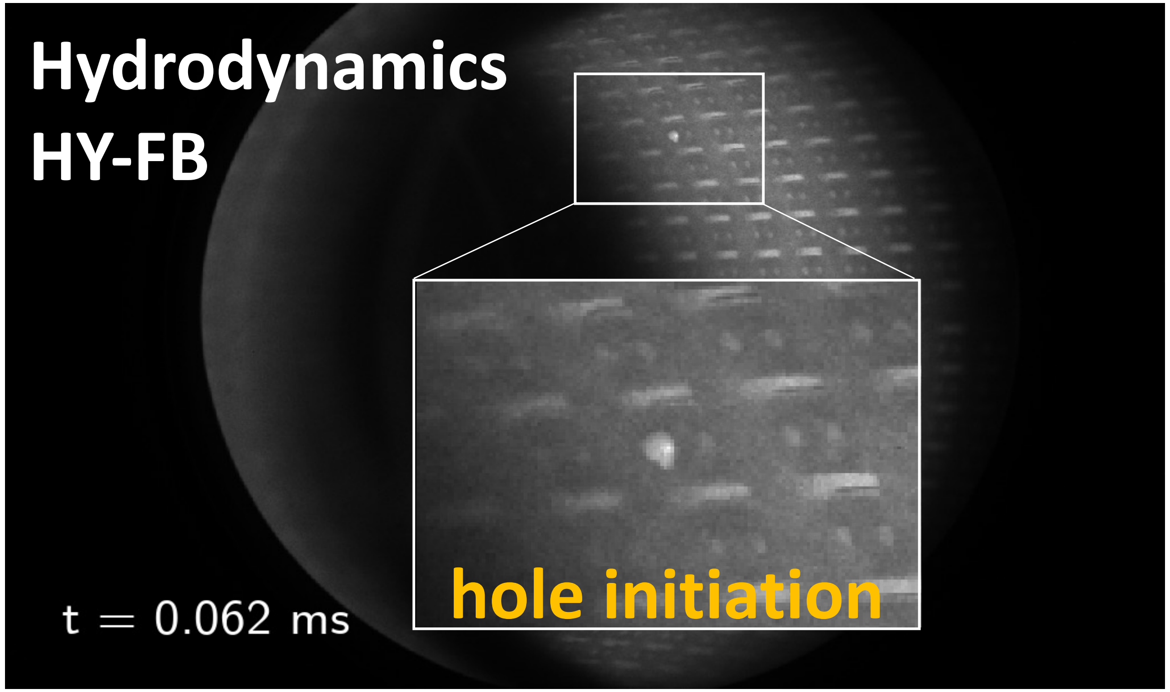
(2) Flame acceleration with flame fingers along hot walls

(3) Flame propagation in the bulk with thermo-diffusive instabilities

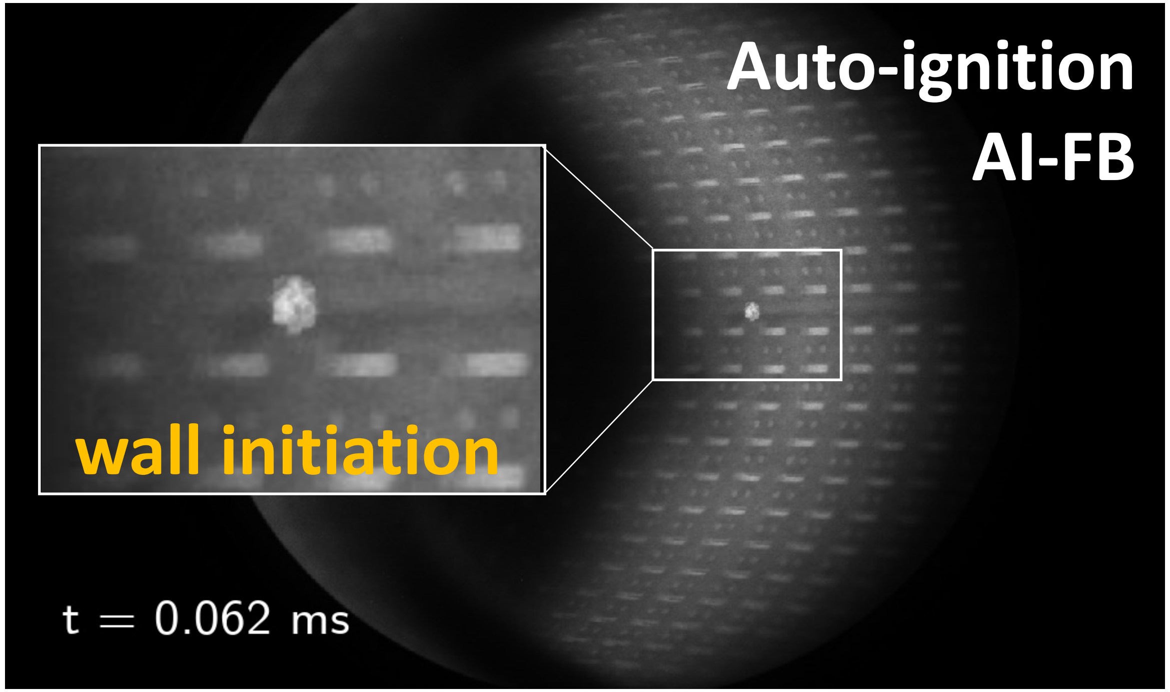
Flashback mechanisms

Pers et al. IJHE (2023) 48:10235

ϕ = 0.60, PH2 = 100%, 3 kW



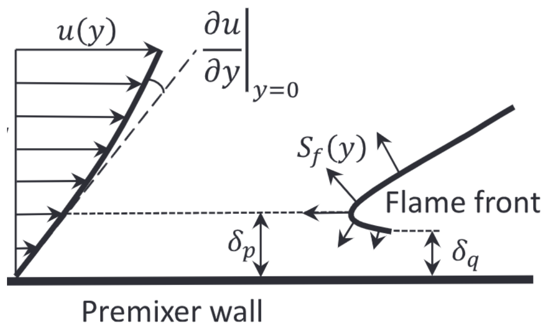
ϕ = 0.78, PH2 = 65%, 3 kW

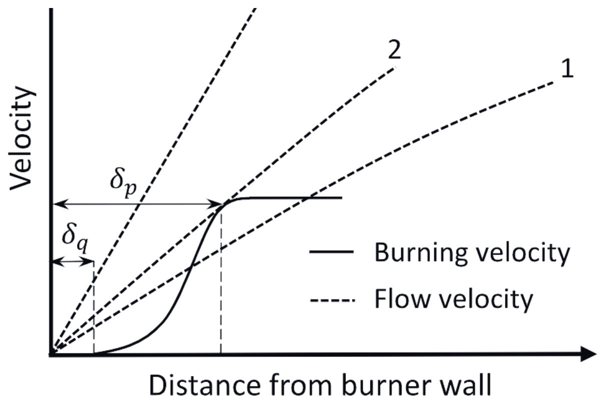


Flashback can be initiated from a hole or from a hot solid surface

FB-HY: Hydrodynamic flashback

Flashback theory for laminar flames



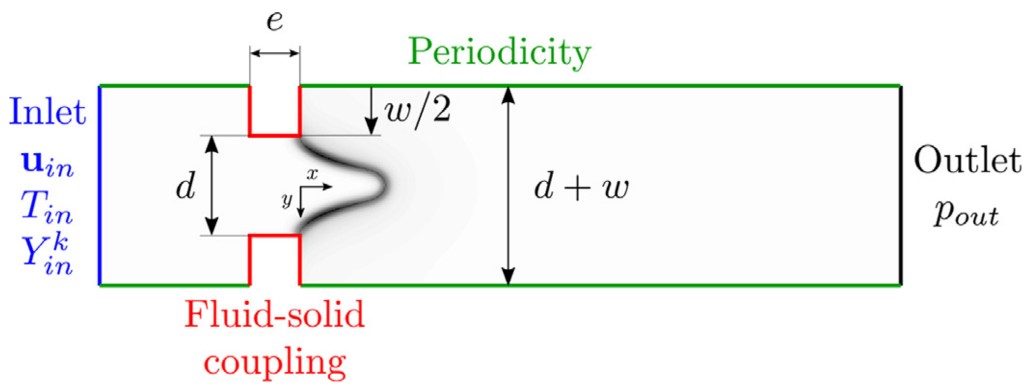


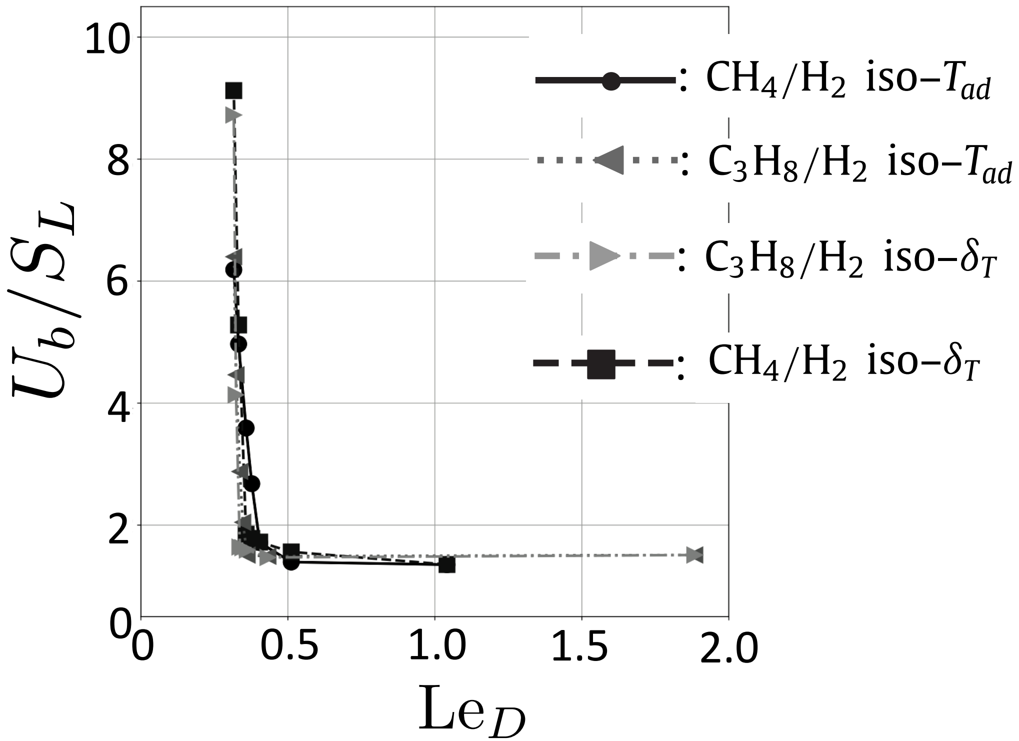
U_b bulk velocity at which flashback takes place in a slit of width d

$$\frac{U_b}{S_L} \propto \frac{d}{\delta_T}$$ is a constant

that depends on mixture Lewis number Le_D

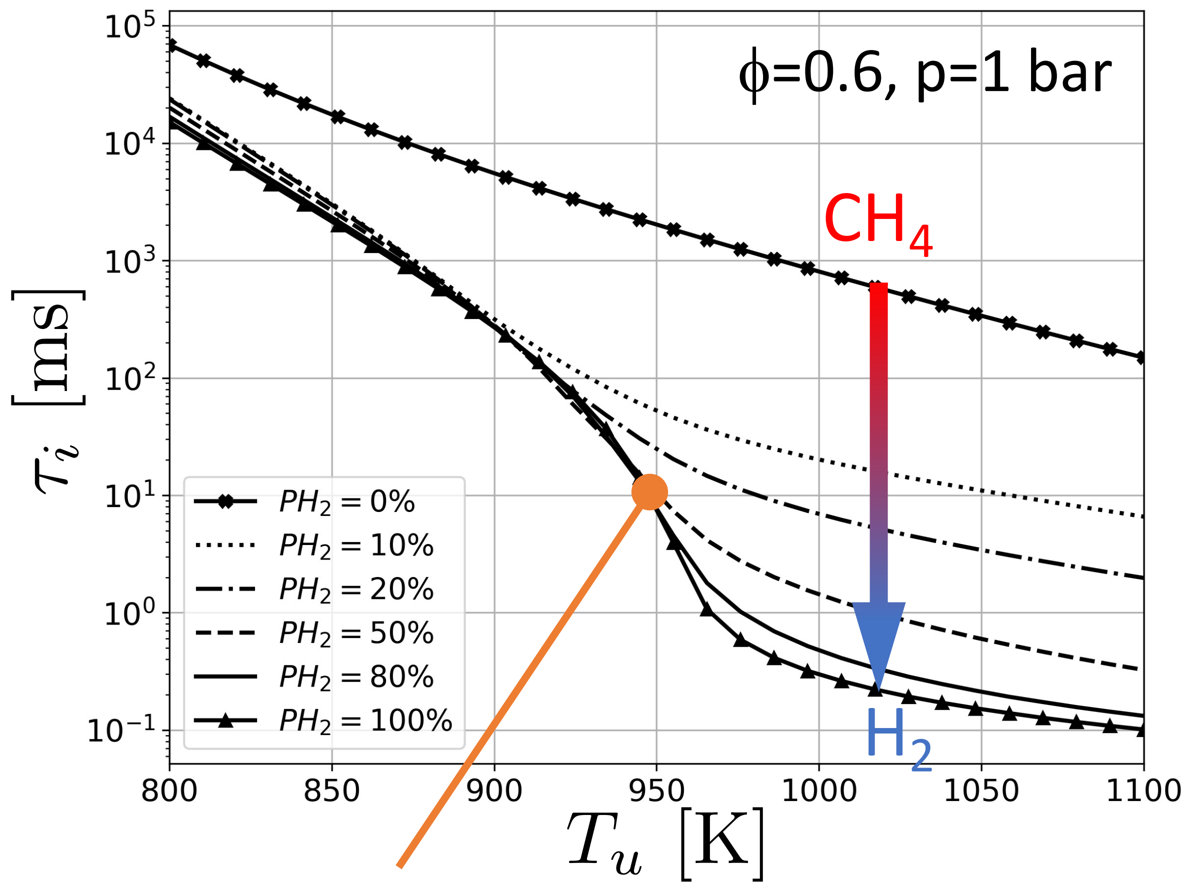
Flores-Montoya et al. CNF (2023) 258:113058



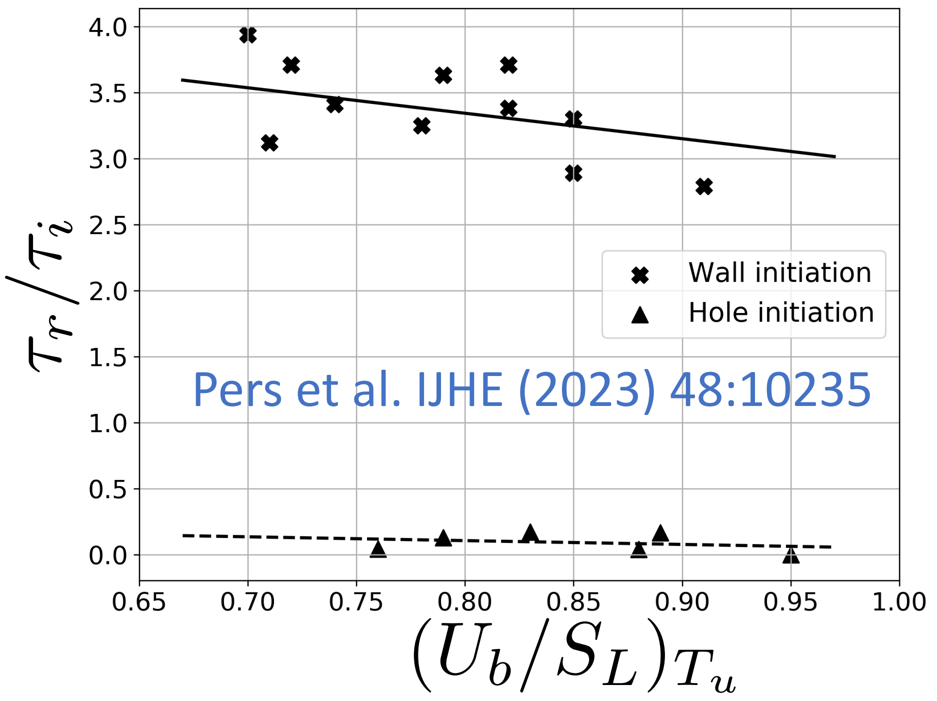


FB-AI: Flashback induced by auto-ignition

Auto-ignition delay time



Auto-ignition takes place when residence time is larger than auto-ignition time



Crossover temperature T_c

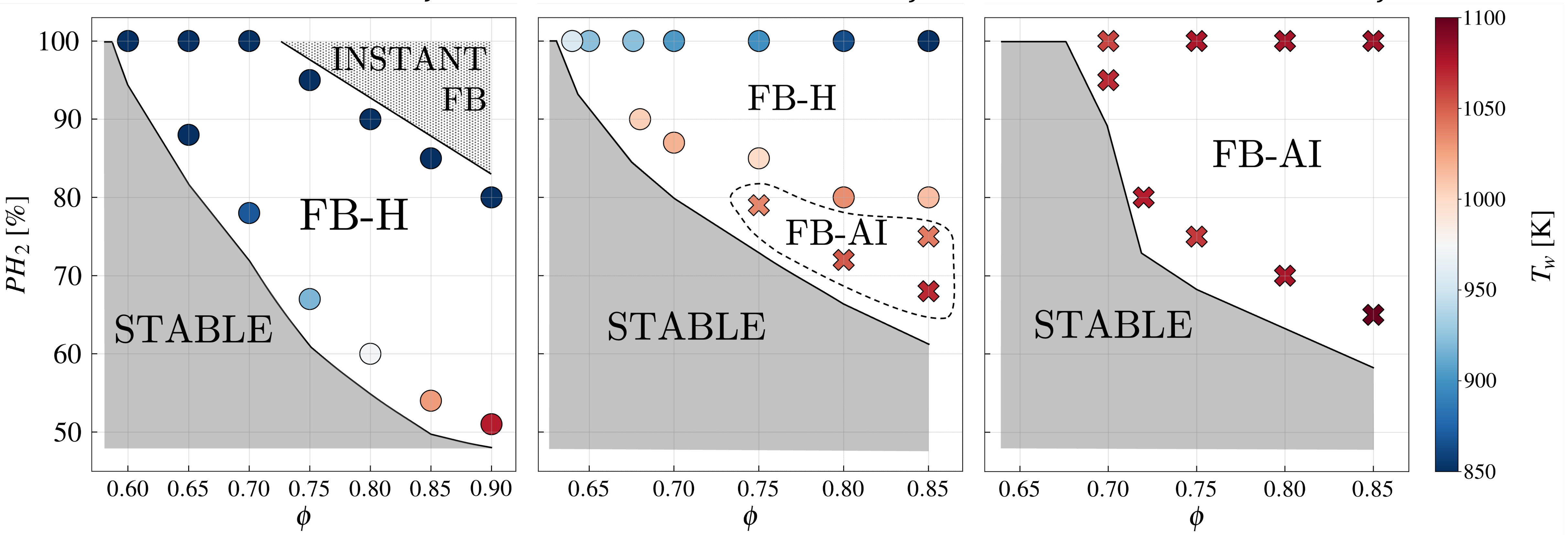
Sanchez & Williams PECS (2014)

Above T_c, chain branching explosion leads to a sudden drop of ignition delay

Impact of hole size

Pers et al. CNF (2024) in revision

W = 0.6 mm ~ $2.0\delta_f$ | W = 0.4 mm ~ $1.2\delta_f$ | W = 0.3 mm ~ $1.0\delta_f$

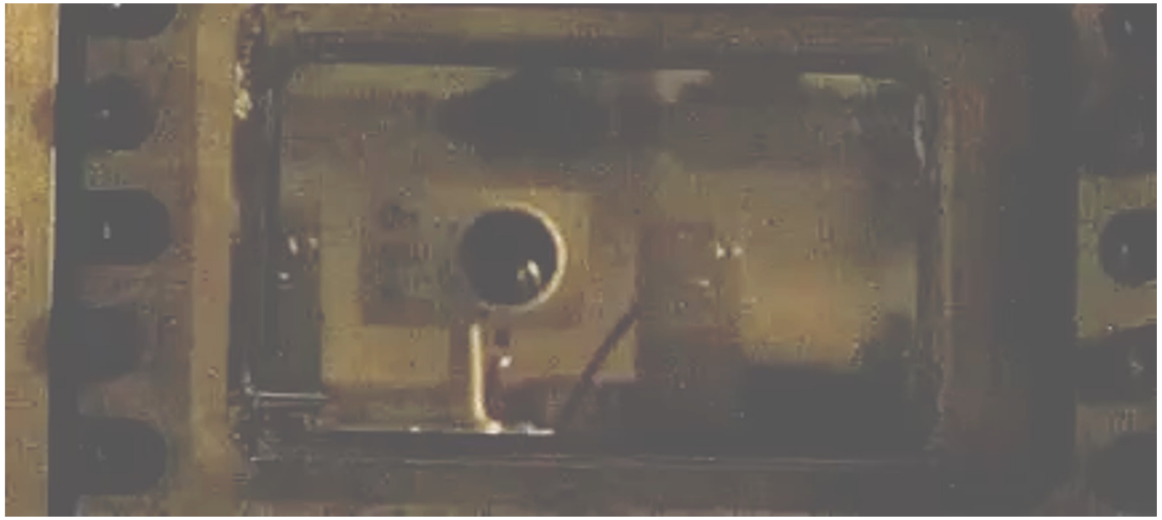


Reducing the hole size does not reduce flashback propensity

2. Jet flames ignition dynamics

Ignition is a critical issue in many combustors

Courtesy of C. Mirat EM2C



Good ignition

- Systematic ignition of flammable mixture
- Smooth transition of flame kernel to burner stabilized flame with the desired shape
- Limited pressure overshoot

Chamber pressure evolution

$$V \frac{dp}{dt} = (\gamma - 1)\,\dot{Q} - c^2 \dot{m}_{out}$$

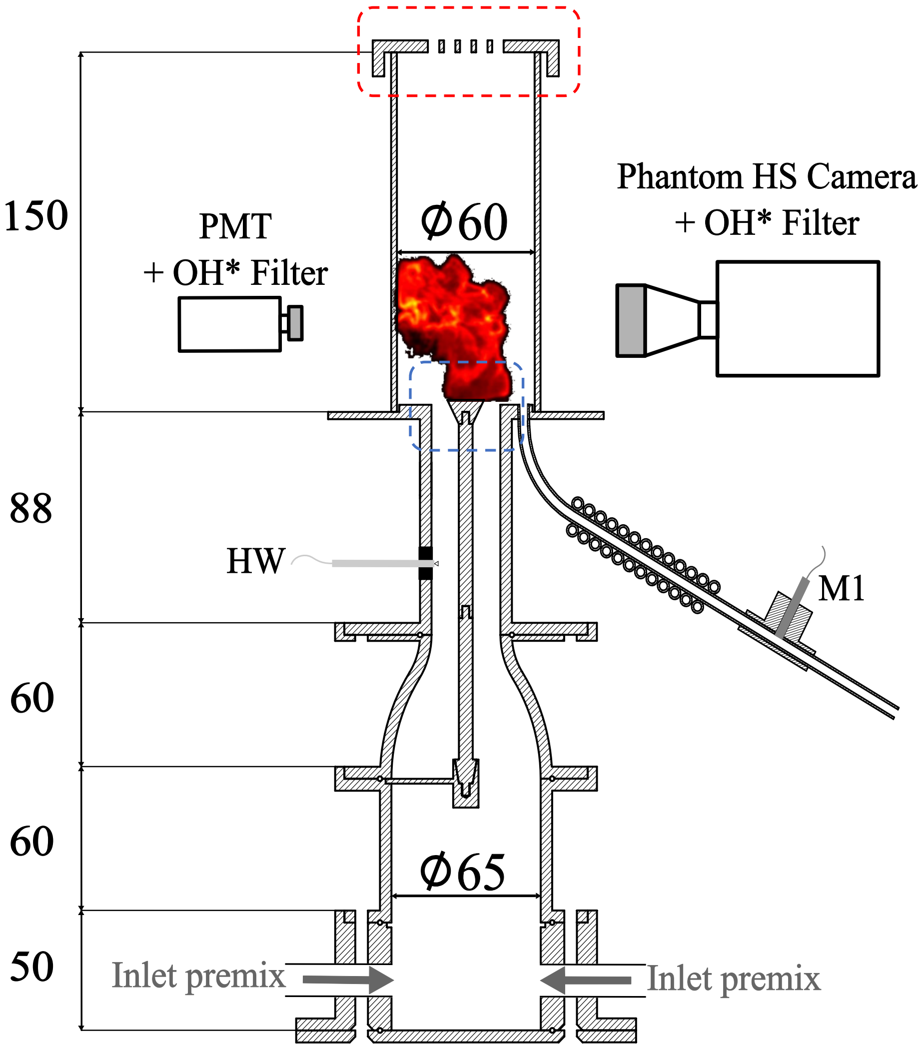
Chamber volume [m³]

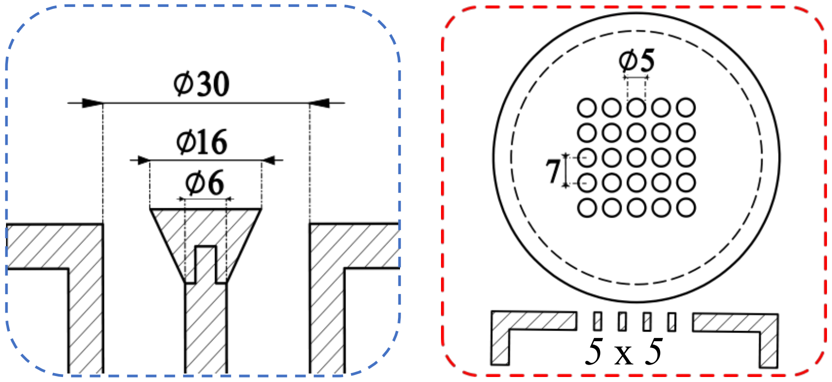
Heat Relase Rate [W]

Mass flow rate leaving the chamber [kg/s]

Ignition dynamics of CH4/H2/air mixtures

Premixed non-swirling jet burner





The chamber back pressure can be increased with perforated plates at the combustor exhaust

Yahou et al. (2024) JEGTP, 146:011023

Impact of ignition sequence:

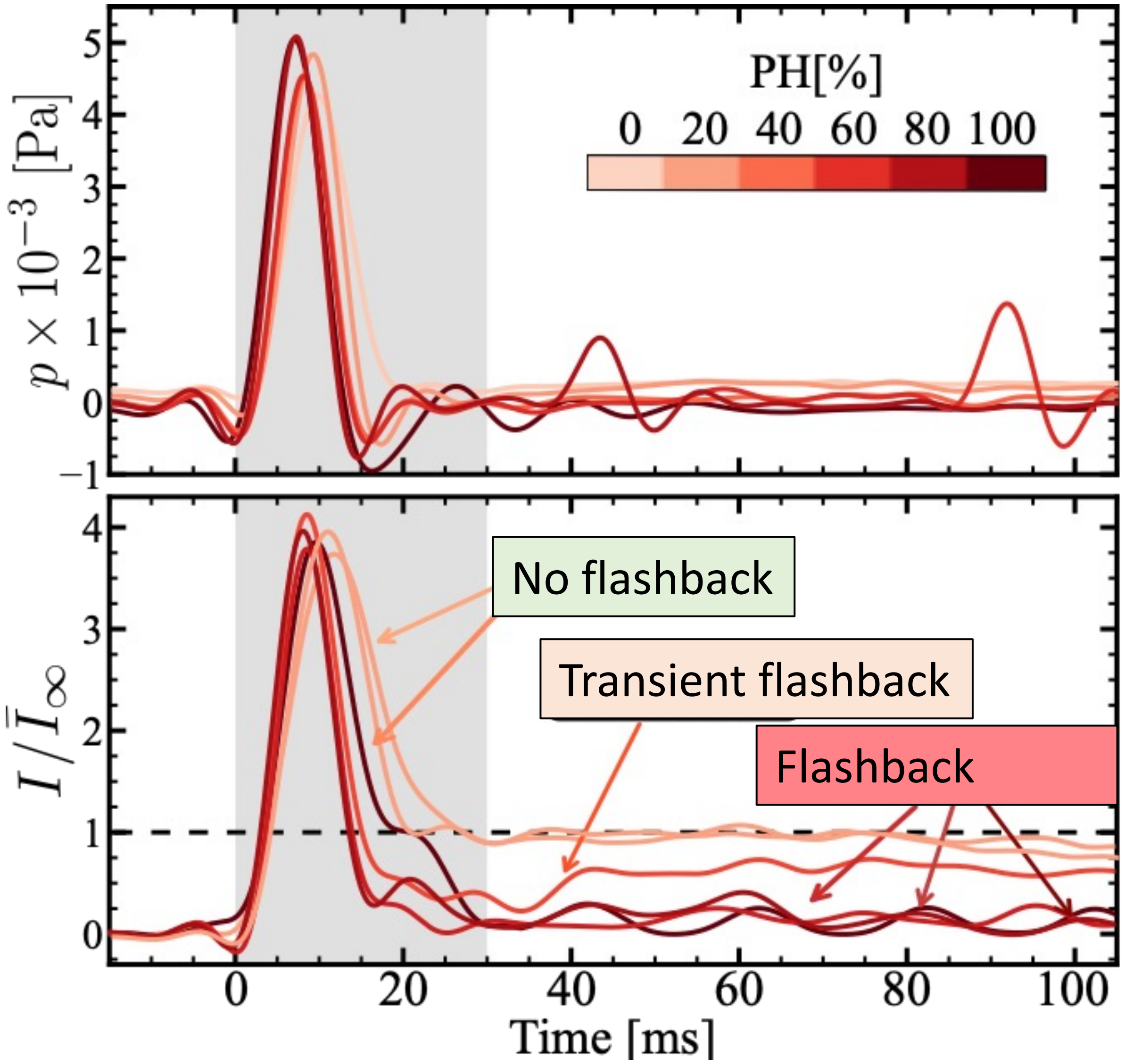
- Fuel first/spark after
- Spark first/fuel after
- Variation of pre-fueling time

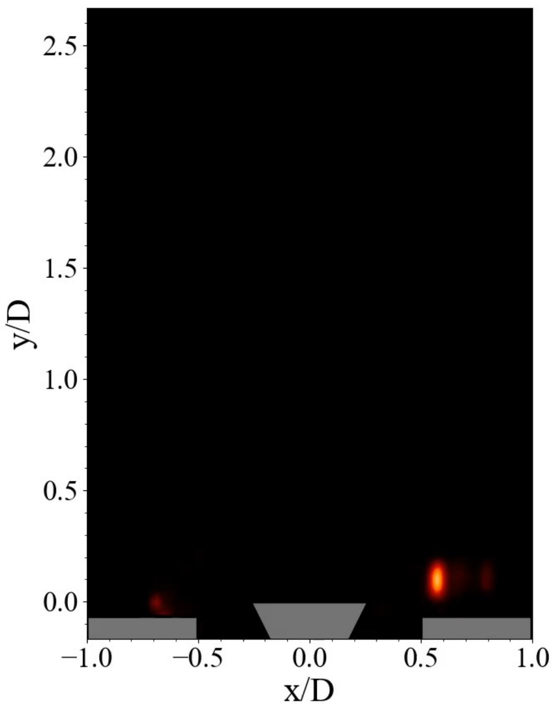
With H2, transient flashback can occur over a broad part of the operability domain

Pressure overshoot

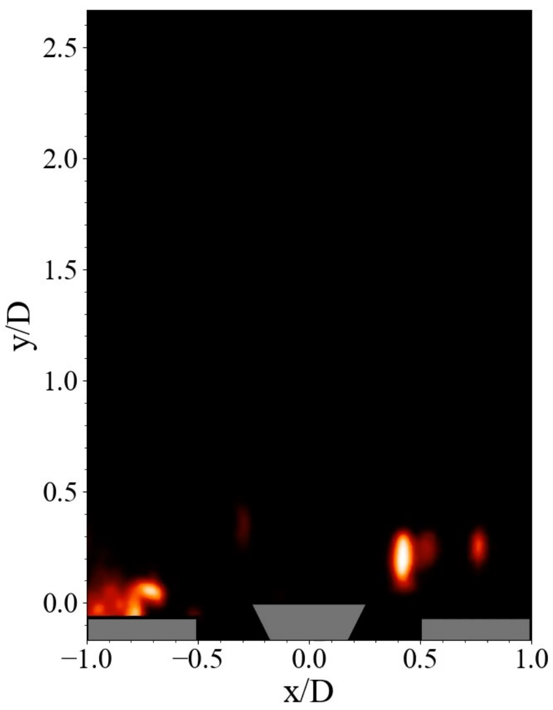
Yahou et al. (2023) PCI, 39:4641

U_b= 5 m/s, S_L=0.25 m/s, U_b/S_L=20





PHO (CH4/air)
No flashback



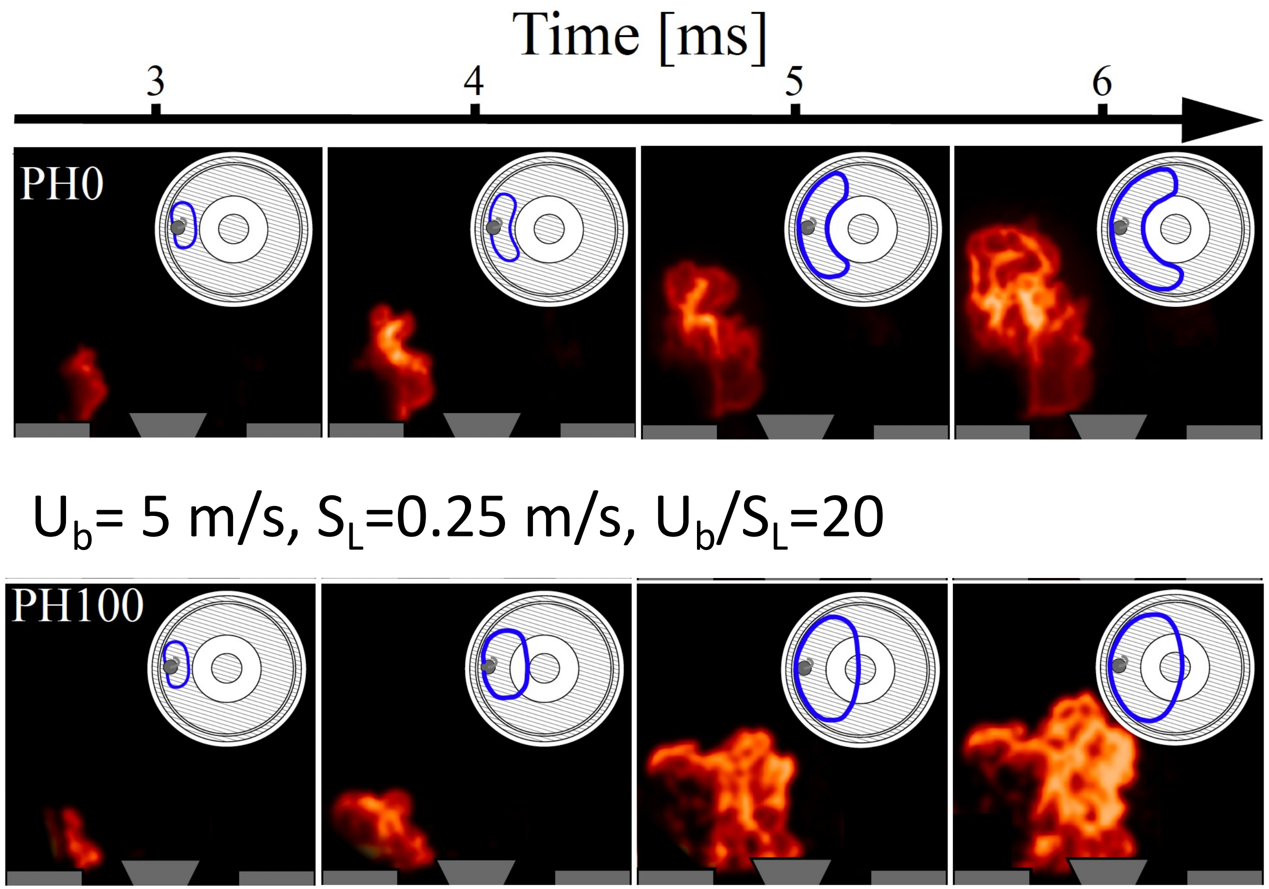
PH100 (H2/air)
Flashback

For the same pressure overshoot, H_2 flames have a higher propensity to flashback

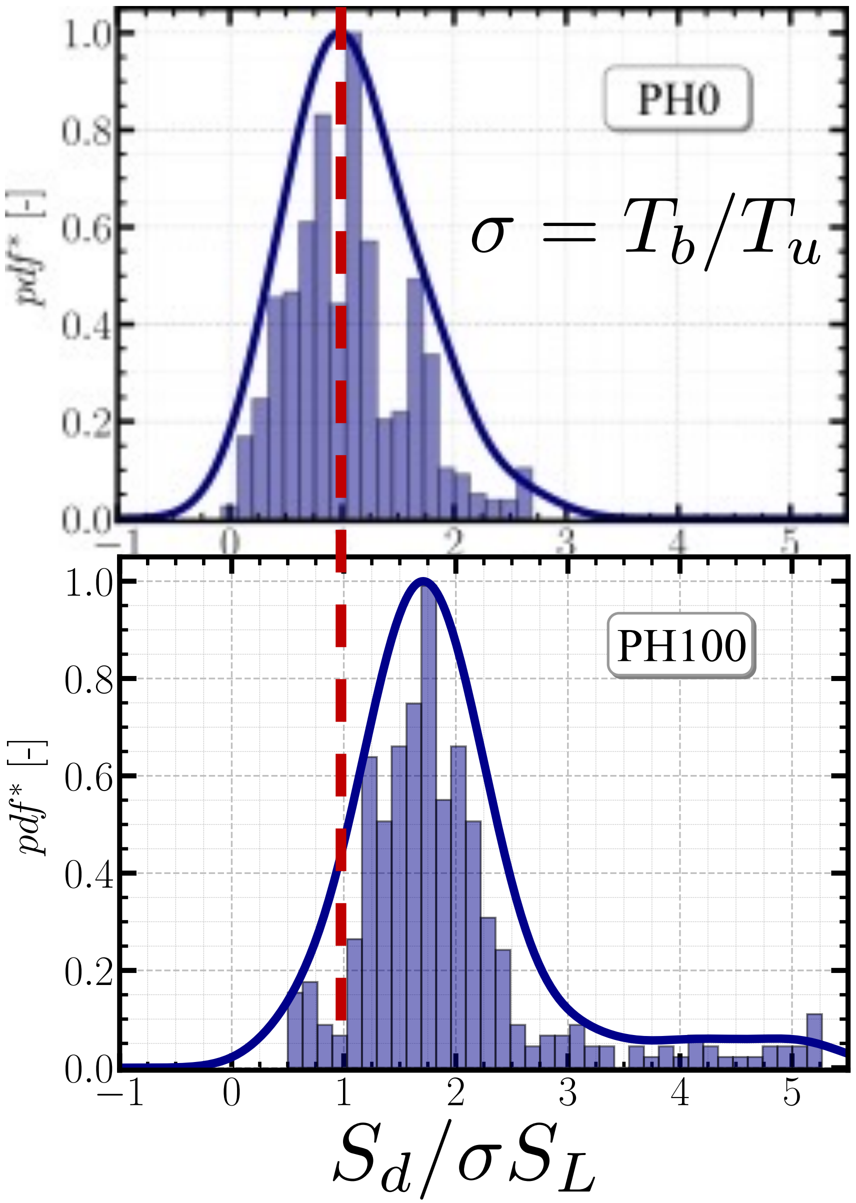
Flame displacement speed

Yahou et al. (2024) CNF, in revision

5 kHz PIV / OH-PLIF



U_b= 5 m/s, S_L=0.25 m/s, U_b/S_L=20



H2 flames have higher resistance to strain rate

Thermodiffusive effects increase H2 flame speed

Yahou et al. (2024) Submitted *Int. Symp. Comb.*, 2024

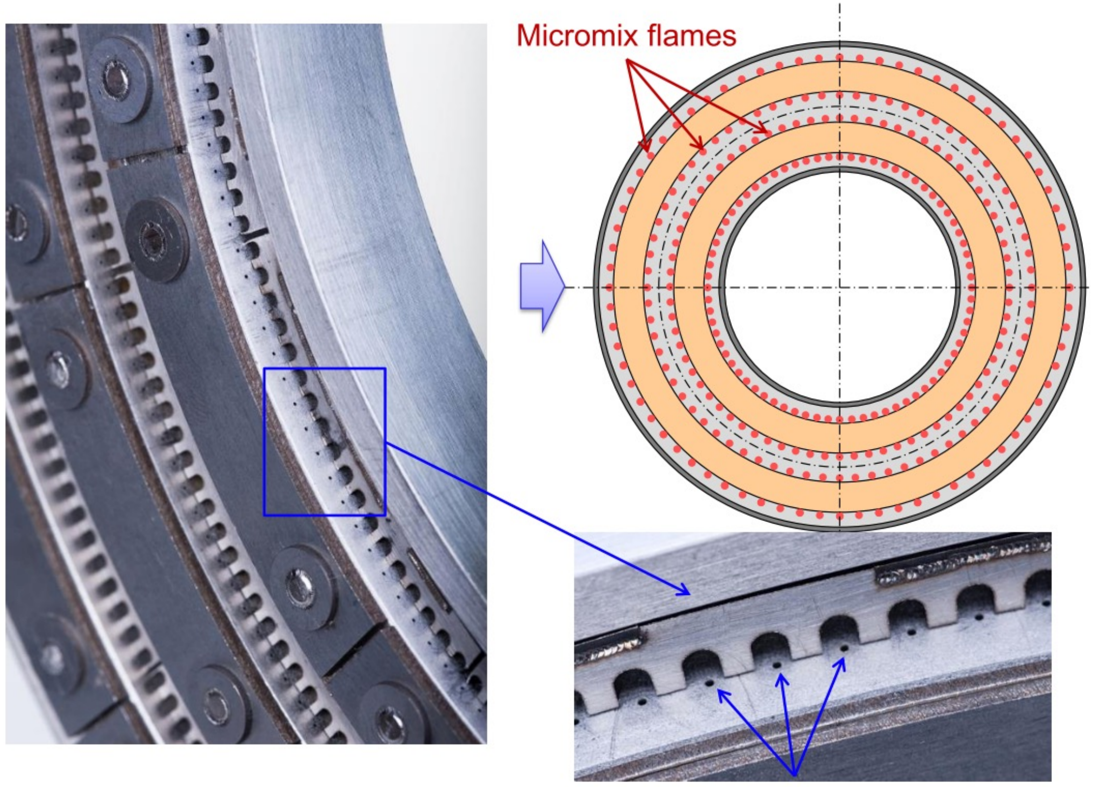
3. Partially premixed model gas turbine burner

Aerojet gas turbine MICROMIX concept

Convential chamber Micromix chamber

Disruptive technology with
a deep modification of
combustion chamber architecture

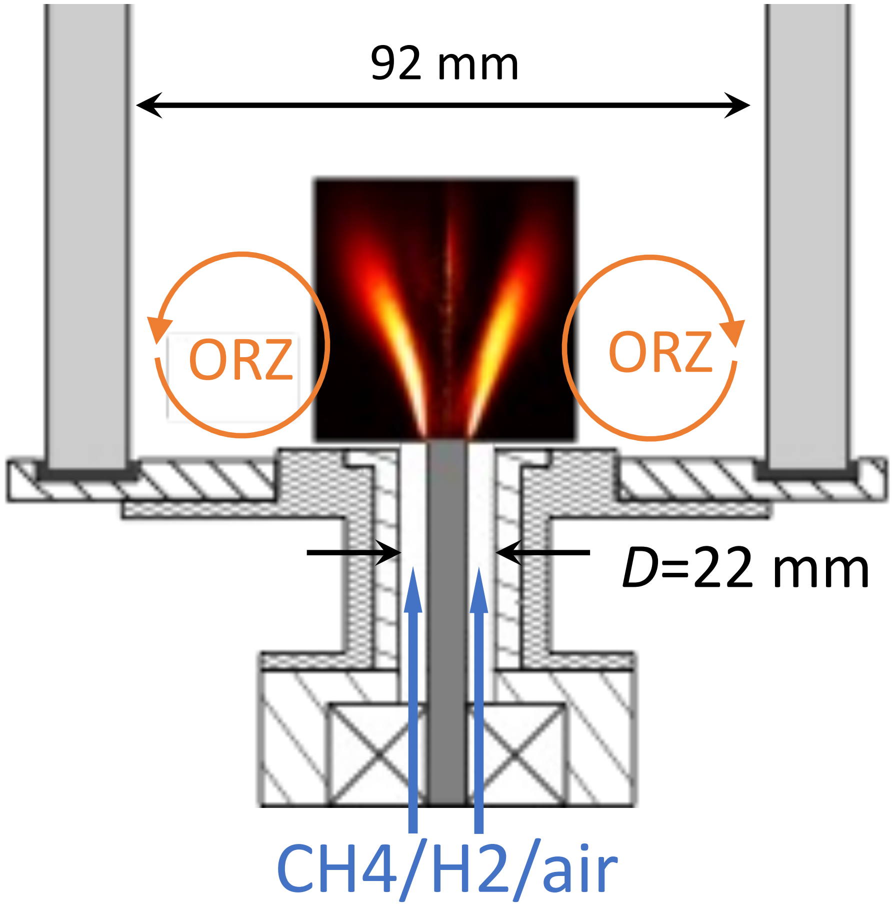
MICROMIX injectors : many small hydrogen jets in air cross-flow

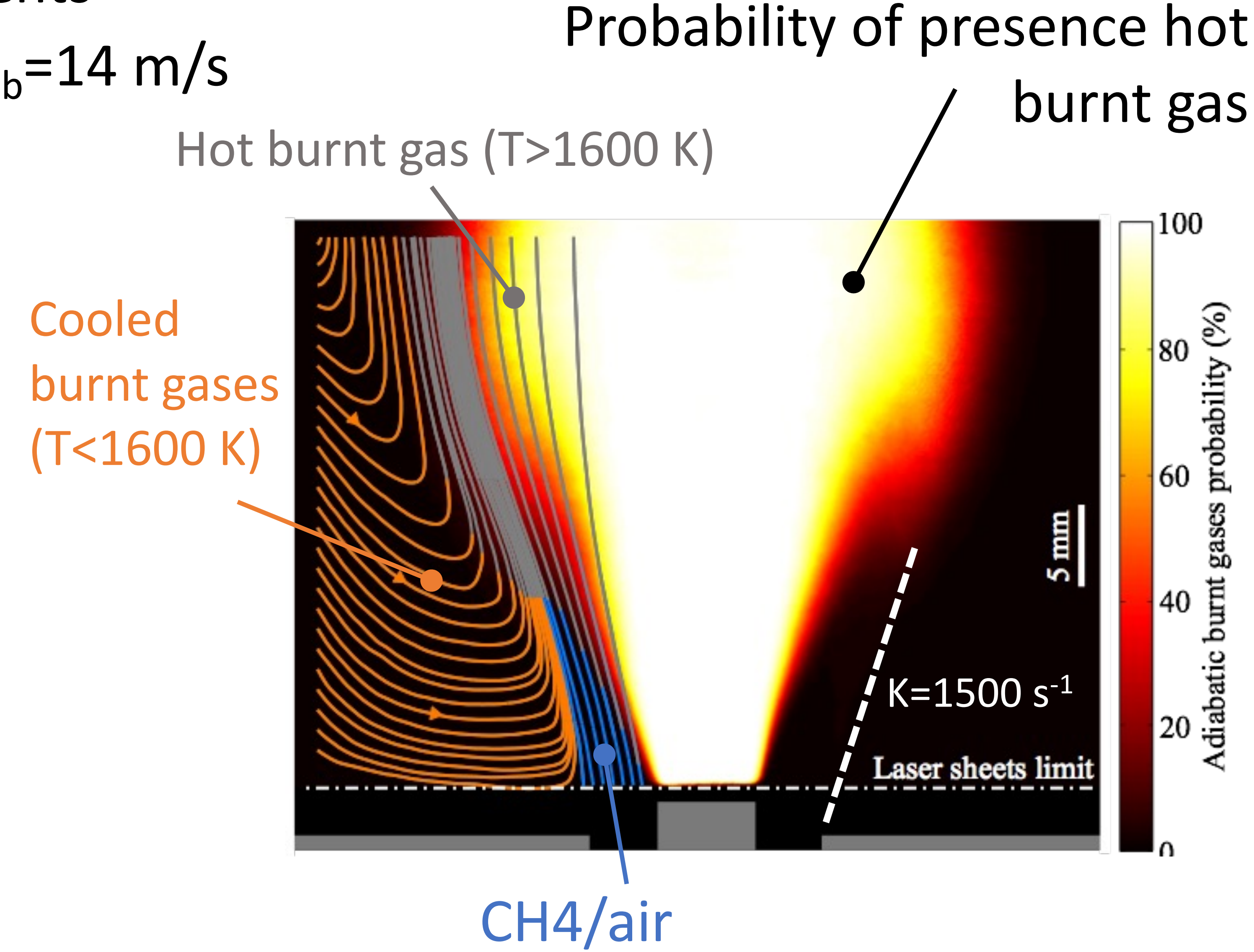


Structure of lean premixed CH4/H2 swirled flame

PIV and OH-PLIF measurements

ϕ=0.79, P=4 kW, X_{H2}=0.55, u_b=14 m/s

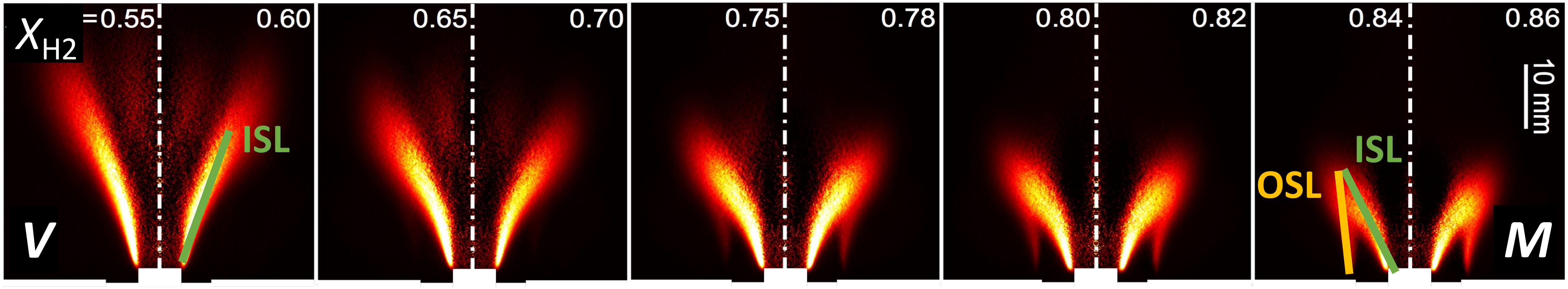




Effect of H2 add. on premixed flame stabilization

Guiberti et al. (2015) PCI, 35:1385 Mercier et al. (2016) CNF, 171:42

ϕ=0.79, P=4 kW, OH* chemiluminescence + Abel inversion

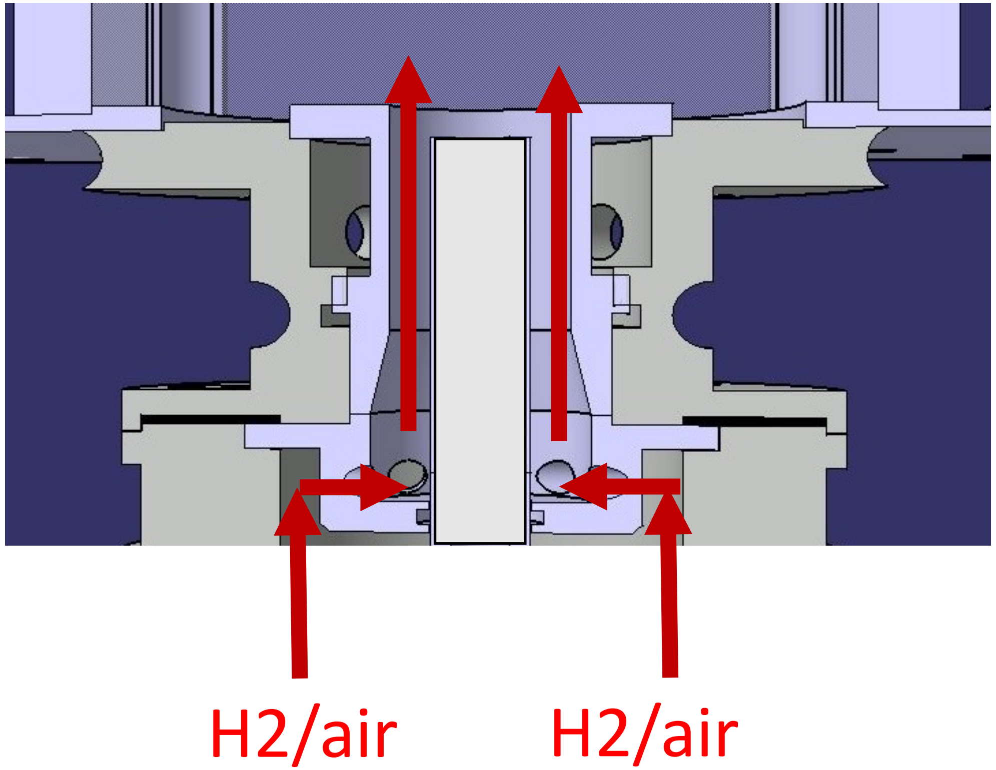


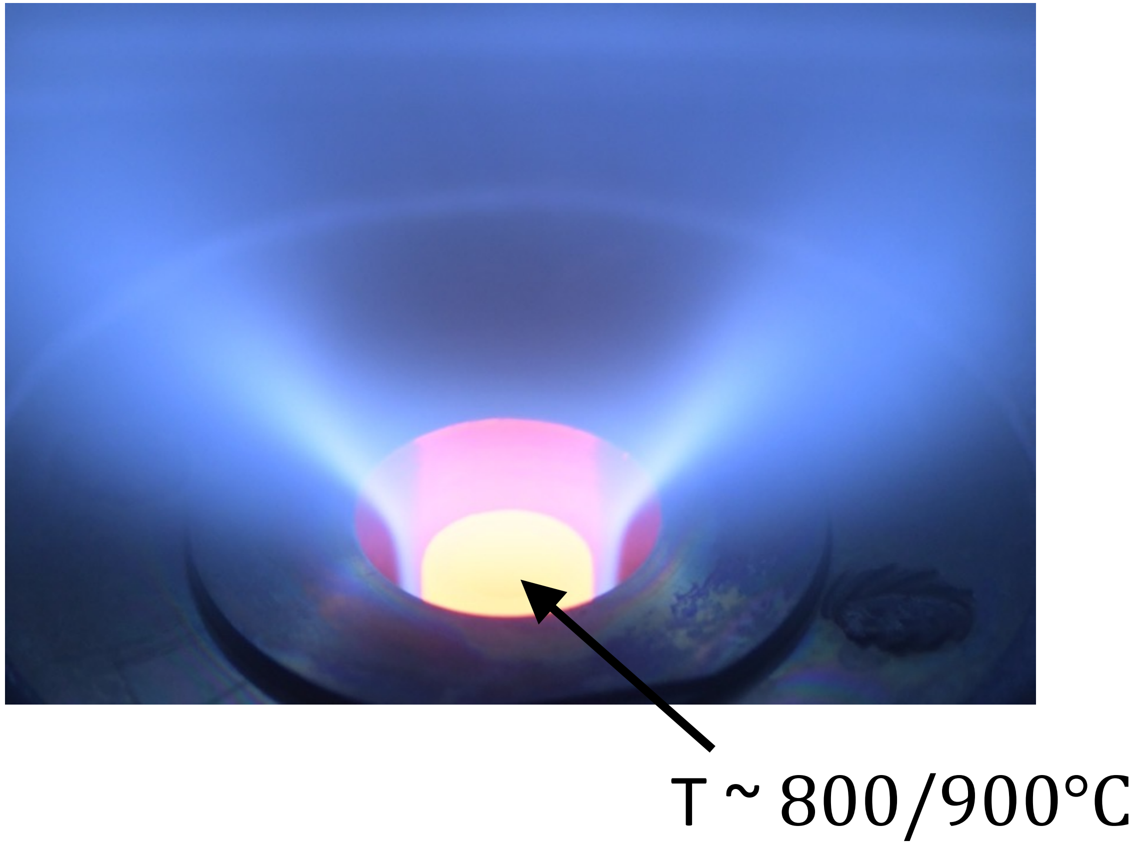
As the H2 content increases, elongated V-flames transit to compact M-flames with an additional reaction layer stabilized in the OSL

Hydrogen enriched premixed flames are more compact and more resistant to aerodynamic strain and enthalpy losses leading to increased thermal stress on the burner

Fully premixed H2-air swirled burner

S. Marragou PhD IMFT

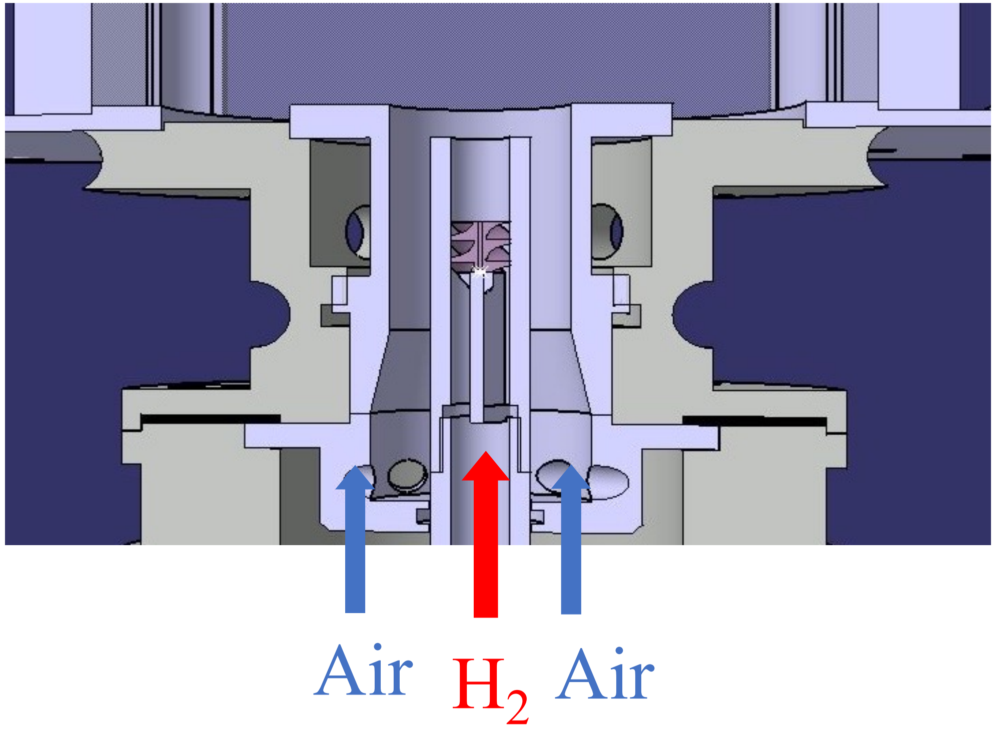


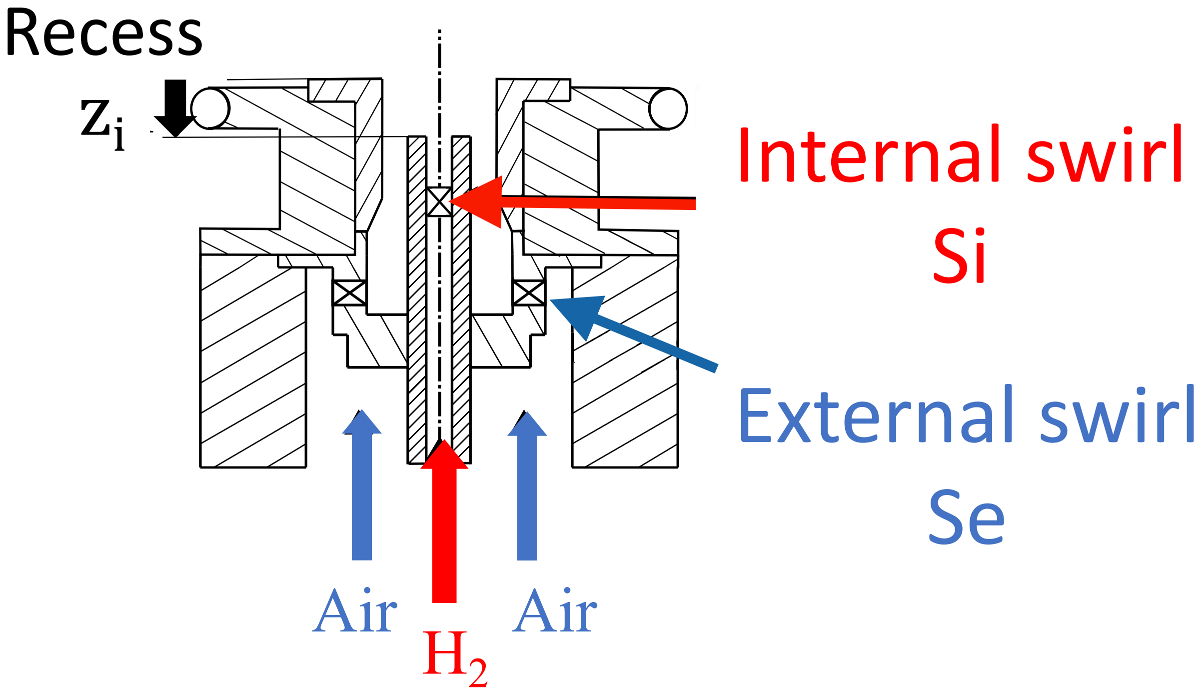


Turbulent lean premixed H2-air swirled flames are extremely sensitive to flashback

HYLON : Hydrogen Dual Swirl Low NOx burner

- Late hydrogen injection — Eliminate the flashback risk
- Swirled hydrogen injection — Improve mixing to reduce NOx emissions





Richard, Viguier, Marragou, Schuller, FR Patent No FR21111267, 2021

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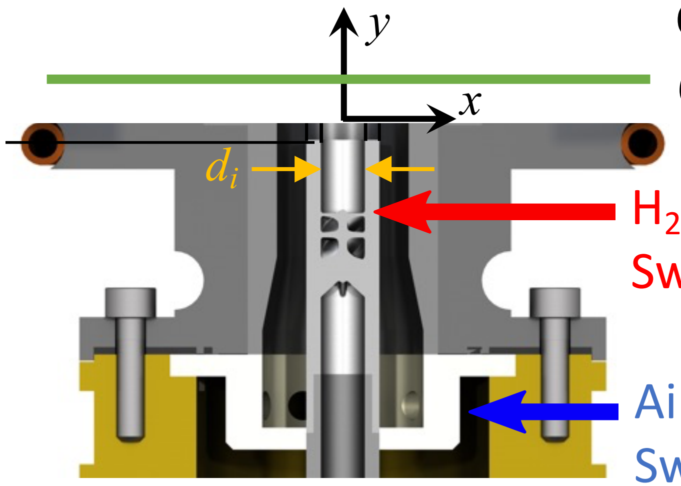
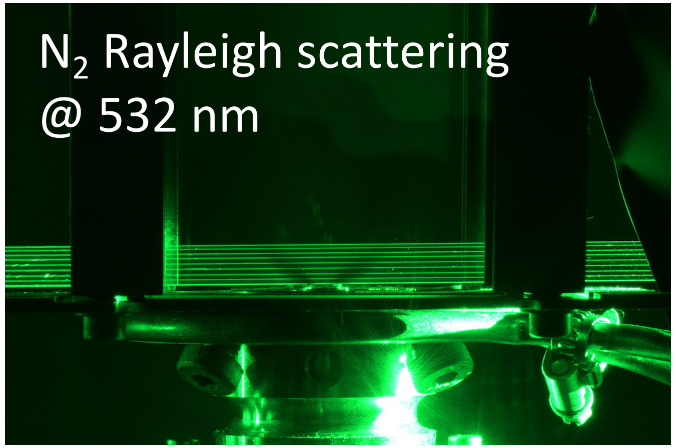
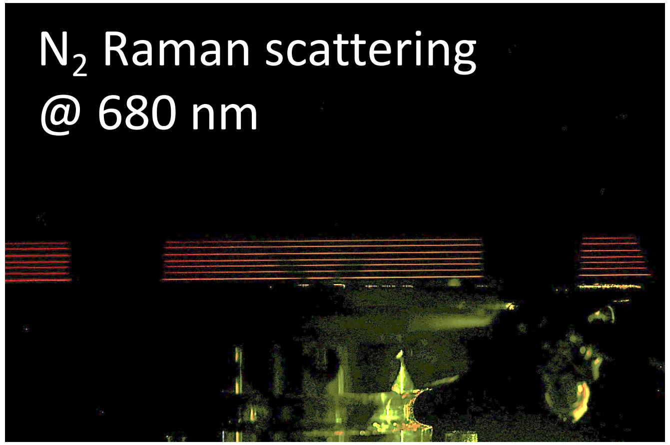
Impact of S_i on H2/air mixing rate

S. Marragou PhD IMFT

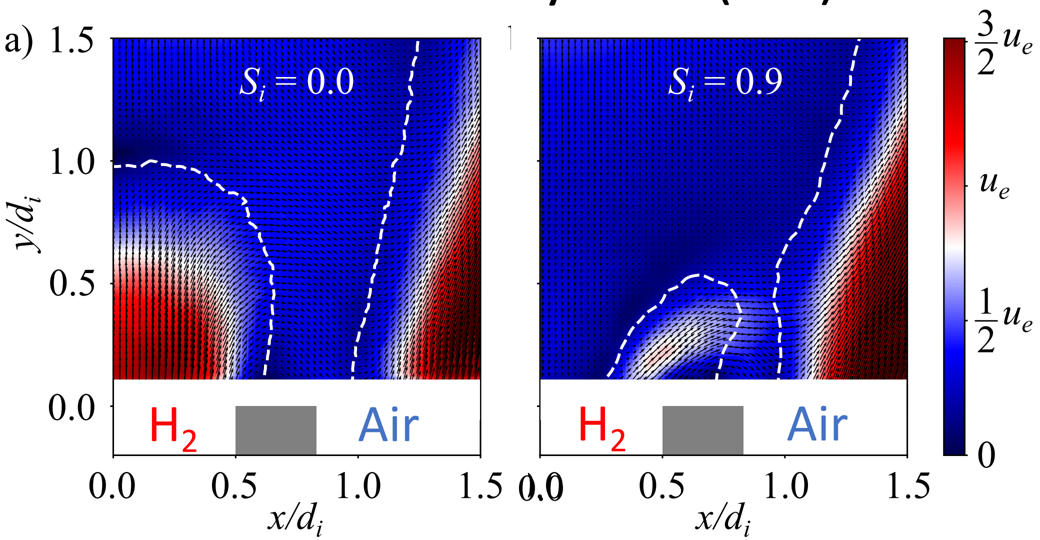


CW laser
@ 532 nm

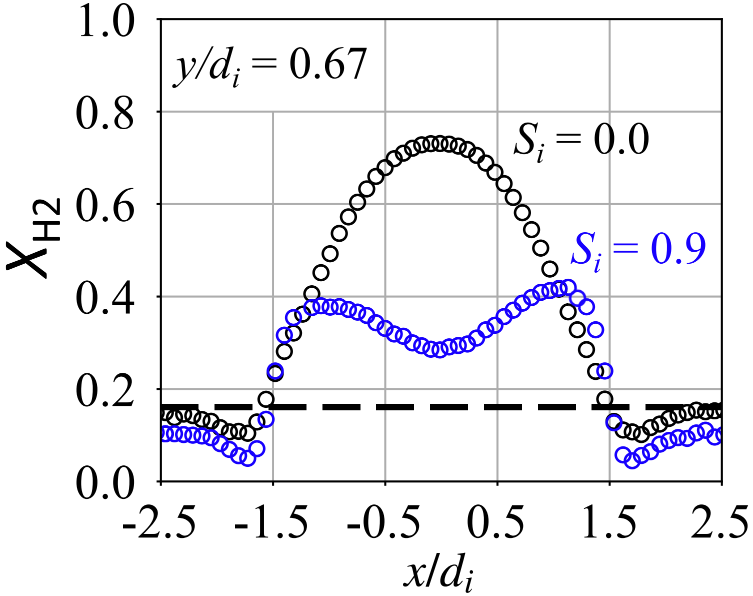




Cold flow velocity field (PIV)



H_2 molar fraction



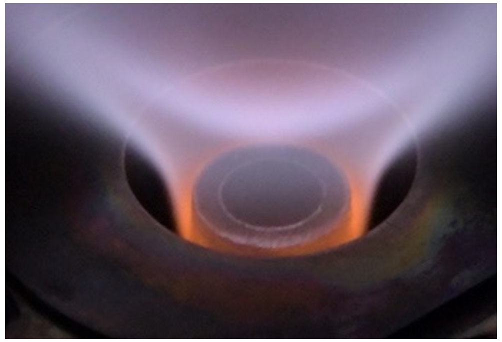
Swirling hydrogen improves the mixing rate at the burner outlet

Well mixed limit

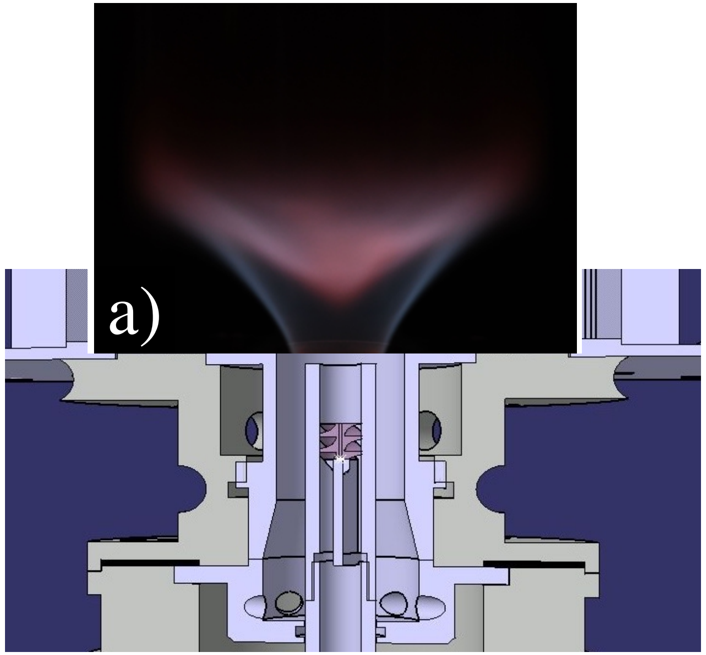
Two stabilization regimes

Marragou et al. (2022) IJHE 47: 19275

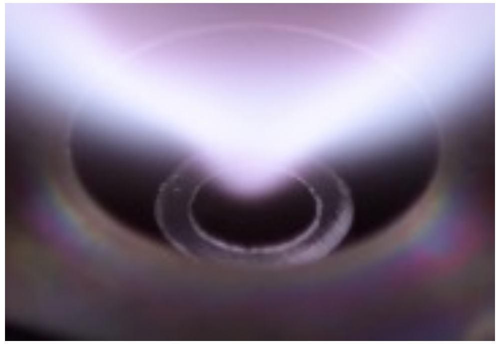
Anchored



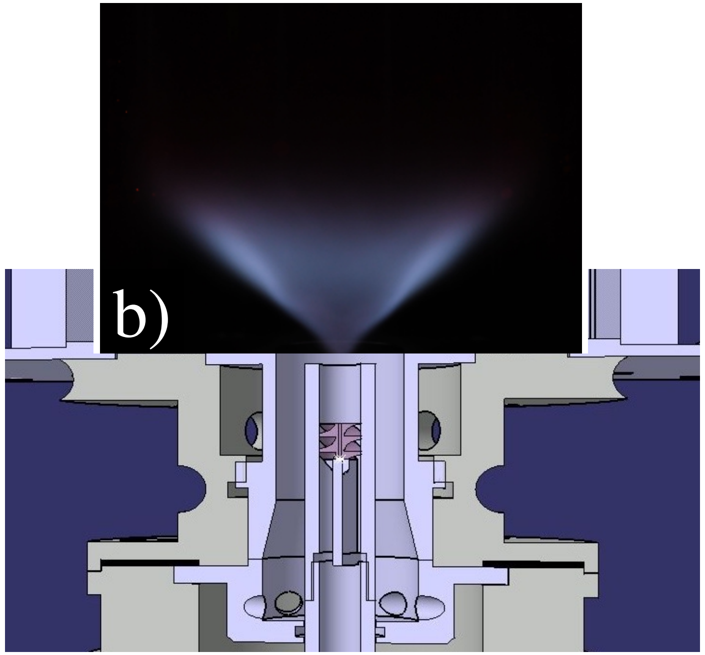
$T \sim 600/700°\text{C}$



Lifted

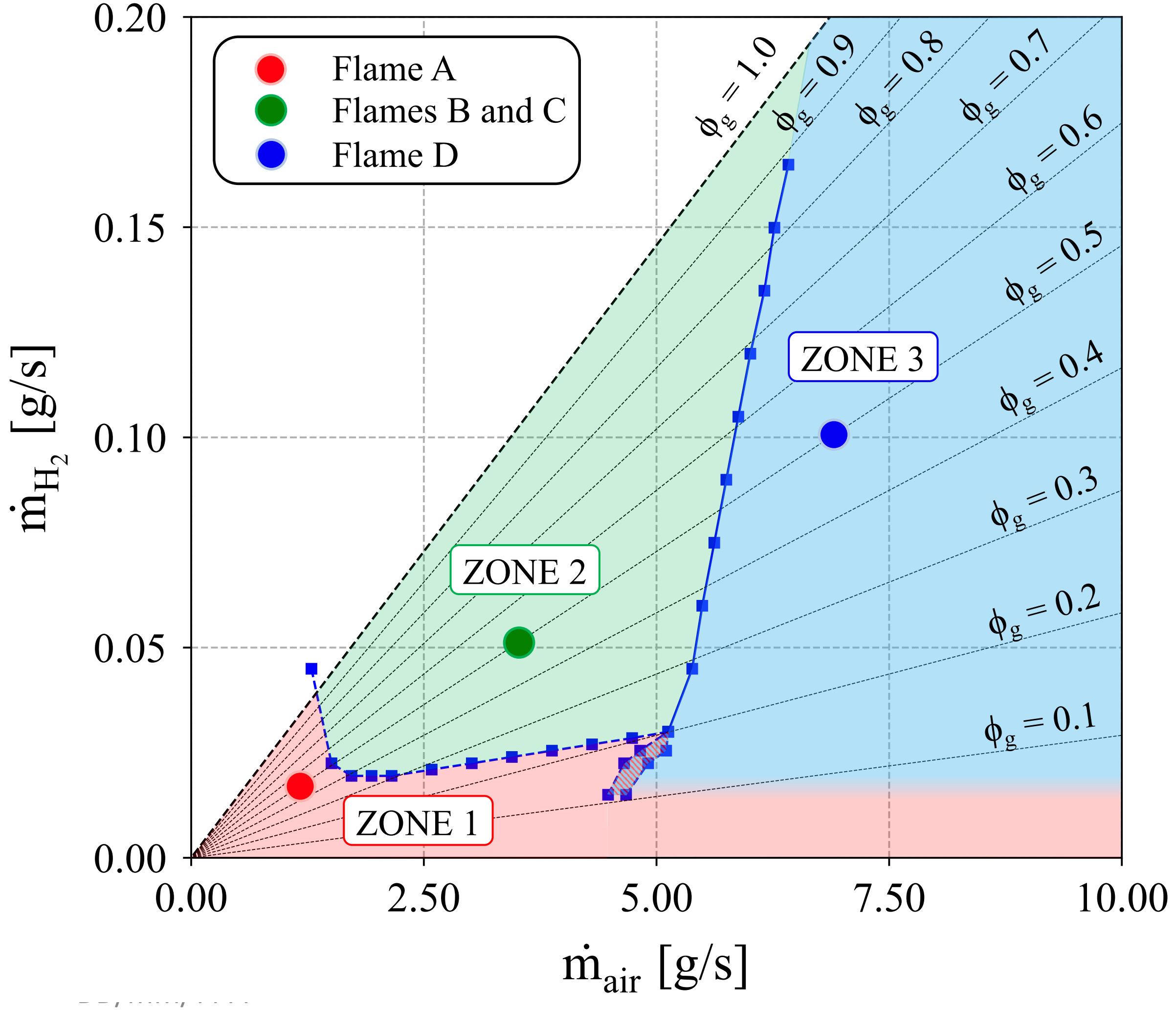


$T \sim 200/300°\text{C}$

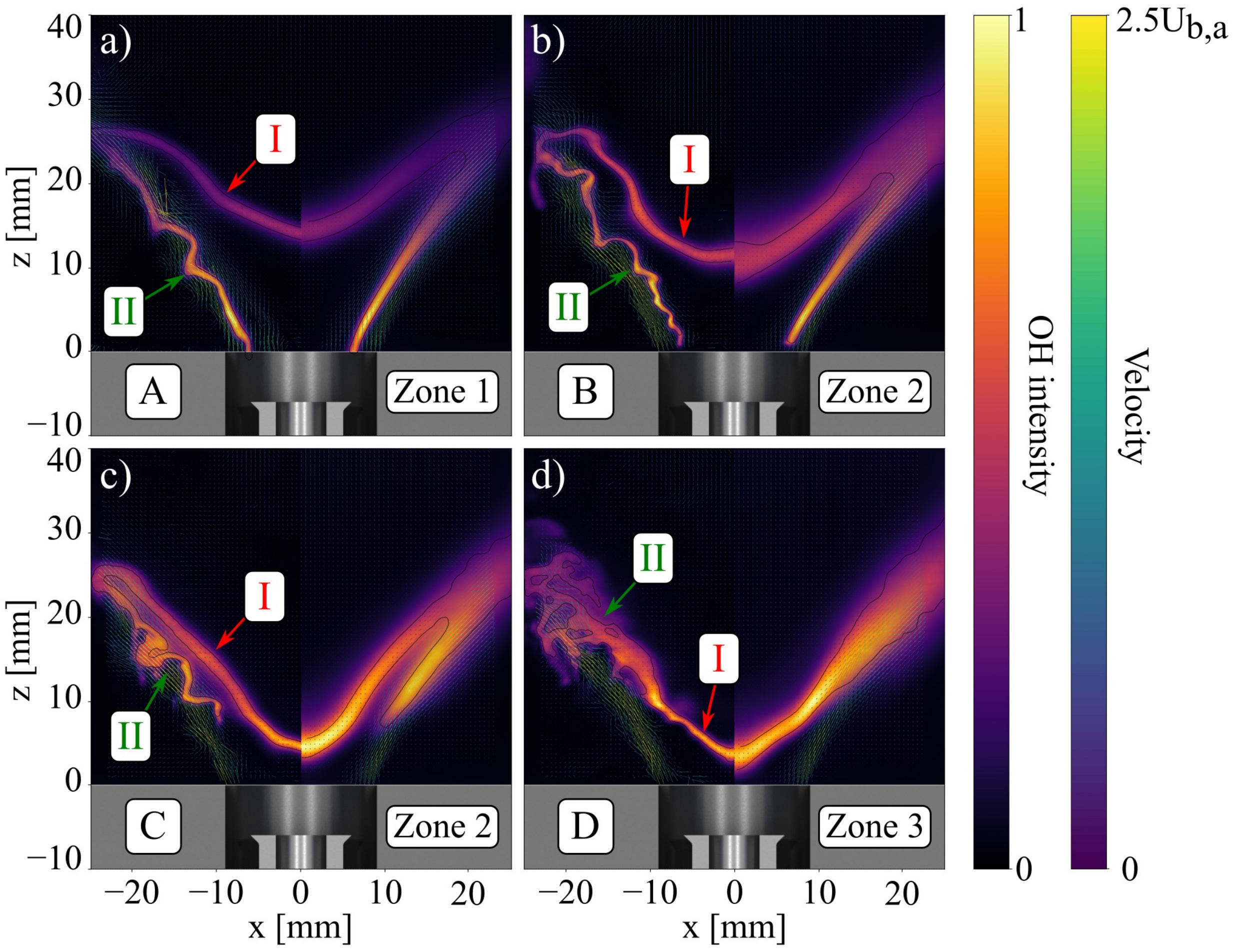


Stabilization chart @ p=1 bar, T=300 K

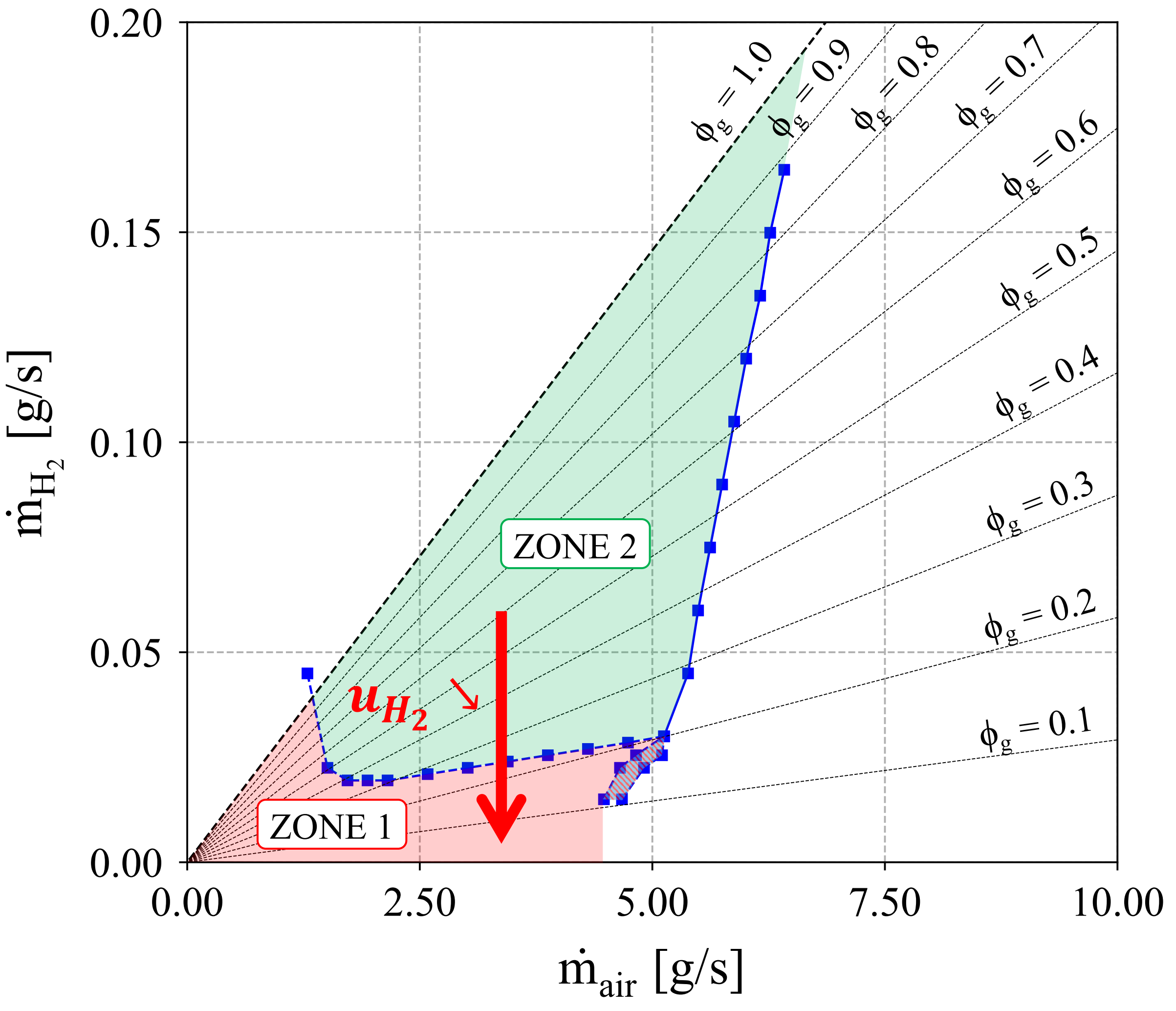
Magnes et al. GT2023-103192



PIV + OH PLIF



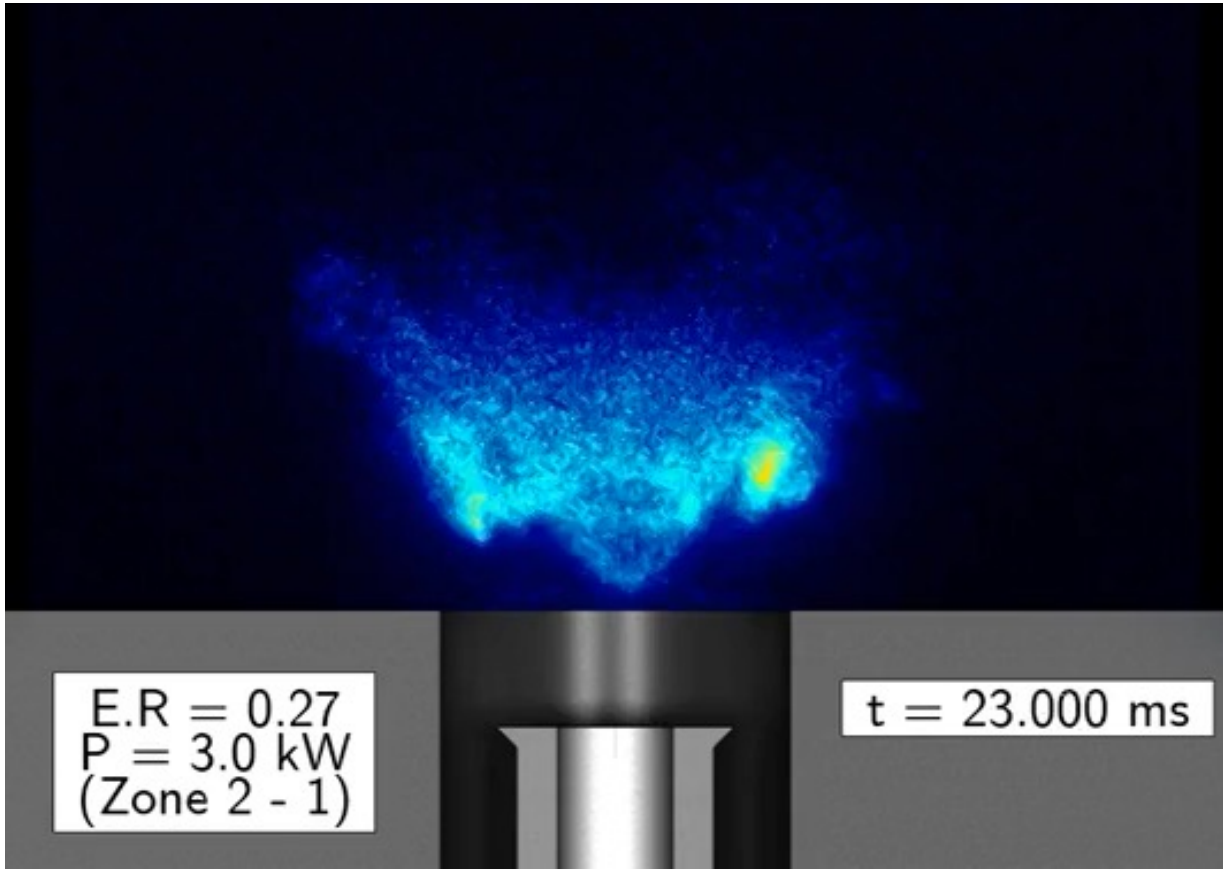
Analysis of flame re-anchoring



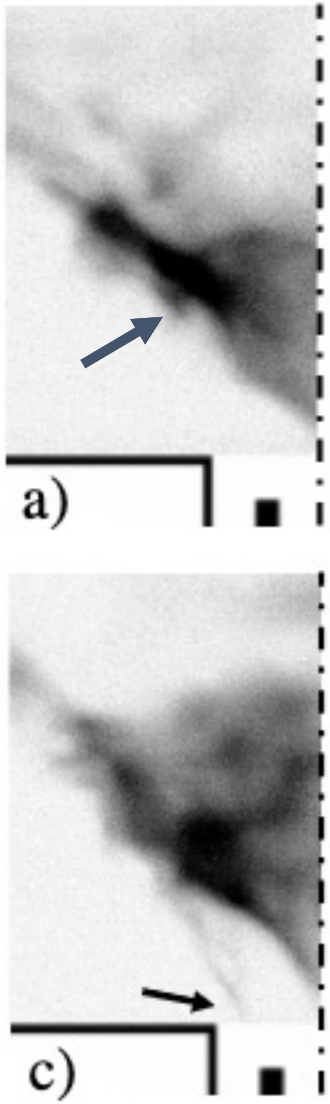
Reduction of the hydrogen injection velocity U_i

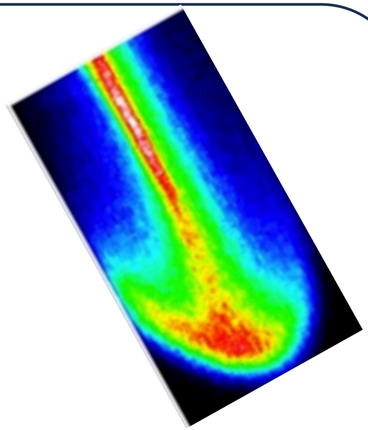
High speed image of flame re-anchoring

Line of sight OH* visualization (16 kHz)



Aniello et al. (2023) CNF, 249:112585





Edge flame

TFUP : Triple Flame Upstream Propagation zone

TFUP zone: $u_t < S_d$

Marragou et al. PCI (2023) 255:112908

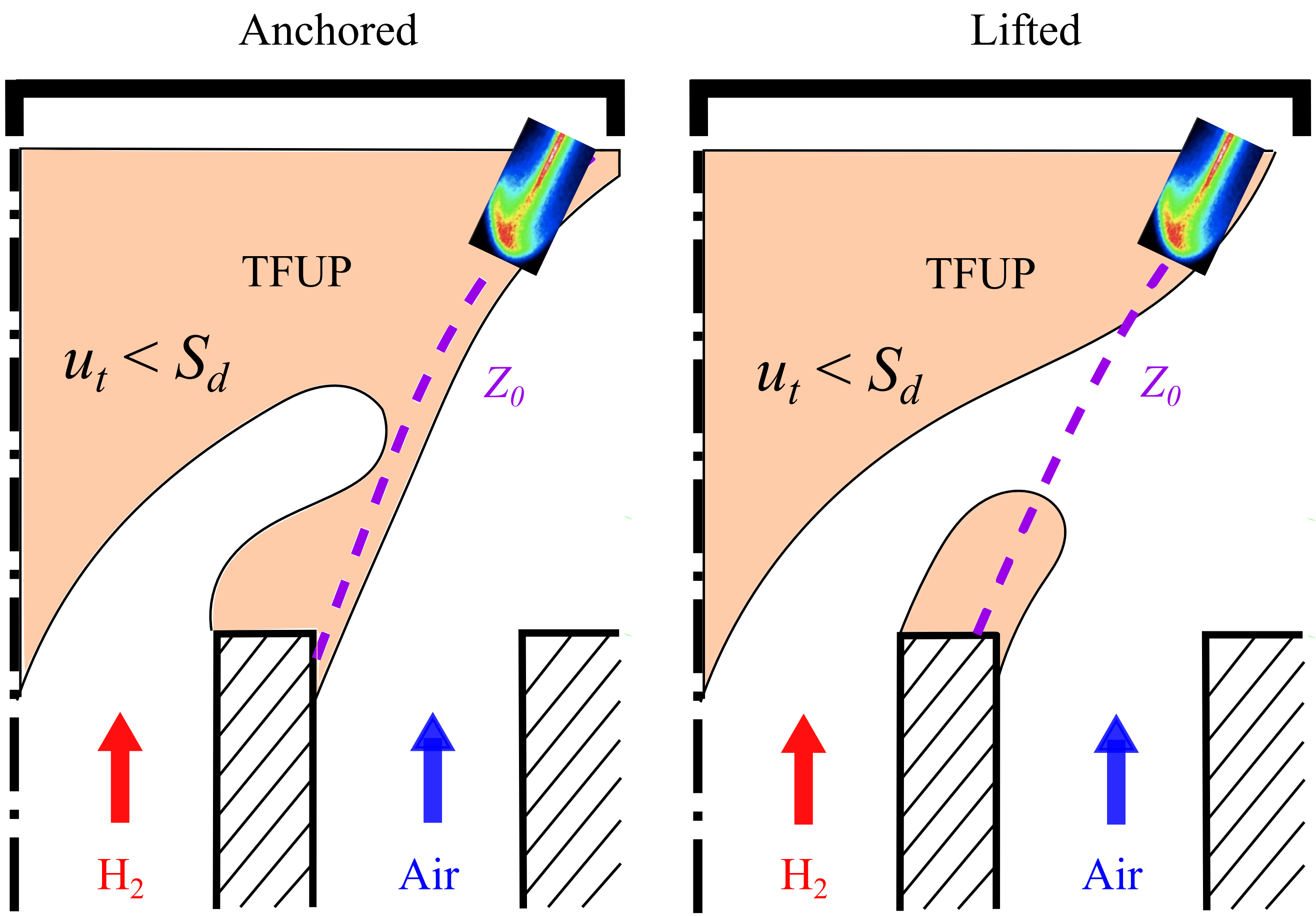
Triple flame displacement speed

$$S_d = S_L^0 \left(\rho_u / \rho_b\right)^{1/2}$$

Flame stabilization deduced from

- cold flow PIV: u_t
- cold flow Raman scattering: Z_0

Marragou et al. CNF (2023) 39:4345

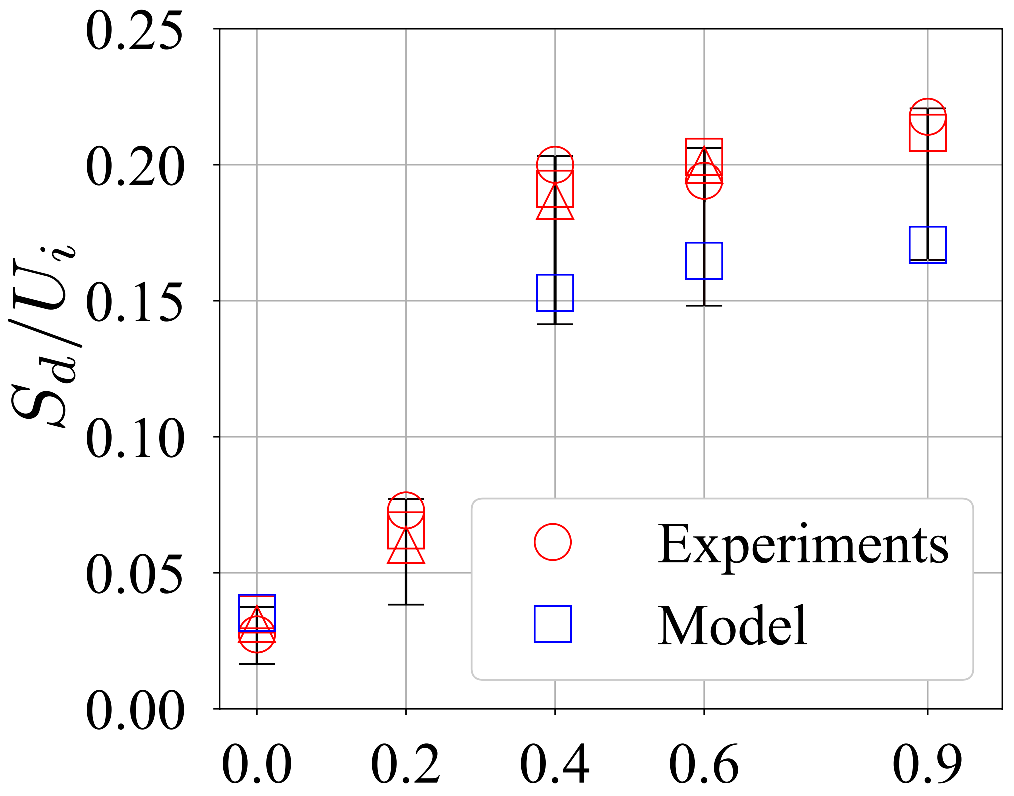


Flame re-anchoring prediction

U_i : hydrogen velocity at which transition to anchored flame takes place

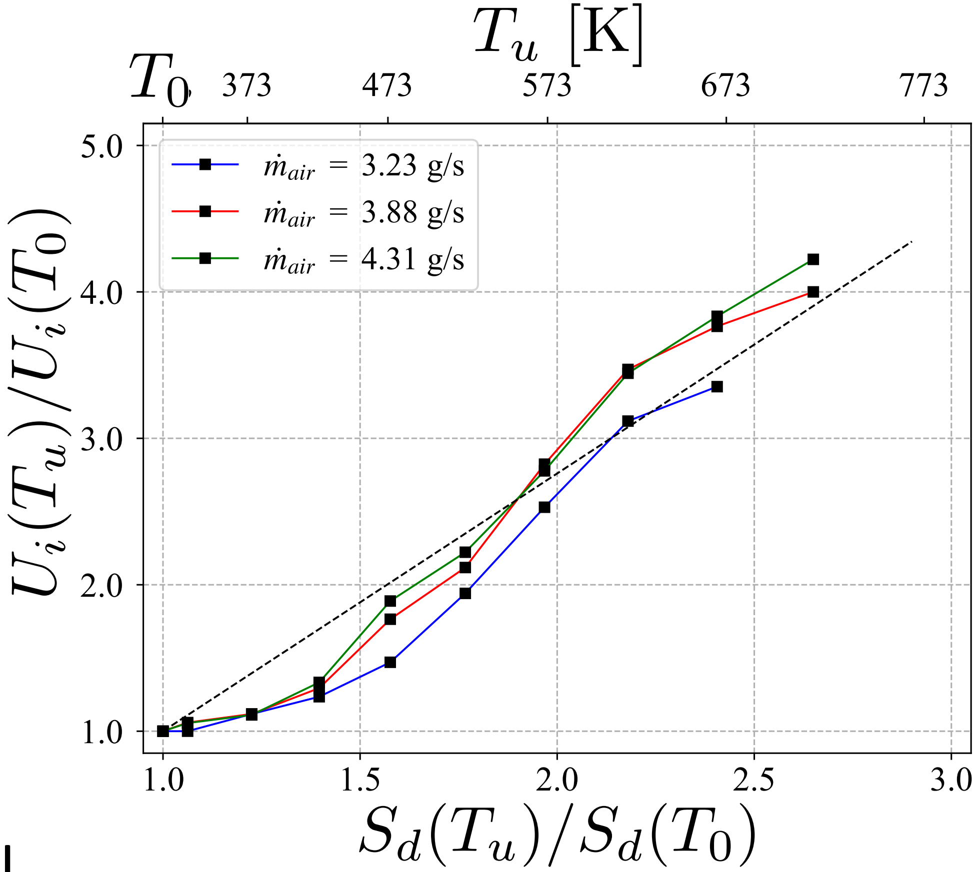
Marragou et al. CNF (2023) 39:4345

Impact of swirl, p=1 atm, T_0=300 K



Magnes et al. JEGTP (2024) 146:051004

Impact of air preheating, p=1 atm, S_i=0.6



High pressure test @ ONERA

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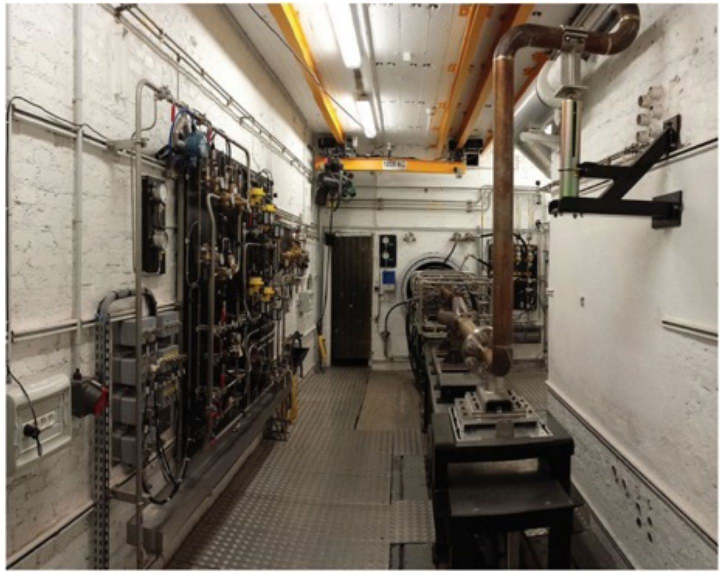
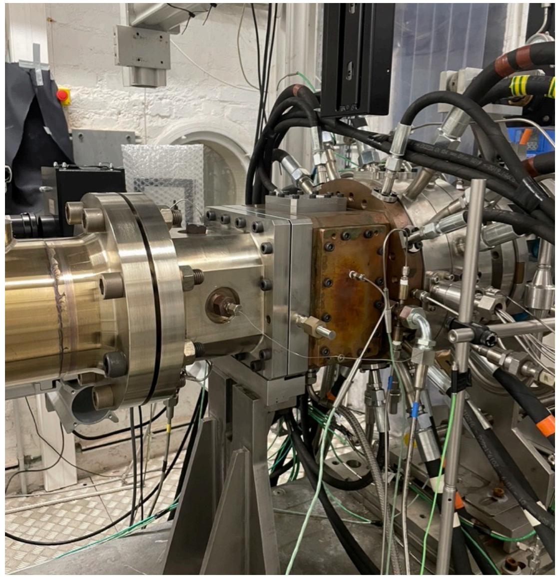
High pressure ONERA Palaiseau Micado test rig

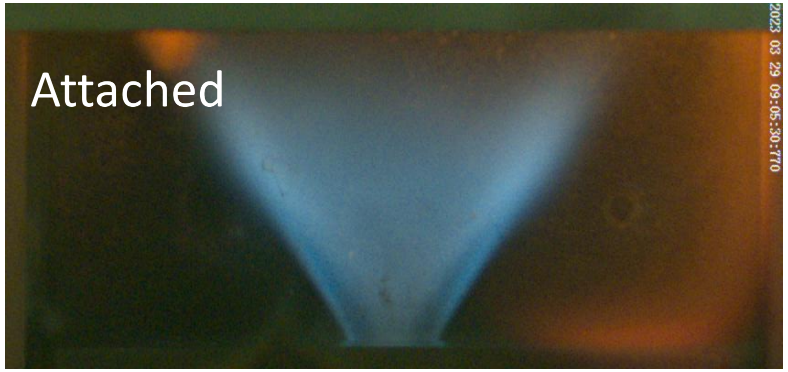


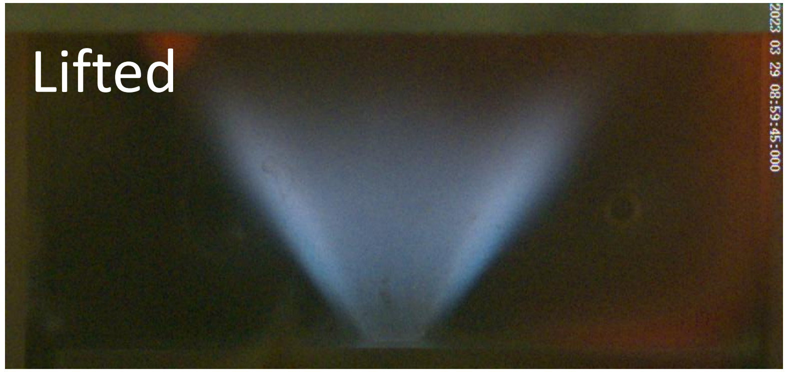


G. Pilla, ONERA

ONERA
THE FRENCH AEROSPACE LAB

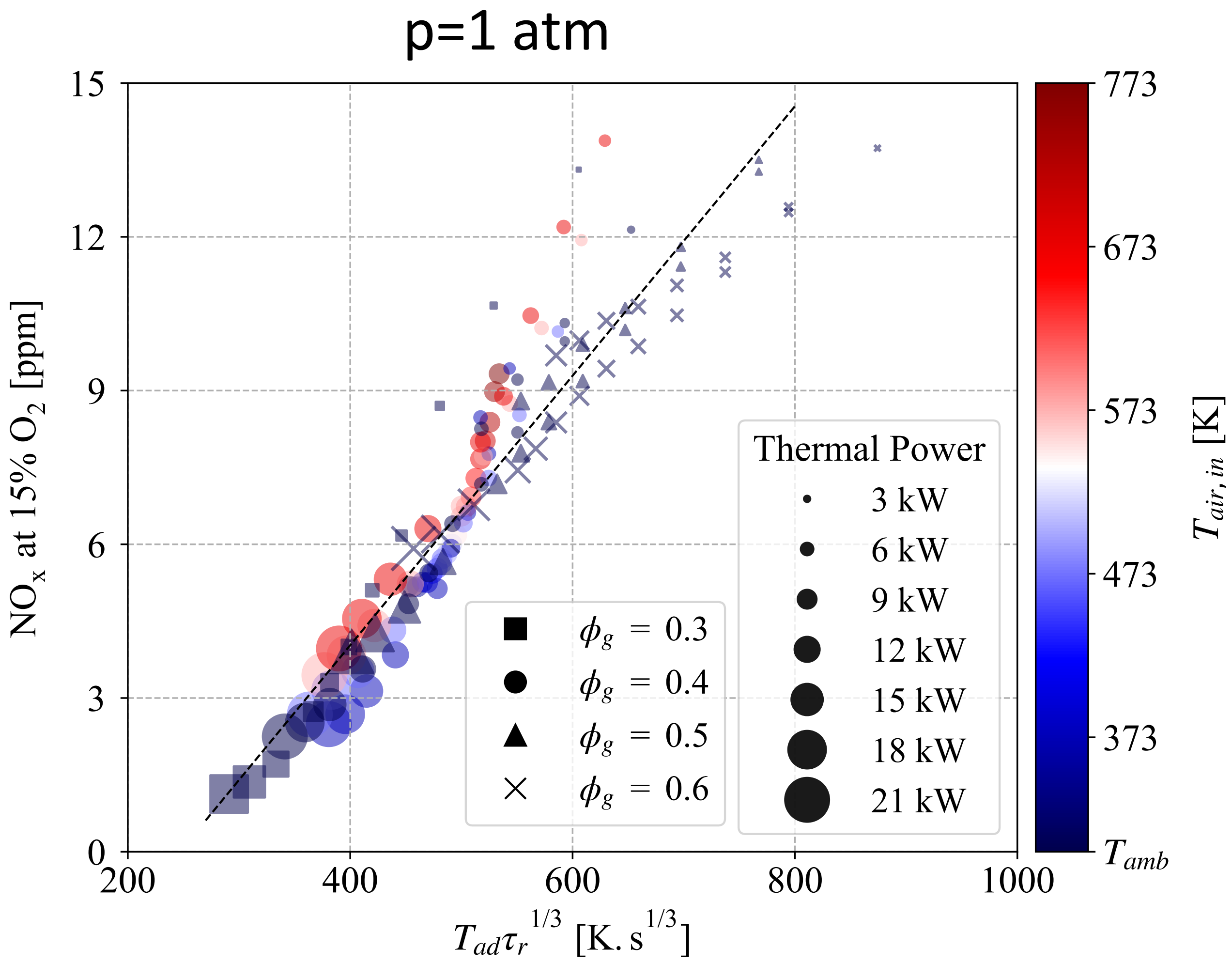
Test at engine relevant thermodynamic conditions

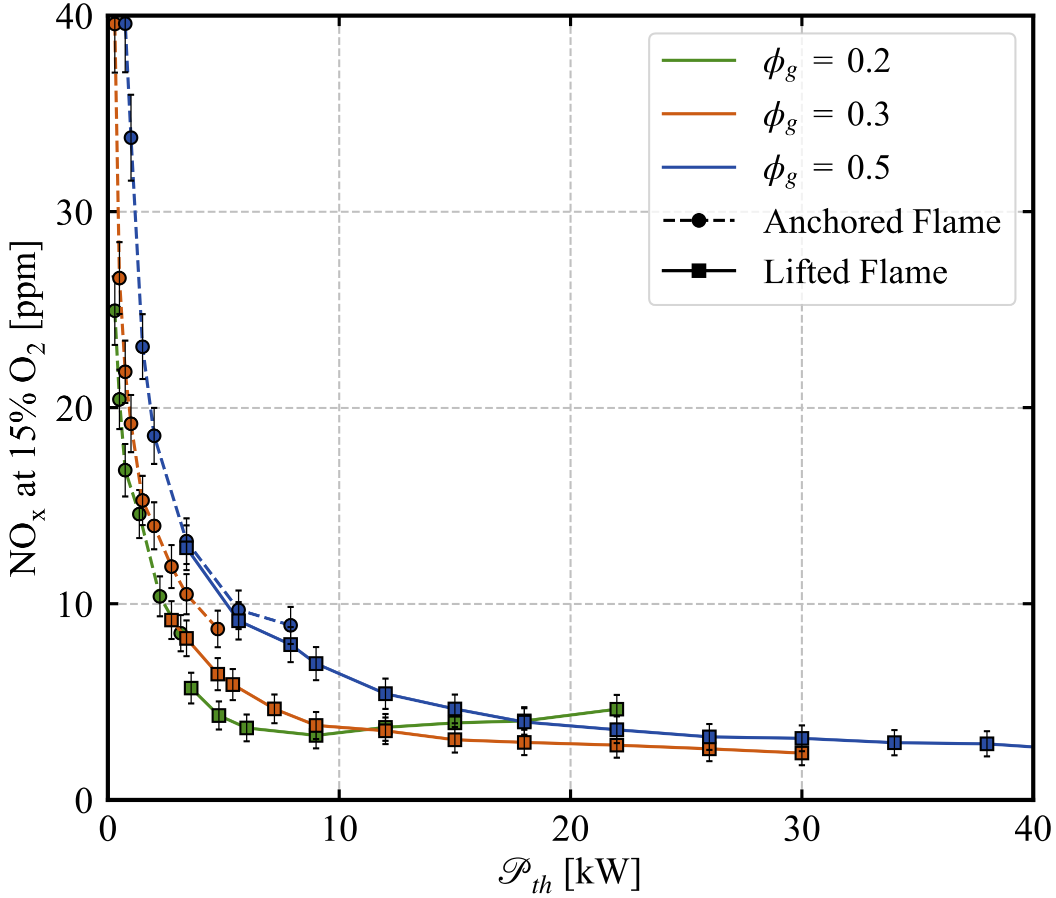




NOx emissions

Magnes et al. JEGTP (2024) 146:051004





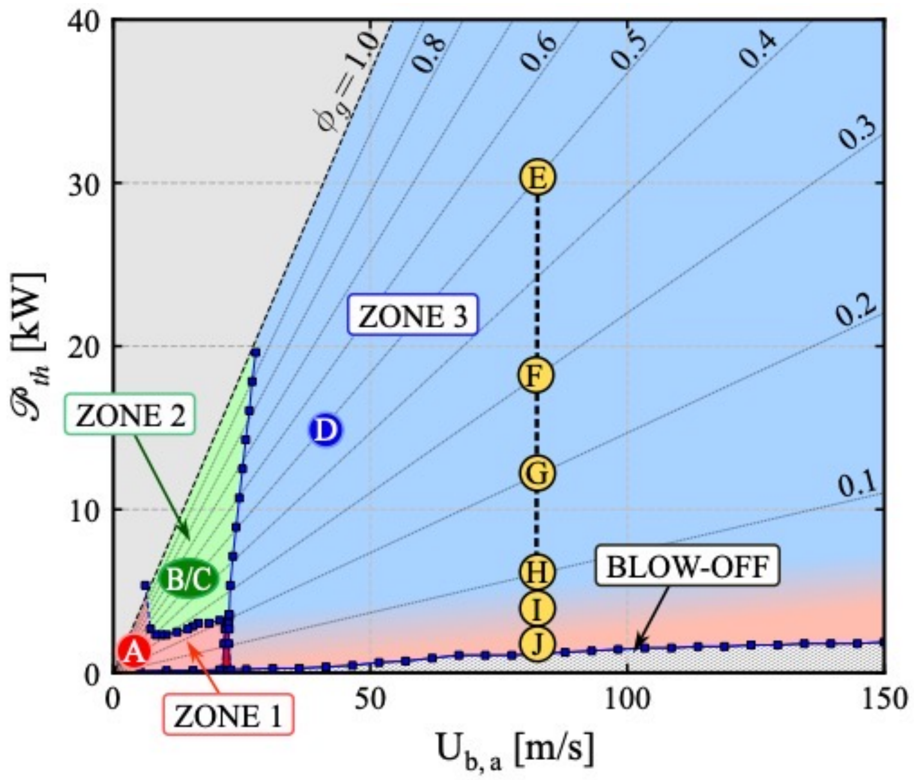
NOx scale with adiabatic flame temperature and residence time

At high power, NOx are independent of thermal power

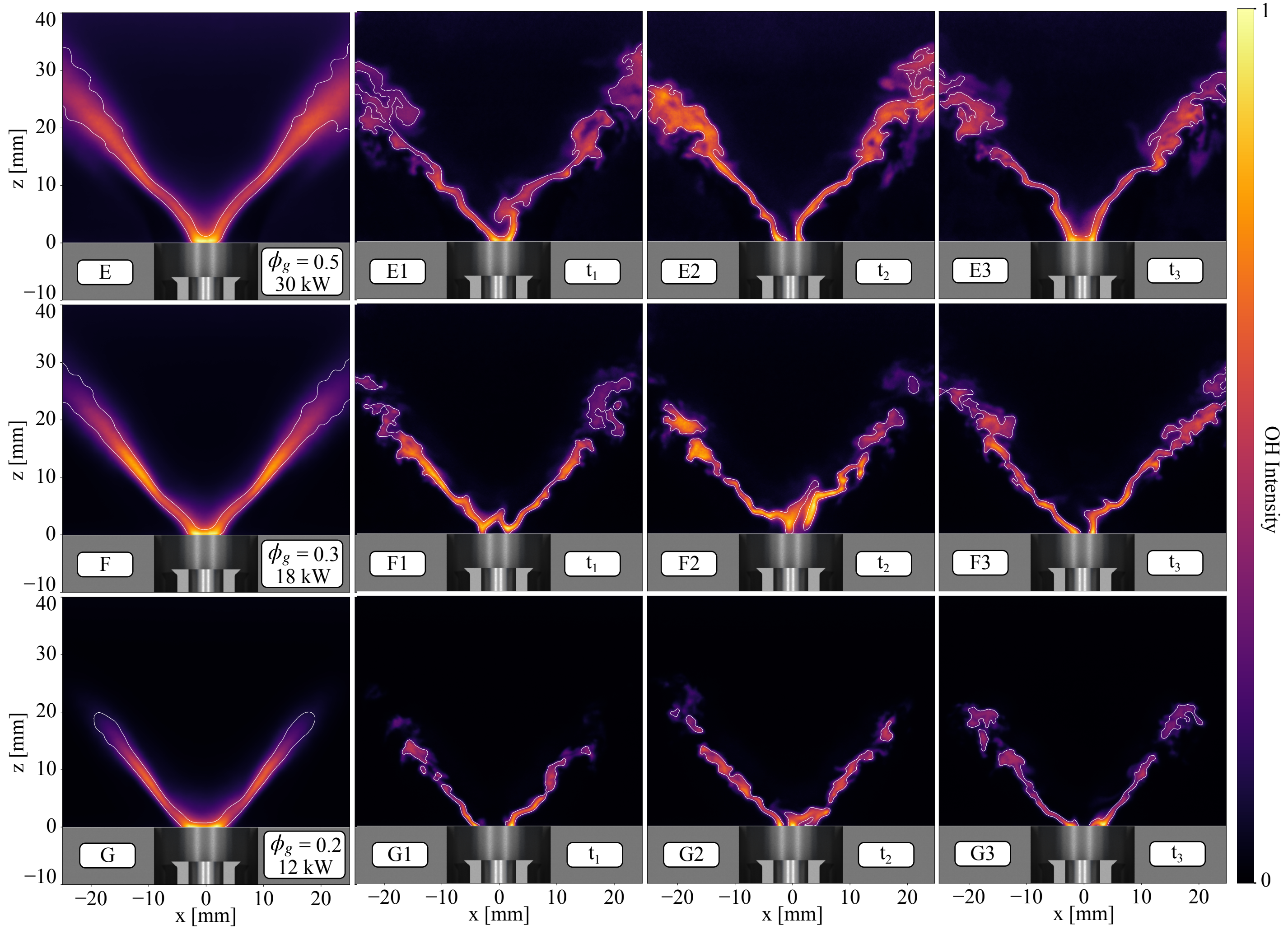
Blow off

Magnes et al. ASME Turbo Expo, June 2024, London

p=1 atm, T_0=300 K



Mean OH-PLIF Instantaneous OH-PLIF snapshots

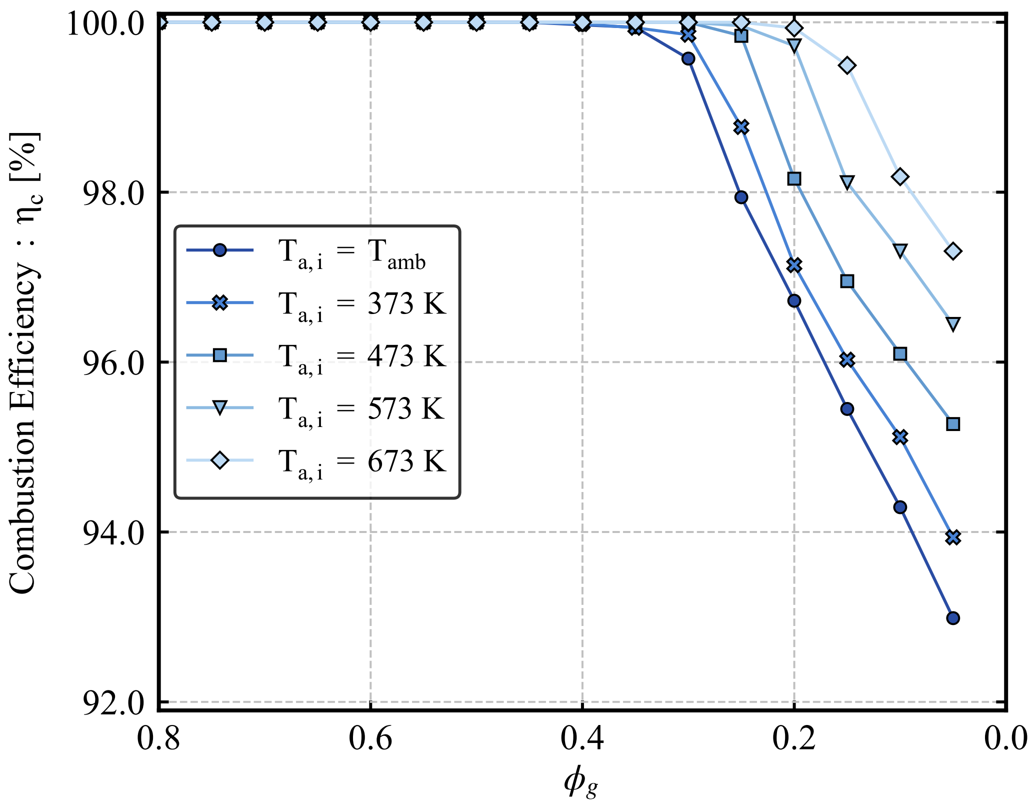


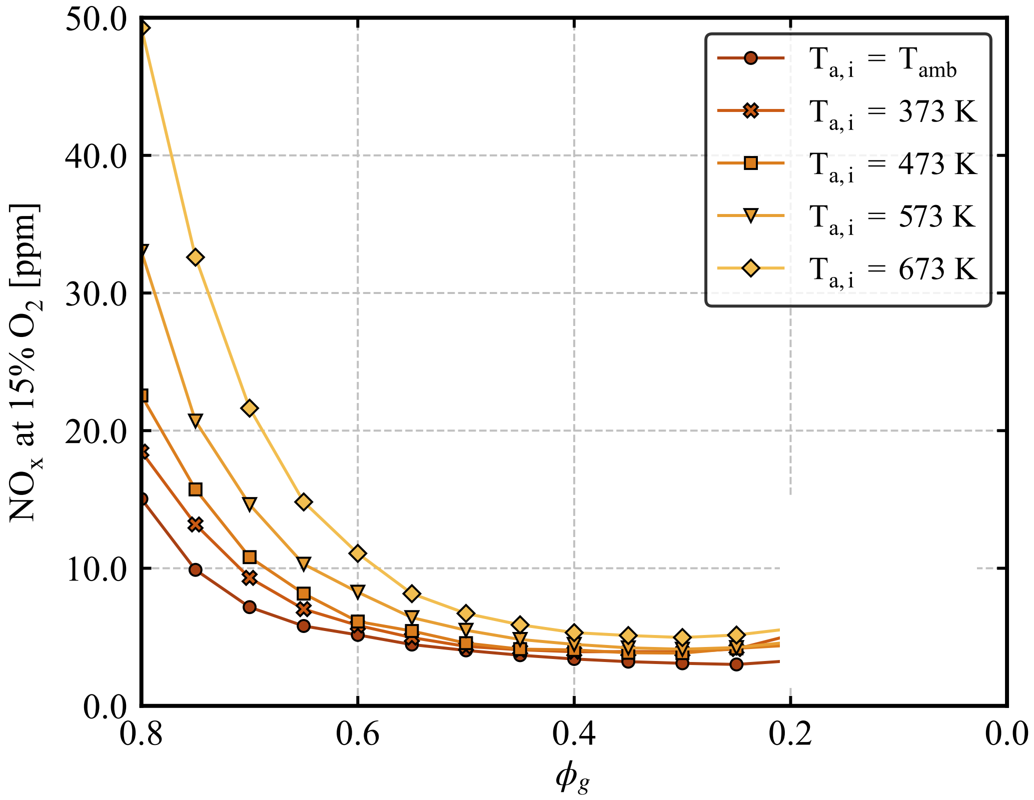
Flame front fragmentation at the tip (local extinctions) at very lean operating conditions

Interplay between unburnt and NOx emissions

Magnes et al. ASME Turbo Expo, June 2024, London

p=1 atm, u_e = 40 m/s





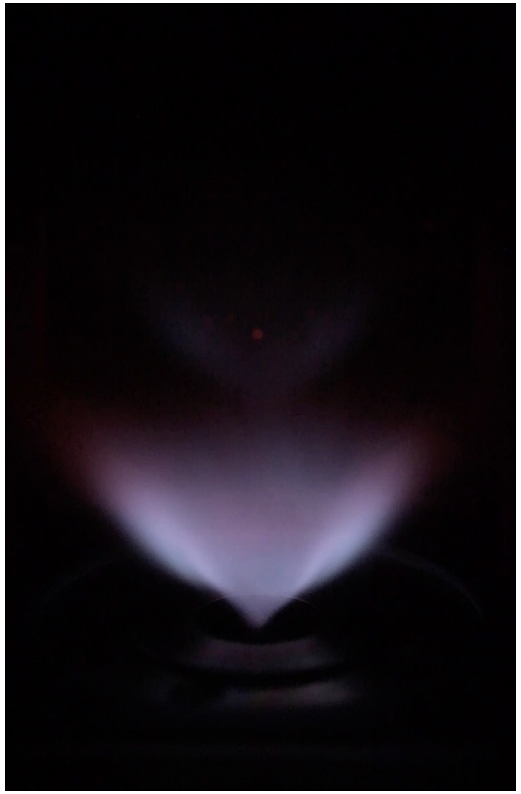
Compromise between NOx and unburnt emissions. Combustion efficiency increases with preheat temperature.

Combustion noise

Marragou, Paniez

P = 7.5 kW, Re_D=25000, ϕ~0.5   HYLON DFDS version

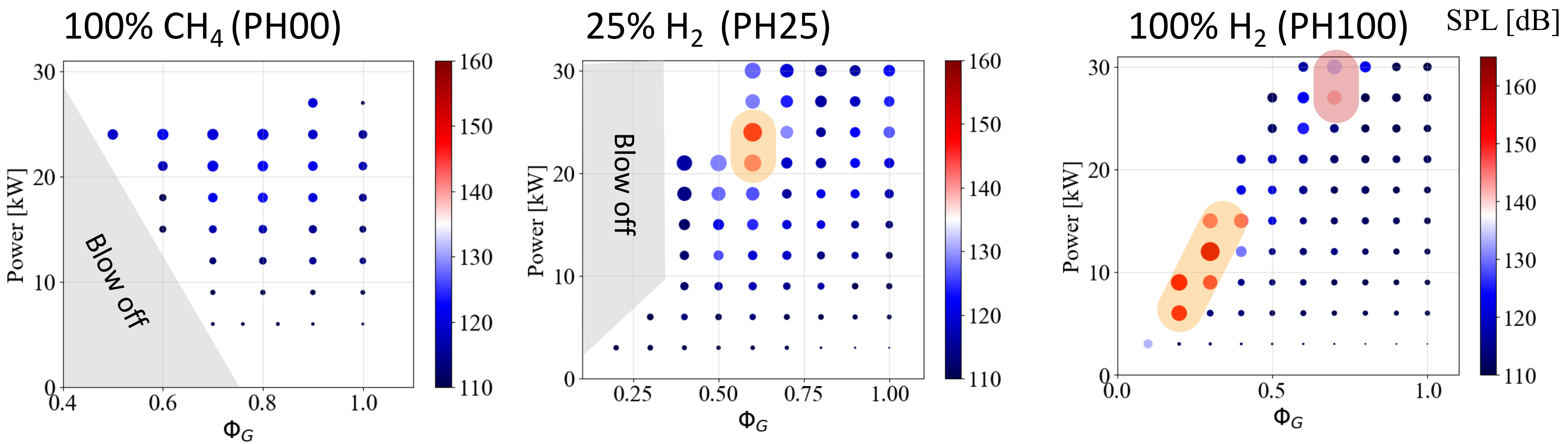
PH20 (H2+CH4/air)   PH100 (H2+air)



Combustion roar noise peaks at higher frequencies with hydrogen

Thermo-acoustic stability

Paniez PHD IMFT



Free of thermoacoustic instability (TAI)

Low frequency TAI ~500 Hz

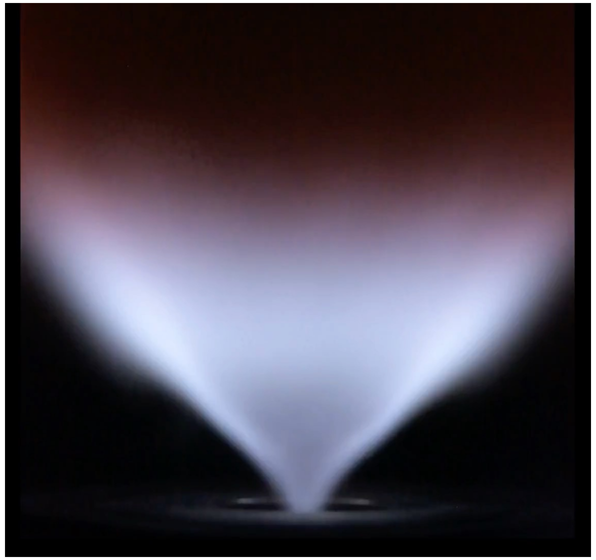
Low frequency TAI ~ 500 Hz

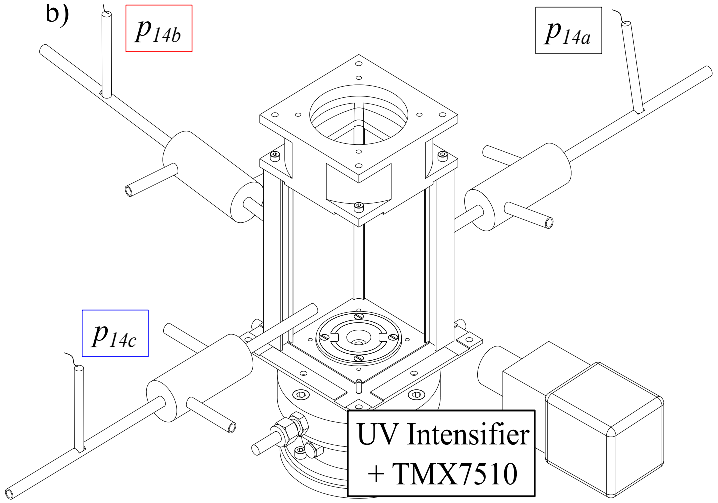
High frequency TAI ~ 5 kHz

Higher H2 content results in (1) broader conditions experiencing TAI
(2) emergence of high frequency TAI

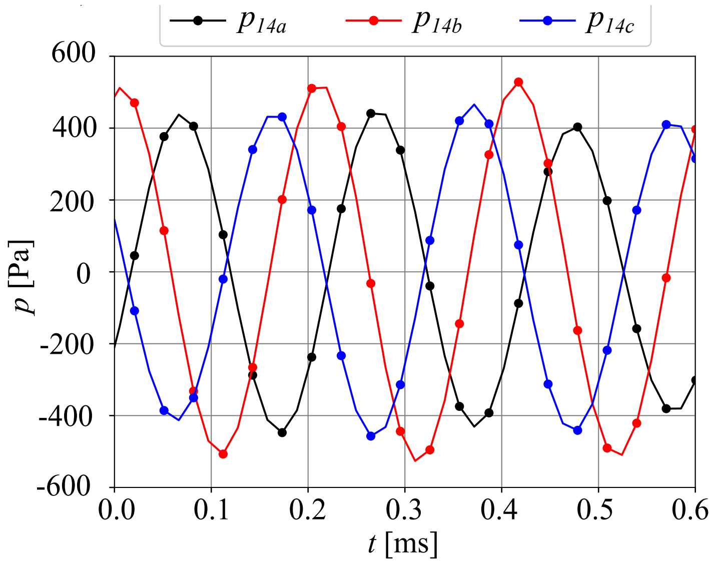
High frequency instabilities

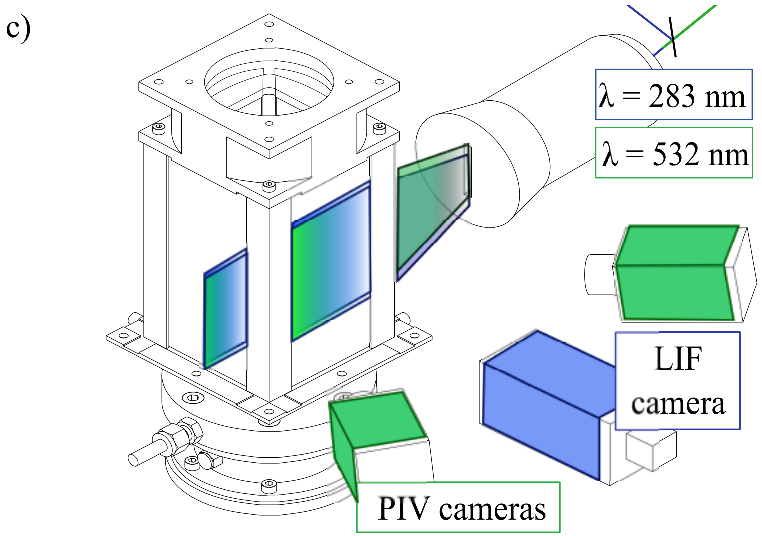
Paniez et al. Submitted *Int. Symp. Comb.*, 2024

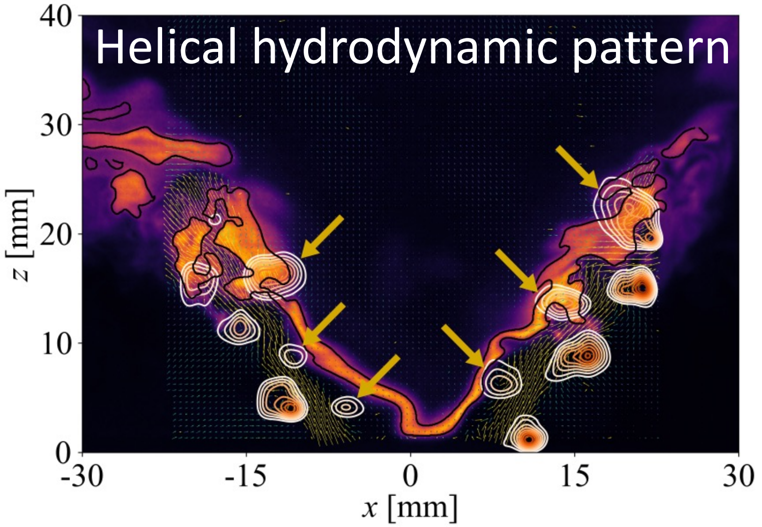




Spinning pressure wave







Conclusion

Efforts to characterize hydrogen flames at IMFT will be pursued with its partners

HESTIA — Thermoacoustics

Select-H — Ignition, combustion noise, hydrogen gaseous leaks, flame wall interactions

High pressure

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جامعة الملك عبدالله للعلوم والتقنية
King Abdullah University of Science and Technology | Clean Combustion Research Center

P < 5 bar (2024)

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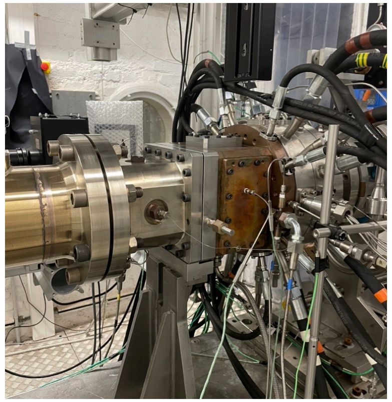
ONERA THE FRENCH AEROSPACE LAB

High pressure Micado test rig



P < 10 bar
<100 kW

Francazal and HYROPE

Francazal H2 techno campus 2025

200 m^2 combustion lab

6 new slots for experiments

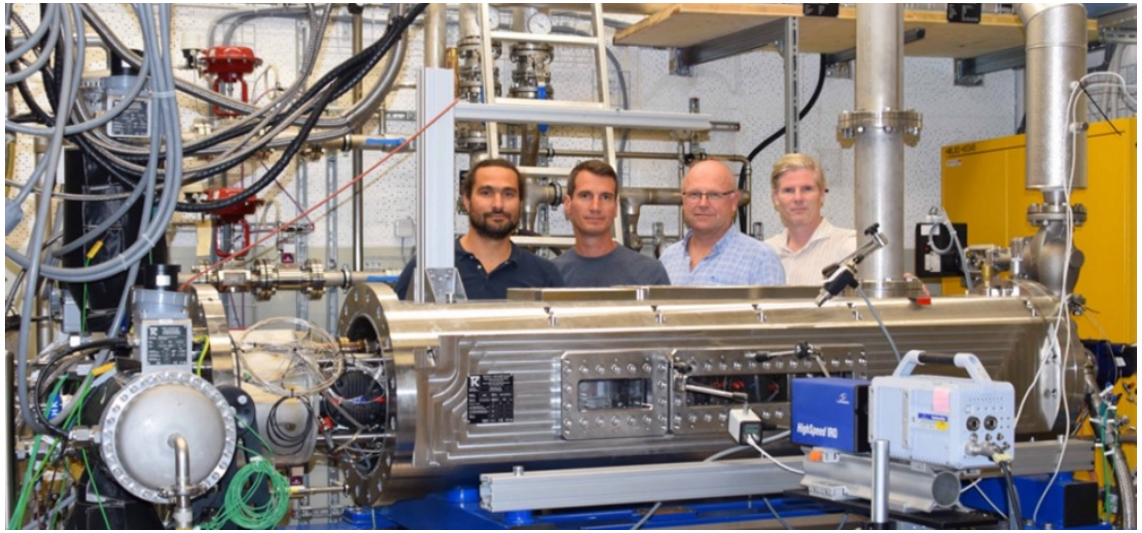
2 high pressure test facilities

HYROPE ERC SINERGY (2024-2030)

ETH Zürich

NTNU

TECHNISCHE UNIVERSITÄT DARMSTADT



IMFT
INSTITUT DE MECANIQUE DES FLUIDES DE TOULOUSE

P < 10 bar (2026)

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Conclusion

- Decarbonization requires high volumetric fractions of (green) hydrogen in the fuel mixture
- Fuel injectors and block gas regulation systems need to be adapted to fuel blends with reduced Wobbe index and reduced calorific value
- In premixed systems, large air excess ratio are needed to limit NOx emissions and flashback but generate in turn higher pressure drops
- Injector nozzle thermal stress and flashback are the main issues due to high flame displacement speed and high resistance to strain of H2 flames
- Growing number of hydrogen injectors are tested worldwide in order to improve burner reliability and operability with limited NOx

Conclusion

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- Growing number of hydrogen injectors are tested worldwide in order to improve burner reliability and operability with limited NOx

But many issues need to be addressed

- Ignition is more violent with hydrogen
- Higher autoignition risk due to lower ignition delay
- Turbul … es
- Therm … laminar flames

H2 combustion raises many exciting challenges for the combustion community

- Hydrogen fueled flames are more receptive to incoming flow disturbances
- H2 kinetics needs to be improved to predict pollutant concentrations (NO, NO_2, N_2O)
- Near wall H2 chemistry is not well known
- ….

Take away message

Urgent need of experiments for model and CFD validations

- Fundamental properties of H2/air flames
- Canonical laminar and turbulent configurations with detailled data
- Engine relevant thermodynamic conditions : T=1000 K, p=30 bar

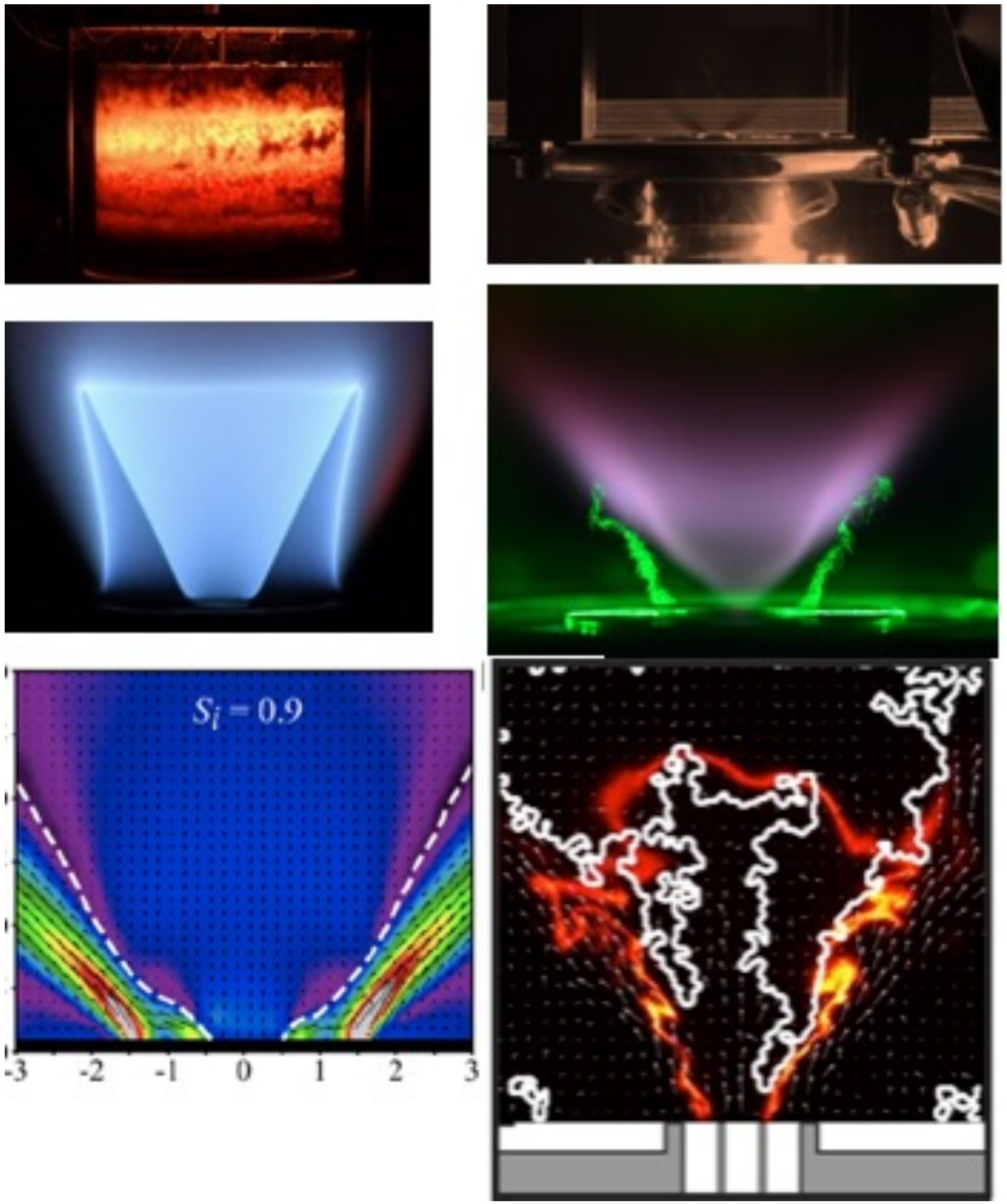
erc
European Research Council
Established by the European Commission

SCIROCCO

Select-H

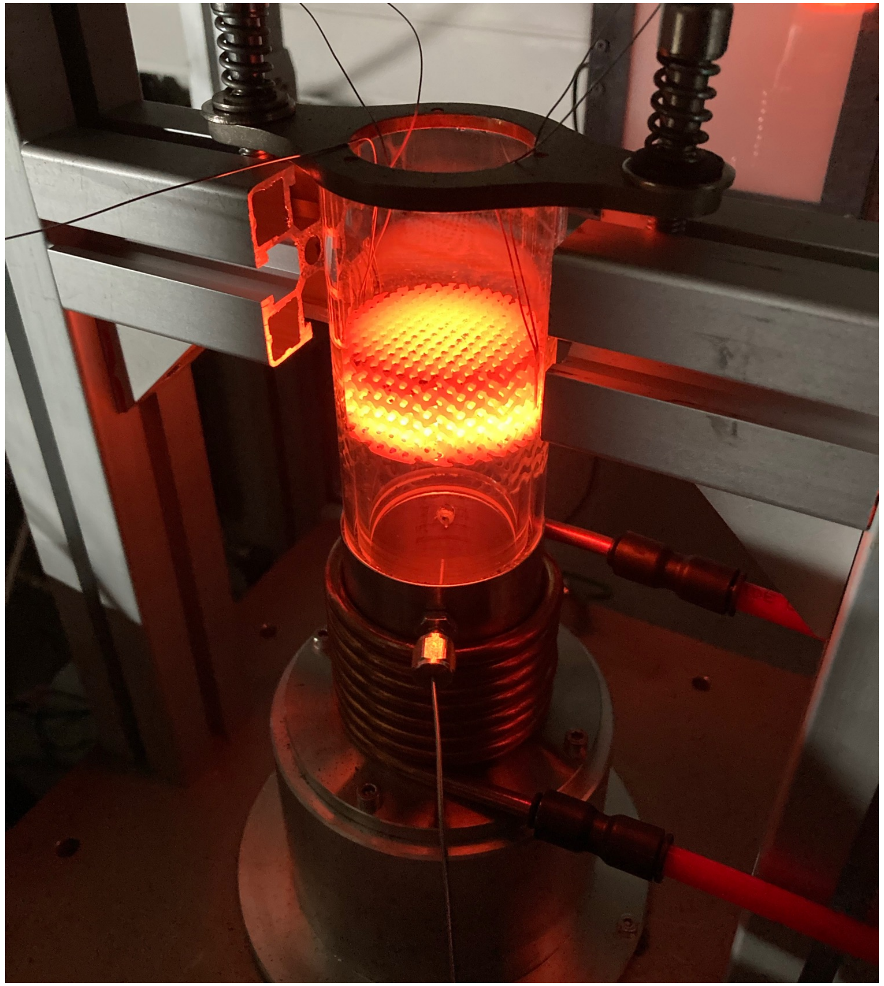
Thanks to

H. Pers
H. Magnes
T. Yahou
T. Morinière
A. Aniello
S. Marragou
E. Flores-Montoya
L. Selle
T. Poinsot



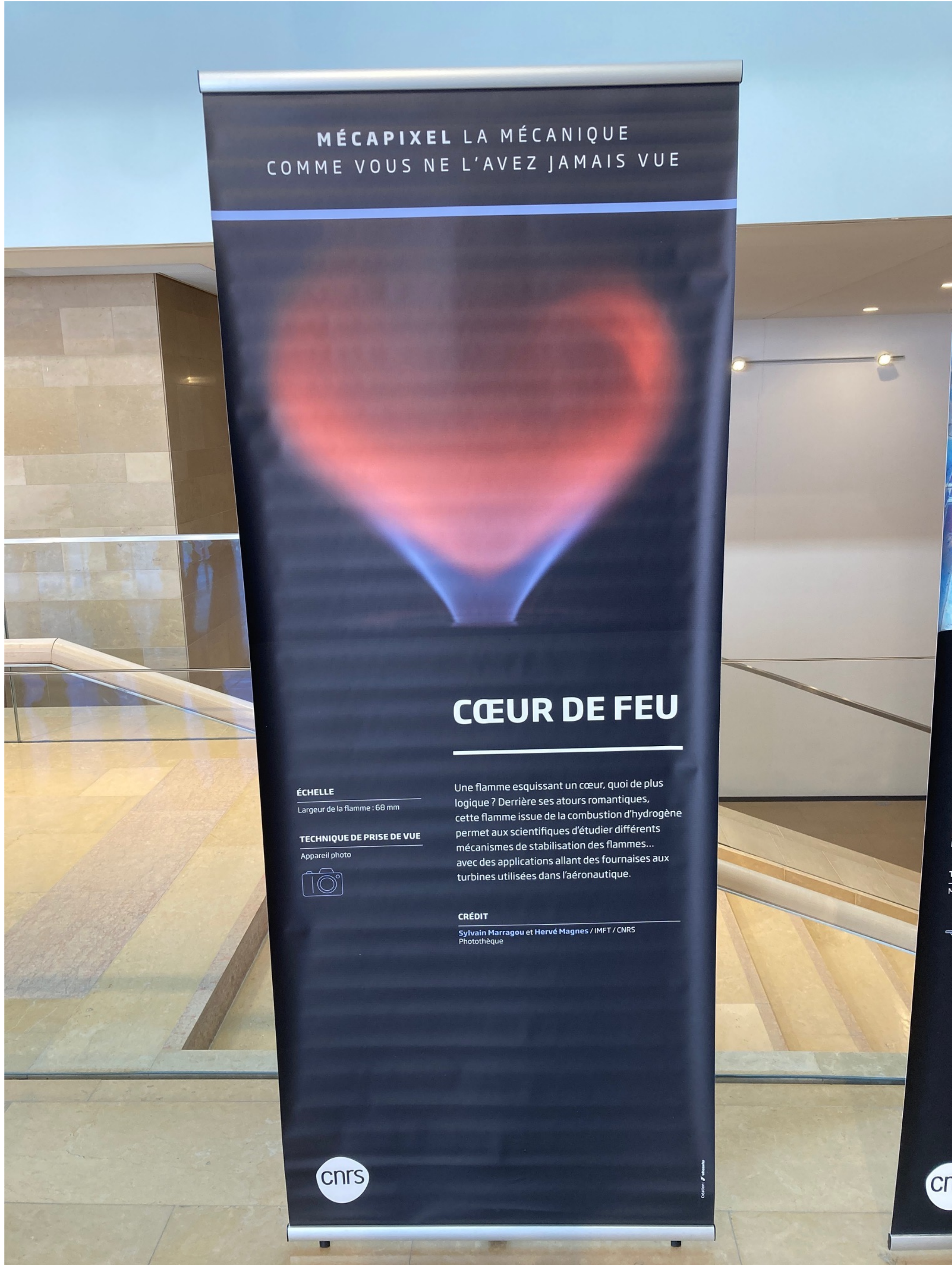
H2 combustion in porous media

Poster
Enrique Flores Montoya



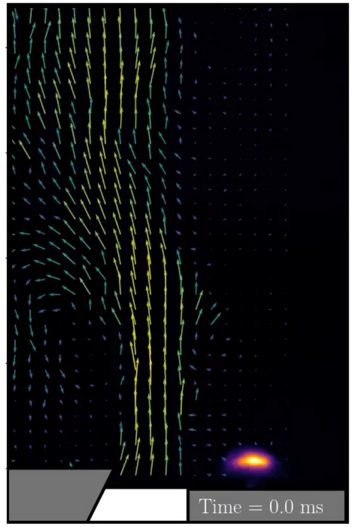
Poster of the HYLON flame

INSTITUT DE FRANCE
Académie des sciences

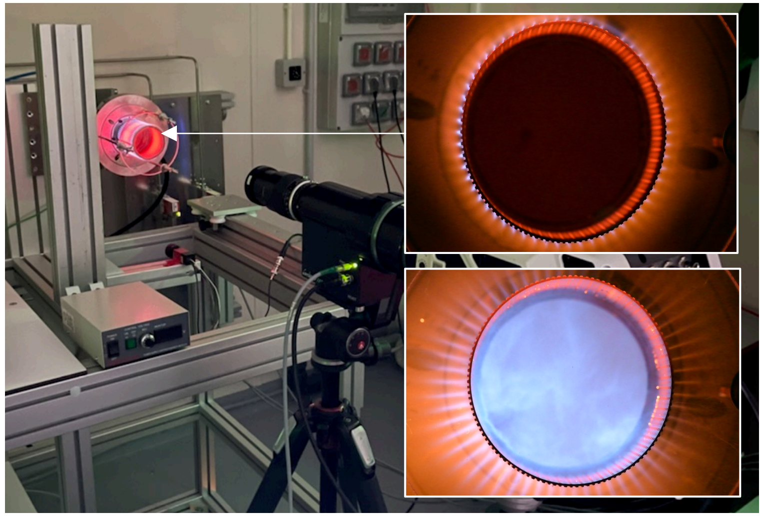


H2 combustion dynamics issues we are not able to predict

Violent ignition

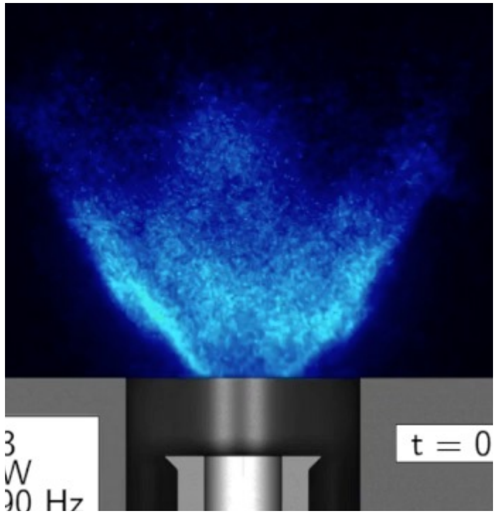


Flashback



Noise

Combustion instabilities



Burners powered by natural gas *two examples*

Domestic boilers

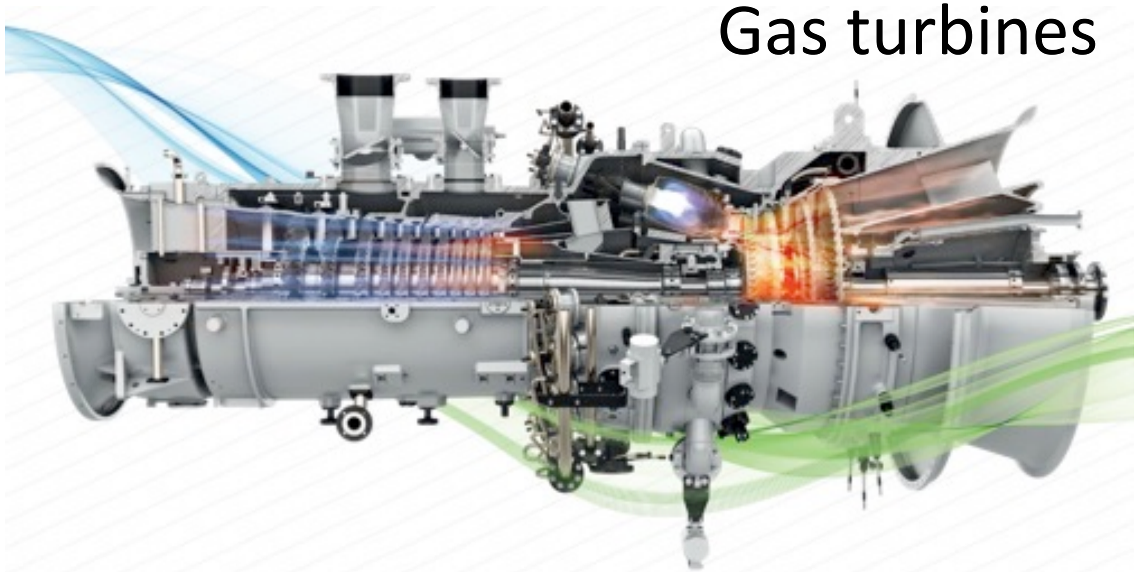
p=1 atm
T= 20°C, ambiant air

Air excess ratio

$$1.15 \leq \lambda \leq 1.55$$
$$0.65 \leq \phi \leq 0.85$$

Laminar flames stabilized on perforates
New boilers are ready for 20% H_2

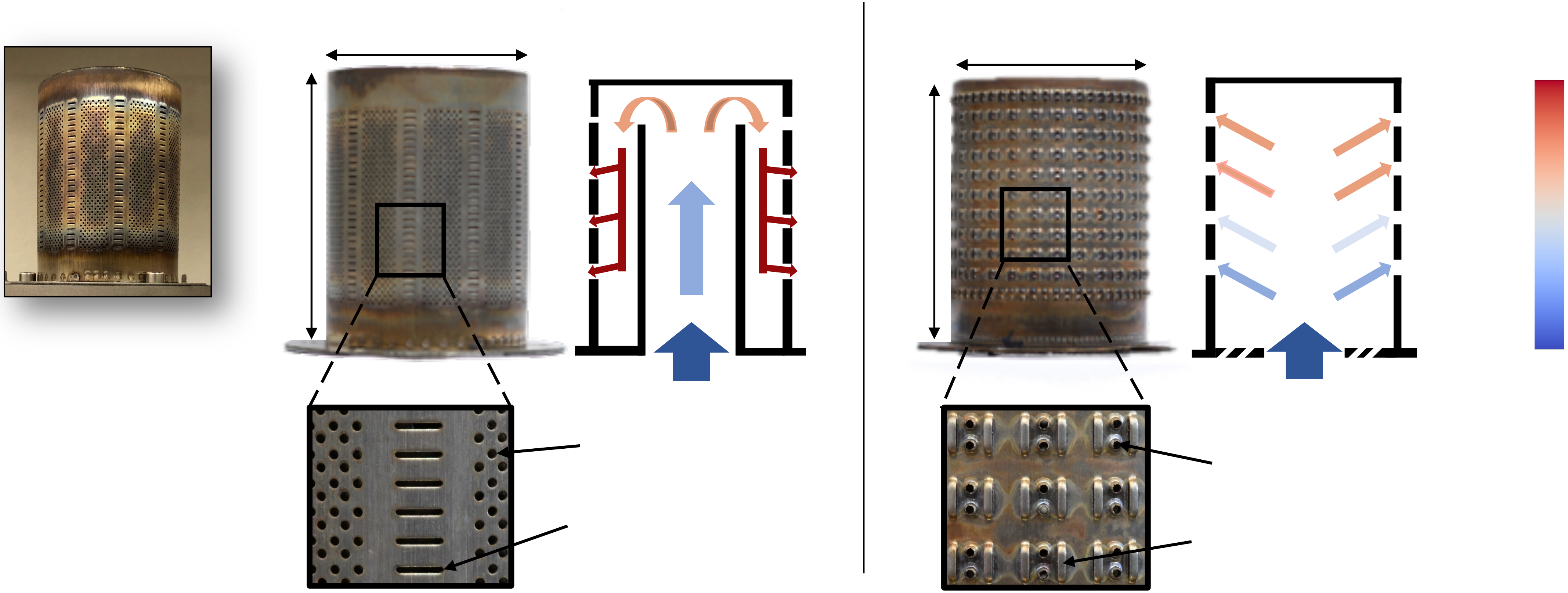
Gas turbines



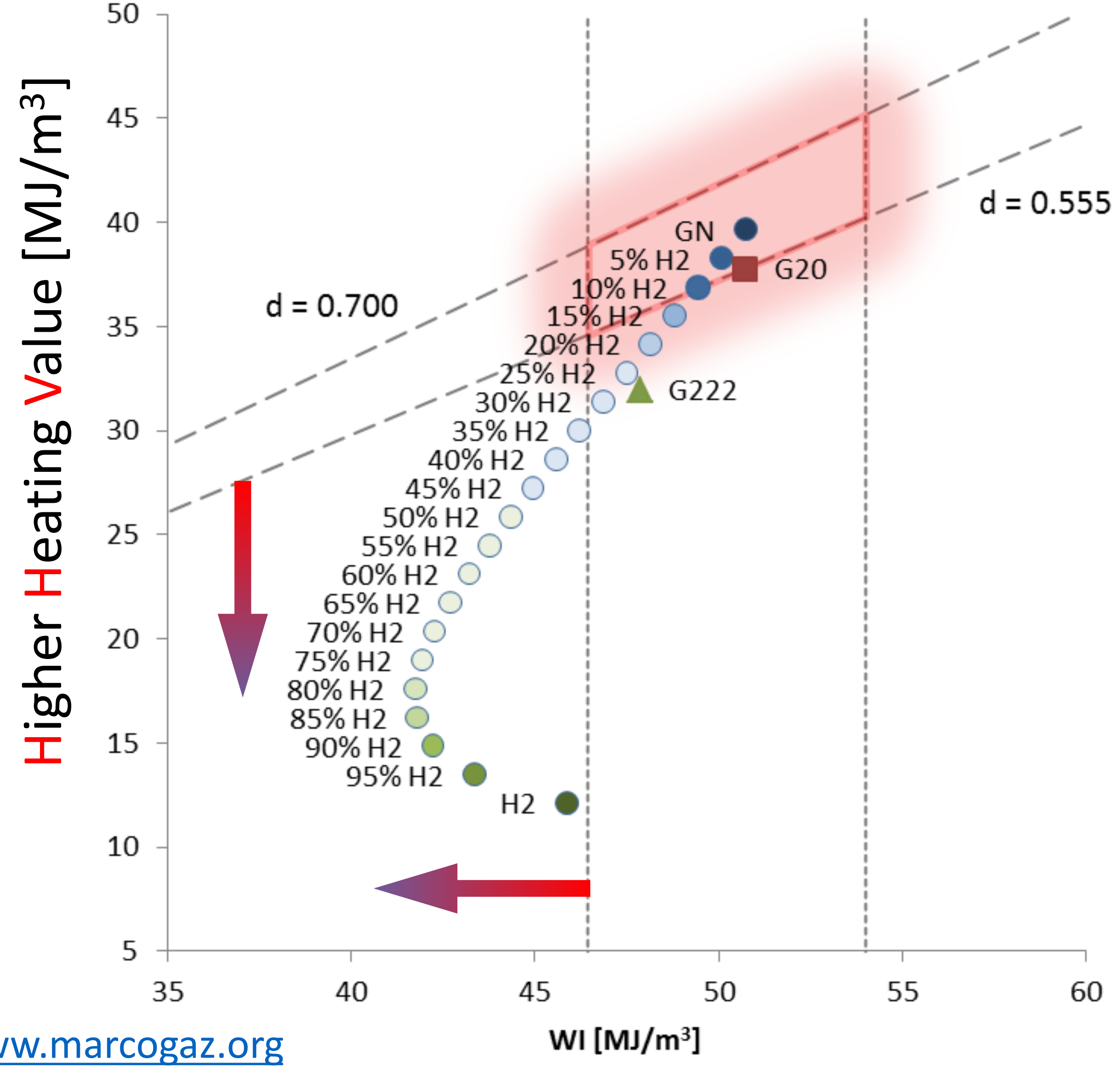
p= 20-40 bar, T=700-900 K, swirling flames
Some turbines already handle 50-70% H_2 in the fuel blend

Systems powered by natural gas are challenged by H_2 injection

Domestic boiler burners



Impact of hydrogen in natural gas network



Wobbe Index [MJ/m³]

$$WI = \frac{HHV}{\sqrt{d}}$$

$$d = \frac{\rho_g}{\rho_a}$$

Relative gas density with respect to air @ 15°C and 1 atm

Hydrogen reduces Wobbe index and calorific value of natural gas when mixed with it

www.marcogaz.org

CH4/H2 fuel blends

$$X_{H_2} = \frac{n_{H_2}}{n_{CH_4} + n_{H_2}}$$

H_2 volume fraction in the fuel mixture

Stoichiometric combustion

$$X_{CH_4} CH_4 + X_{H_2} H_2 + 2\left(O_2 - \frac{3}{2} X_{H_2}\right) \longrightarrow X_{CH_4} CO_2 + (2 - X_{H_2}) H_2O$$

CH_4 → H_2

X_{H_2}	0	0.20	0.50	0.80	1.00
Y_{H_2}	0	0.03	0.11	0.33	1.00
$\mathcal{P}_{H_2}$	0	0.07	0.23	0.54	1.00
EF [-]	1.00	0.93	0.77	0.46	0
Fuel Emission Factor (gCO_2/MJ)	55	51		25	0

Fraction of power originating from H2 combustion

$$\mathcal{P}_{H_2} = \frac{Y_{H_2} Q_{H_2}}{Y_{CH_4} Q_{CH_4} + Y_{H_2} Q_{H_2}}$$

Decarbonization of combustion devices requires large volumetric fractions of H_2 in the fuel mixture

Decarbonization

CH_4 → H_2

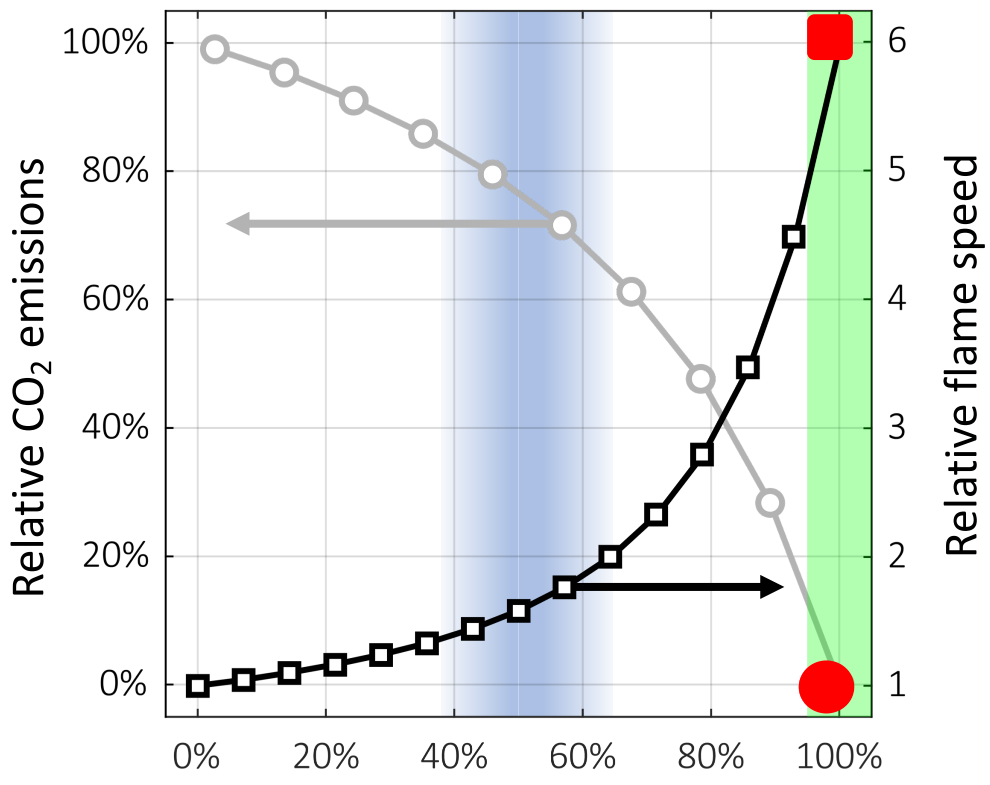
X_{H_2}	0	0.20	0.50	0.80	1.00
Y_{H_2}	0	0.03	0.11	0.33	1.00
$\mathcal{P}_{H_2}$	0	0.07	0.23	0.54	1.00
EF [-]	1.00	0.93	0.77	0.46	0

Fuel Emission Factor (gCO_2/MJ)	55	51		25	0

Fraction of power originating from H2 combustion

$$\mathcal{P}_{H_2} = \frac{Y_{H_2} Q_{H_2}}{Y_{CH_4} Q_{CH_4} + Y_{H_2} Q_{H_2}}$$

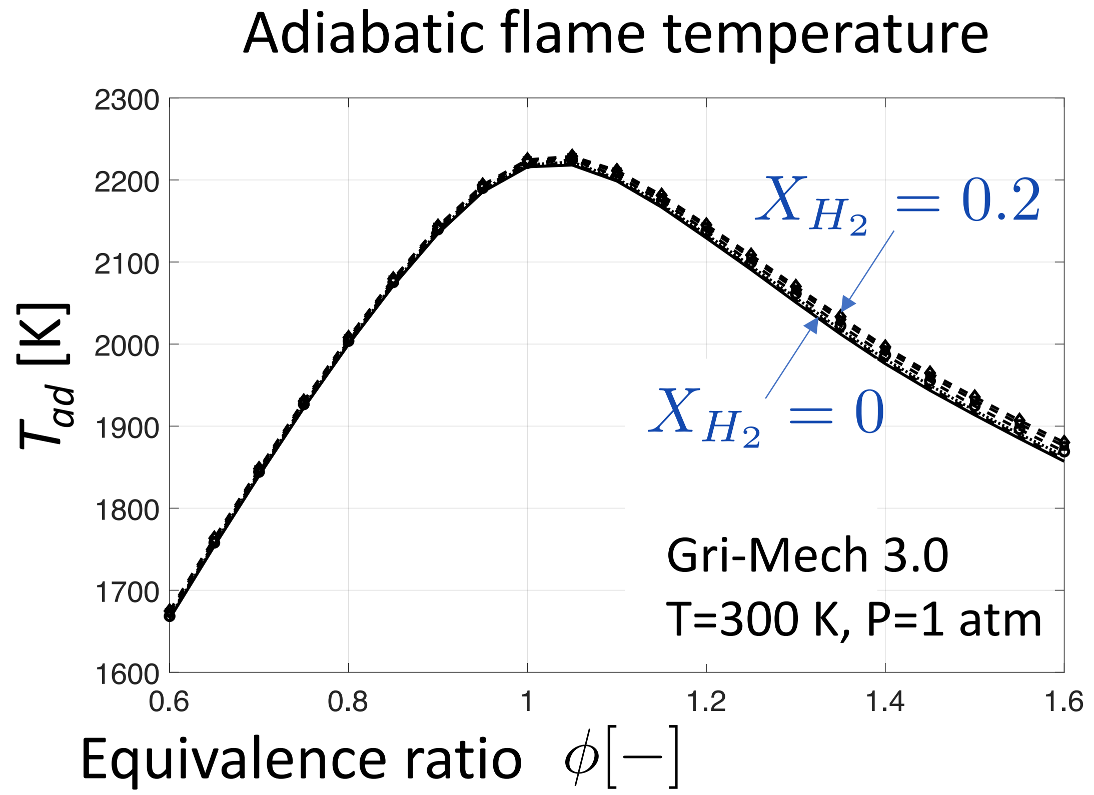
We are here → *We need to go there*

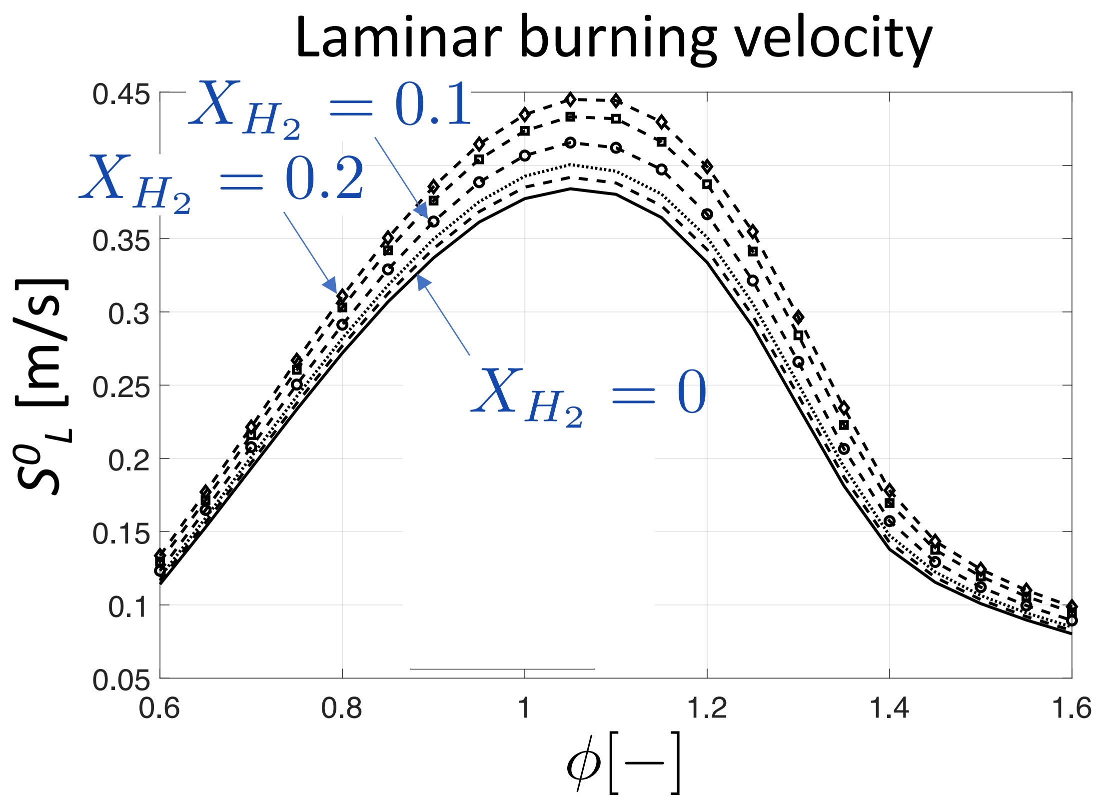


Decarbonization of combustion devices needs large volumetric fractions of H_2 in the fuel mixture

CH4/H2-air mixture properties

$$X_{H_2} = \frac{n_{H_2}}{n_{CH_4} + n_{H_2}}$$

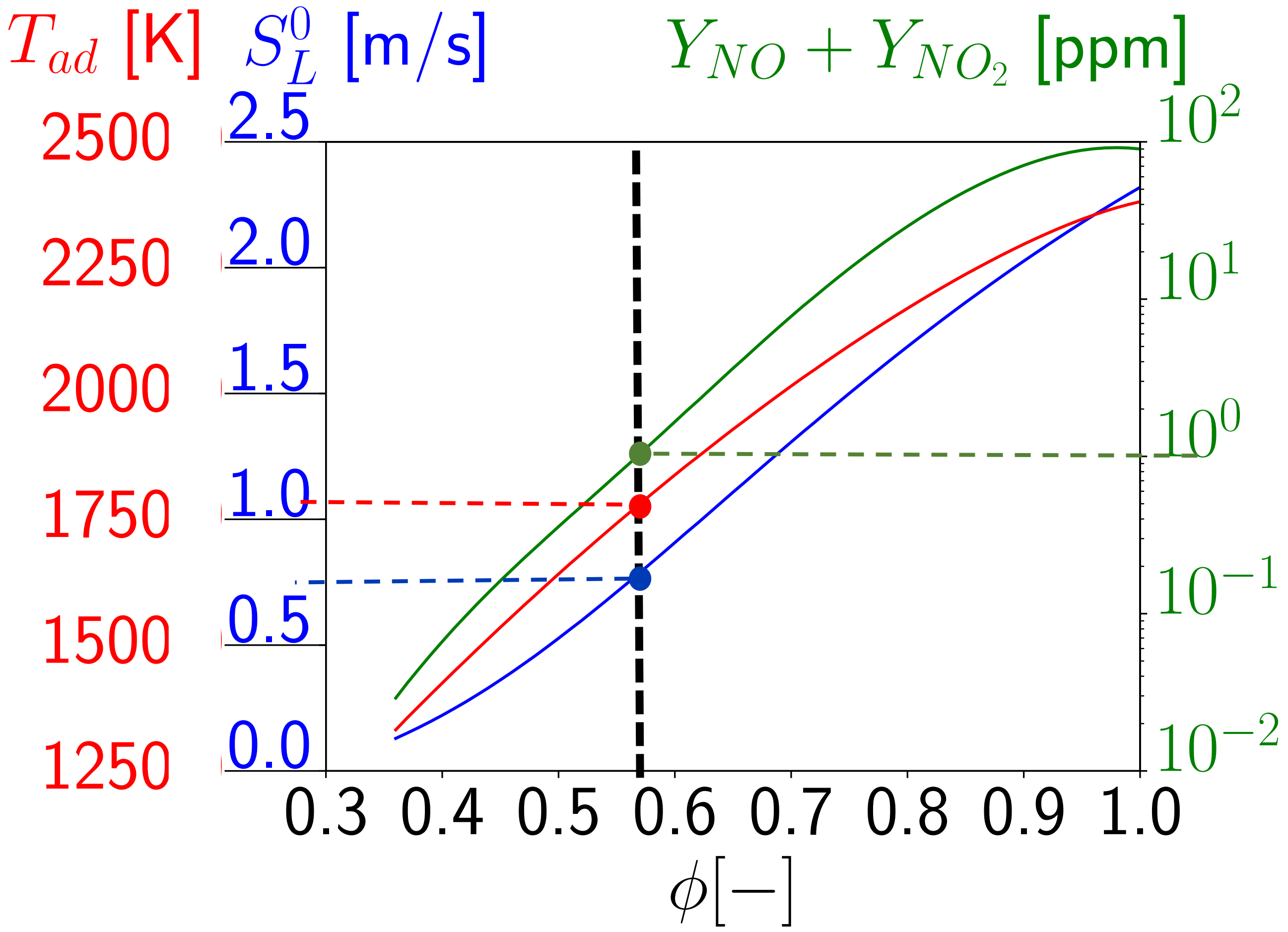




For lean combustible mixtures (ϕ < 0.8), hydrogen injection does not alter T_{ad} for X_{H2} < 0.2, but drastically increases S^0_L for X_{H2} > 0.1

H2/air mixtures properties

Adiabatic flame simulations, UCSD chemistry, p=1 atm, T=300 K



Thermodynamic equilibrium

To limit NOx emissions, increase of air excess ratio:

$\lambda > 1.65$ $T_{ad} < 1800$ K

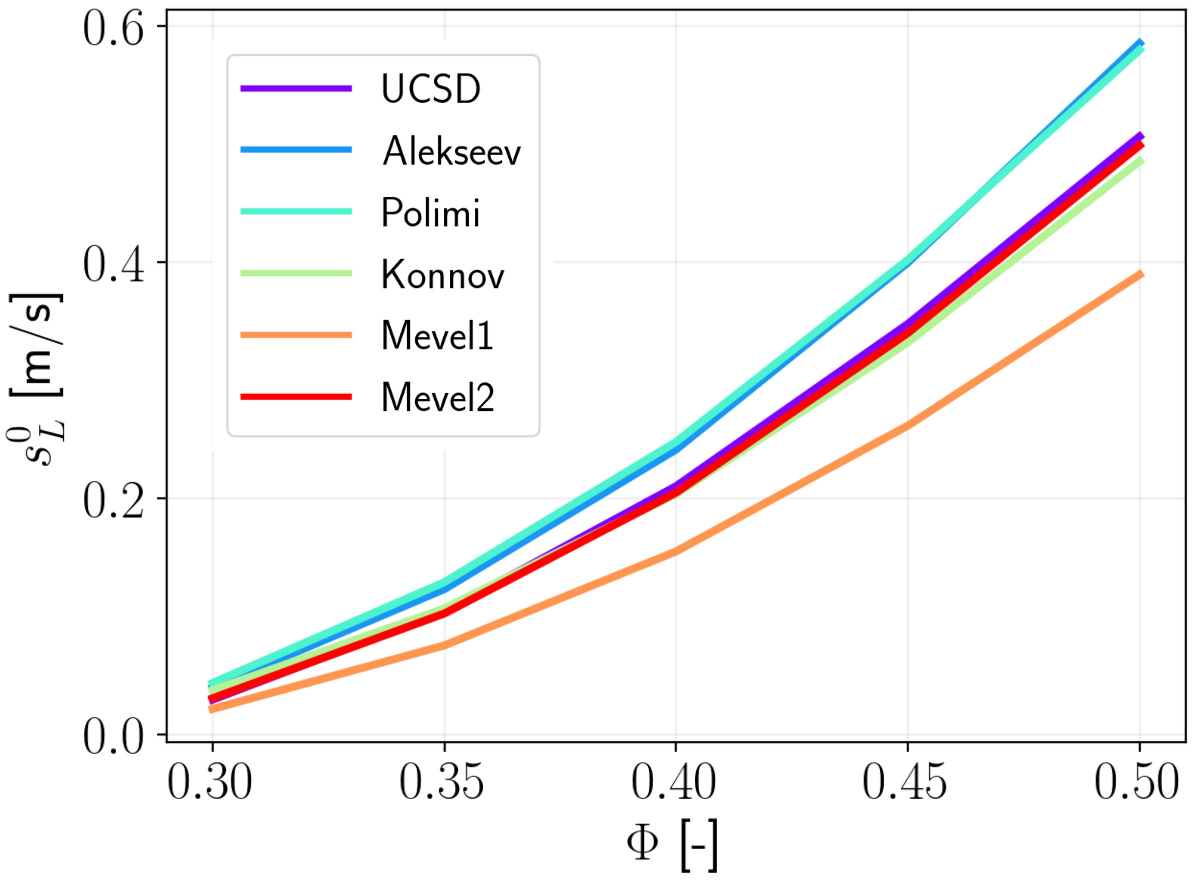
$\phi < 0.6$

Flame still burns 2 times faster than NG/air flames

$\phi = 0.5$ $S_L = 50$ cm/s

Flame speed of H2/air mixtures

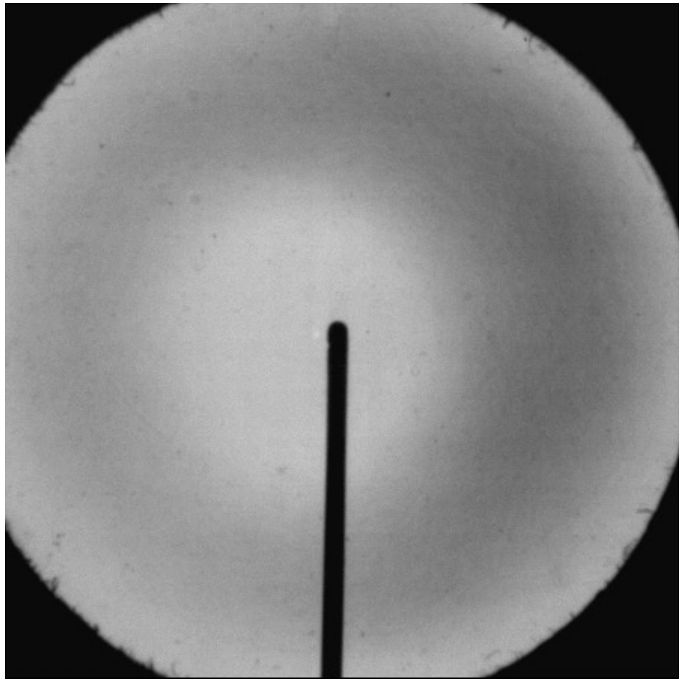
H2/air - T=300 K, p=1 atm



Courtesy of Jean-Jacques Hok @ Cerfacs

Beeckmann et al, PCI (2017) 36:1531

Constant volume bomb experiments

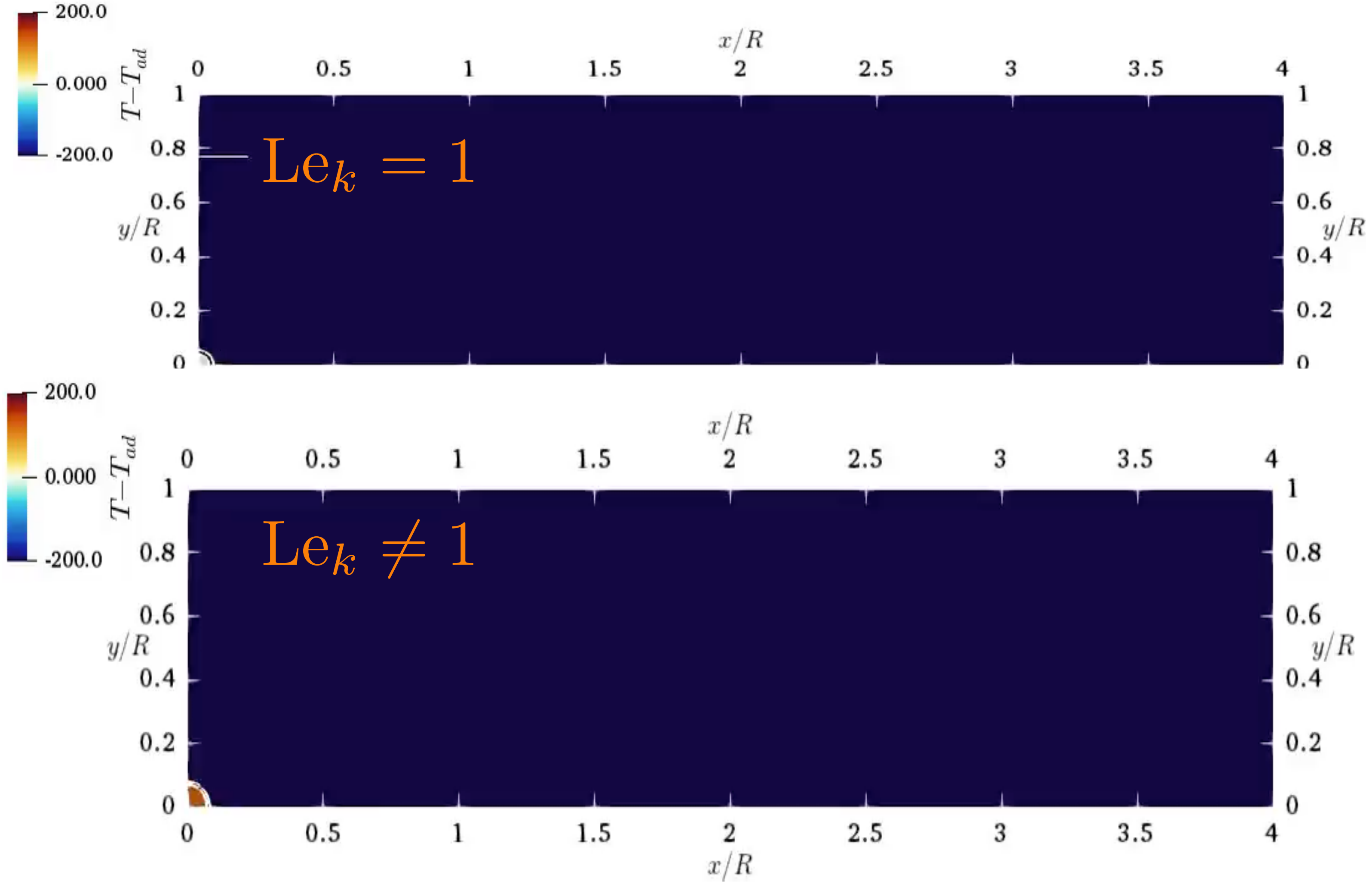


Wide disparity of laminar burning velocity for lean H2/air flames

Thermo-diffusive instabilities of lean H2/air flames

Hok et al. ICDERS 2022

H2/air - ϕ = 0.36, T=300 K, p=1 atm



The displacement speed of lean hydrogen premixed flames is strongly altered by non equidiffusive transport properties

Berger et al. CNF (2022) 240:111935
Berger et al. CNF (2022) 240:111936

NOx formation pathways et emissions

Capurso et al. CNF 2023: 112581

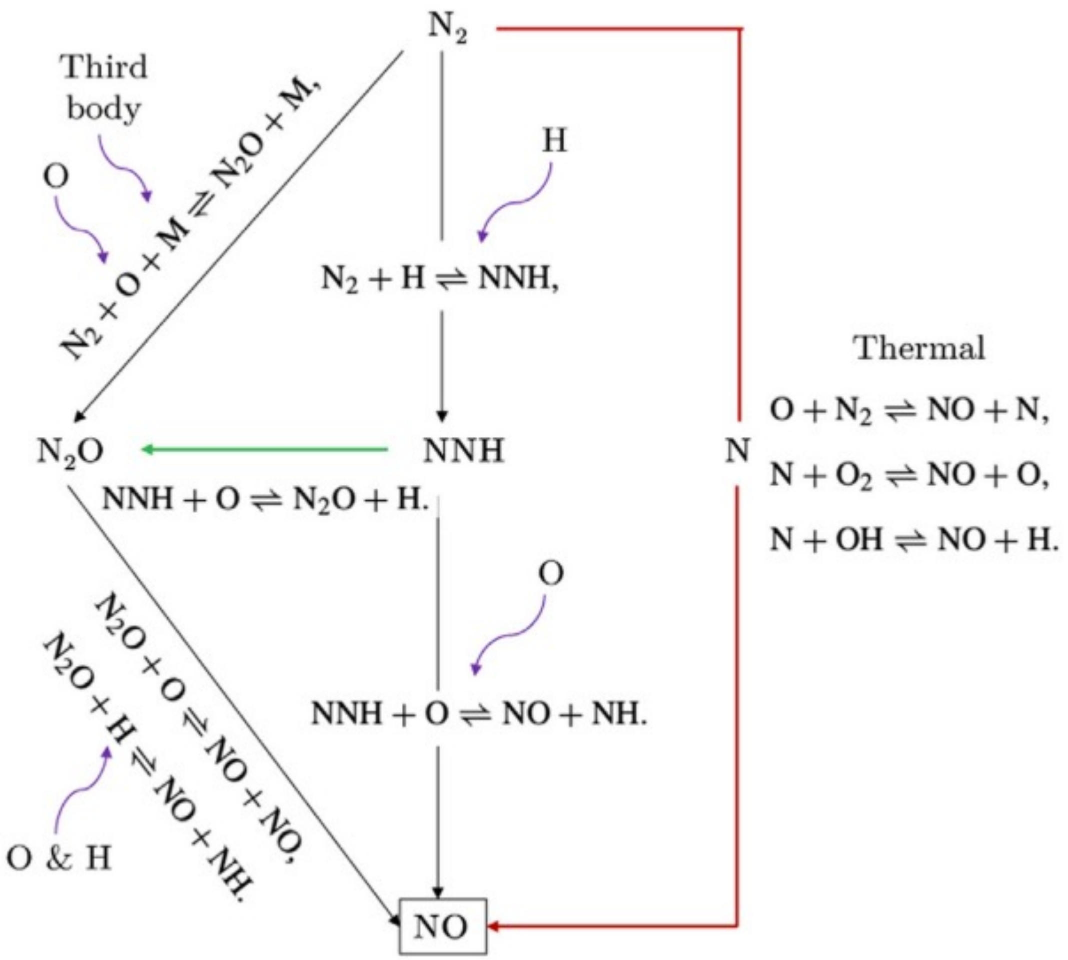
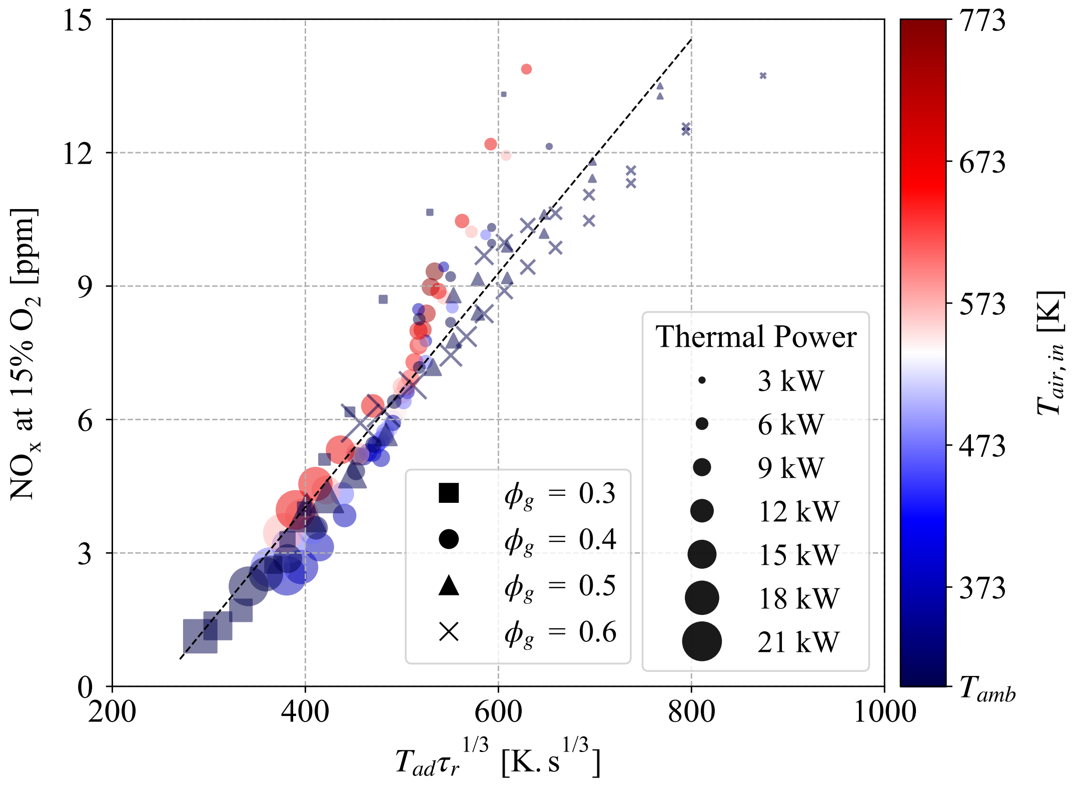


Fig. 17. Schematic representation of the pathways, reactions and molecules involved in the NO formation for H_2/air combustion.

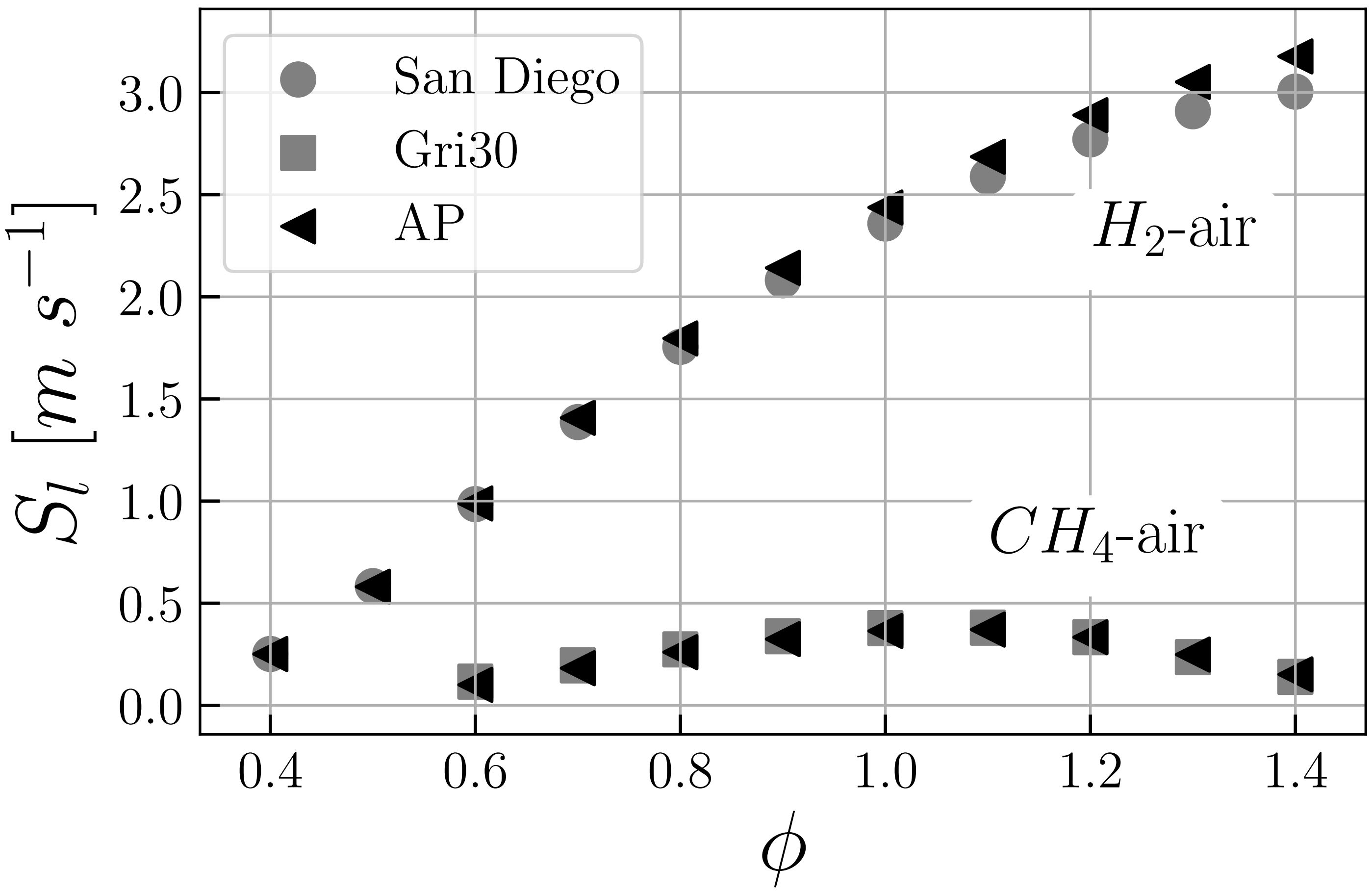
Magnes et al. GT 2023-103192



NOx emissions remain under control, but why?

Laminar flame speed

Scheme validation for mixture used in DNS



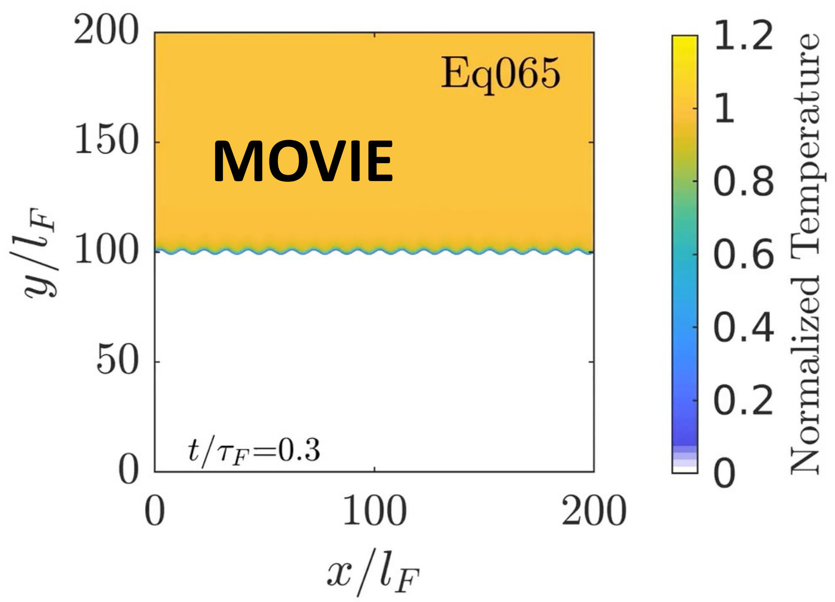
Targeted mixtures

Table 1: Characteristics of the flammable mixtures

Fuel	ϕ	δ_{th}	S_l	T_{ad}
-	-	mm	cm/s	K
CH_4	1.00	0.4449	36.41	2212
H_2	0.45	0.4467	40.09	1529

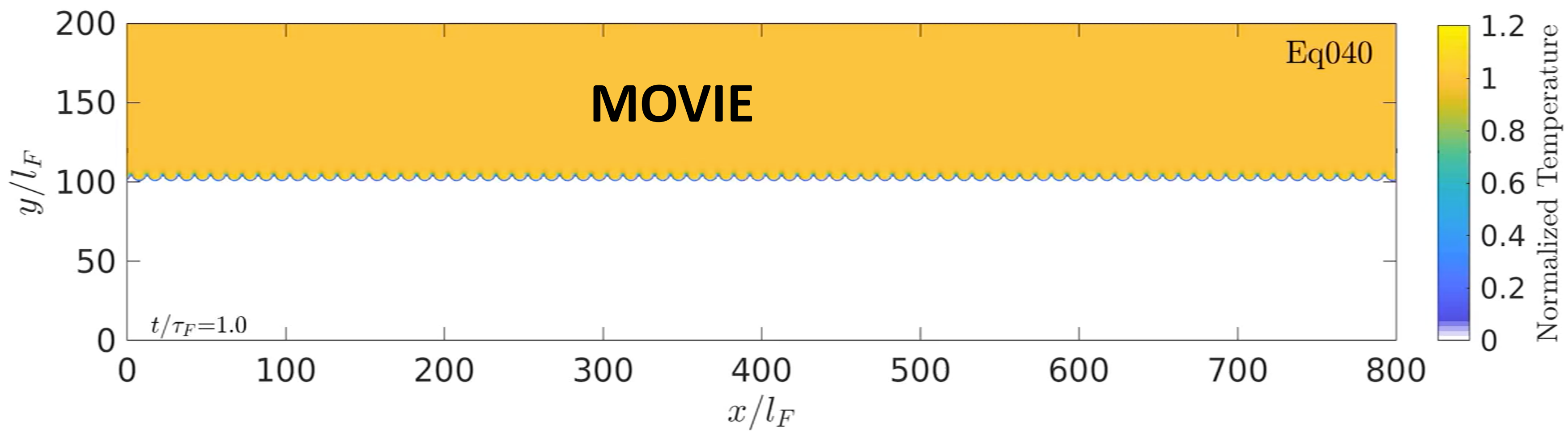
Thermodiffusive instabilities in turbulent H2 flames

Berger et al. (2022) CNF: 111935 & 111936

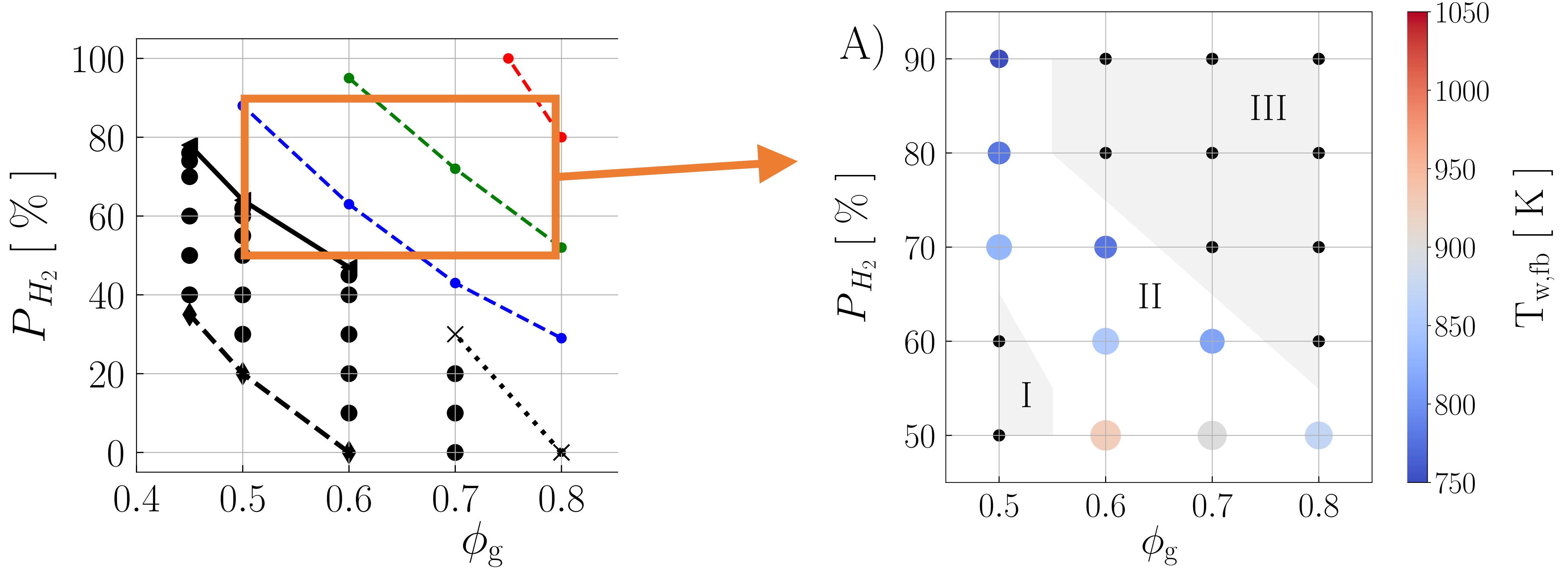


DNS, Tu=298 K, p=1 atm

The consumption speed of lean hydrogen premixed flames is strongly altered by thermodiffusive instabilities



Flashback during thermal transient

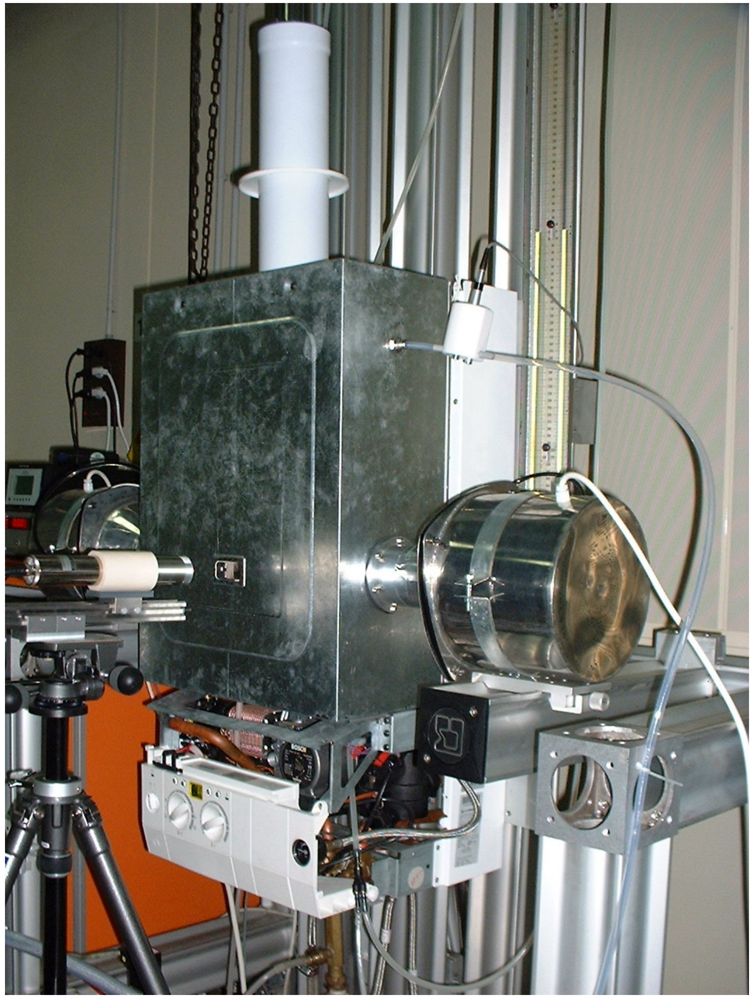


Regime III: Flashback takes place immediately after ignition, $T_{w,fb}=T_a$

Regime II: stable combustion for $T_w<T_{w,fb}$. Flashback takes place when $T_w=T_{w,fb}$

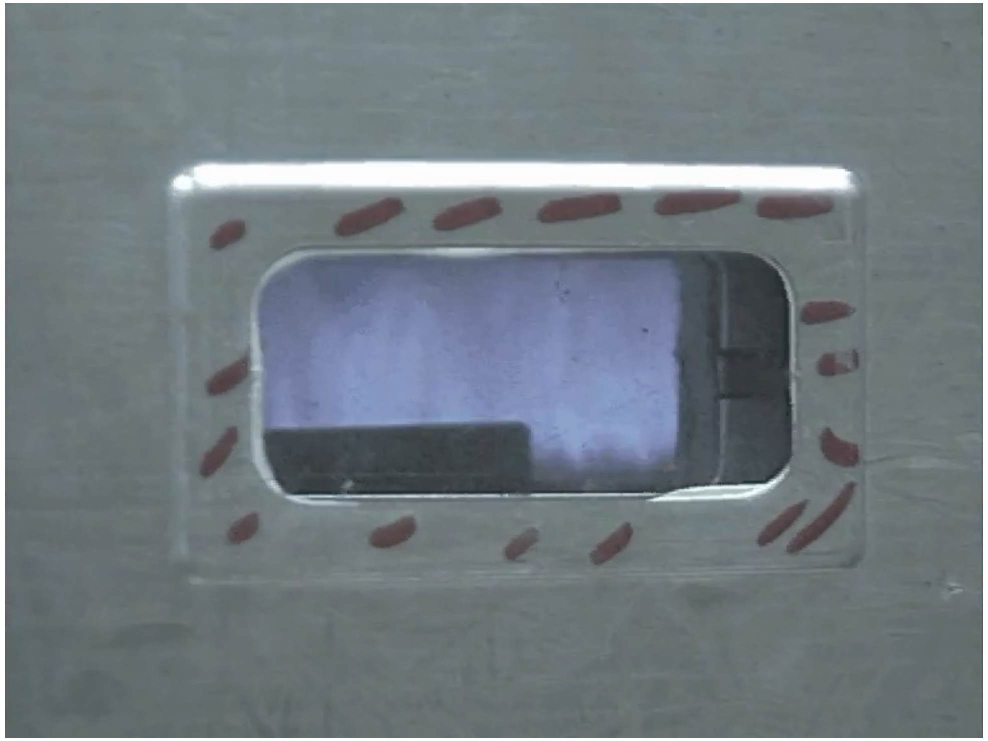
Regime I: combustion remains stable. The burner temperature T_w naturally evolves towards thermal equilibrium.

Thermoacoustic instabilities



D. Durox, EM2C

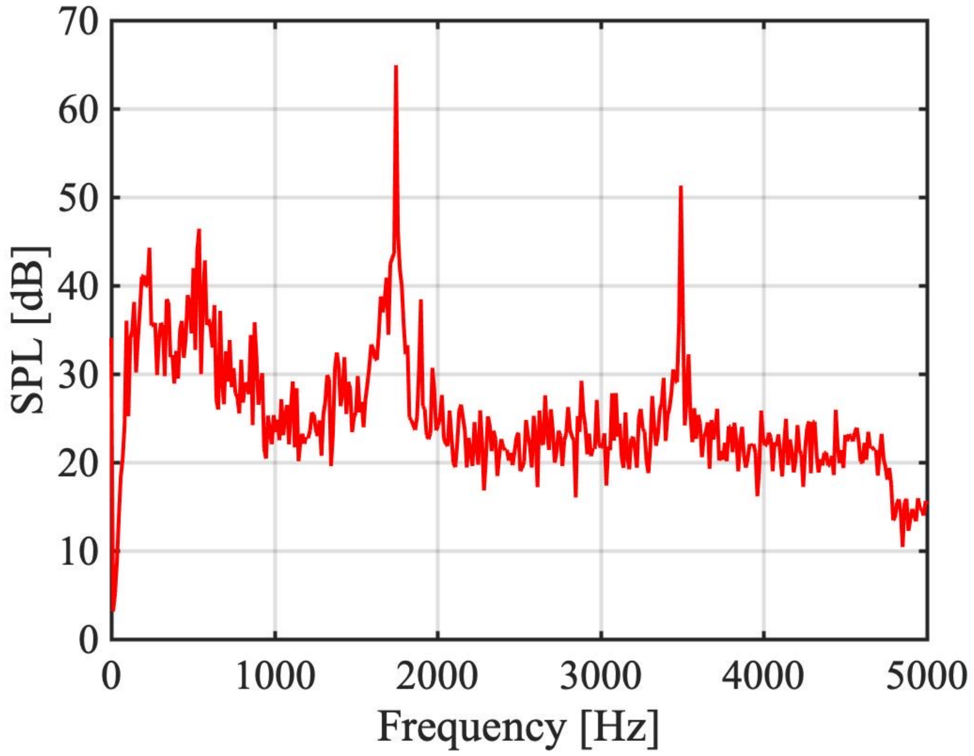
Natural gas fueled domestic boiler



Boiler supplied with natural gas and equipped with an induction mixer. The metal enclosure “breathes” with flames that expand and contract periodically at very low frequency 10-20 Hz

Thermoacoustic instabilities

H2 fueled domestic boiler

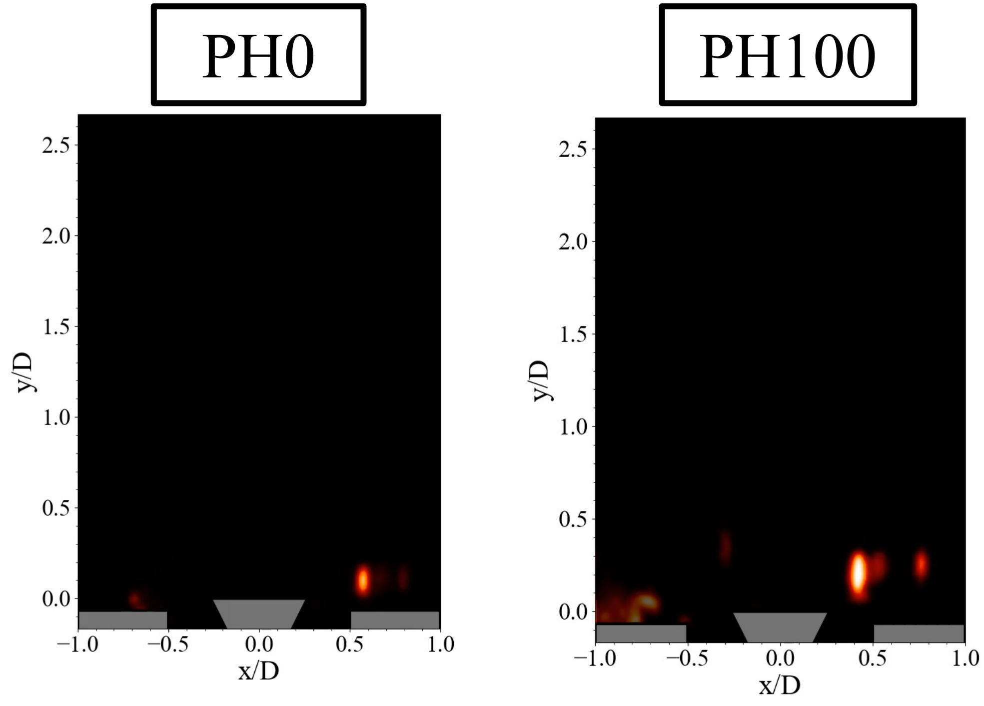


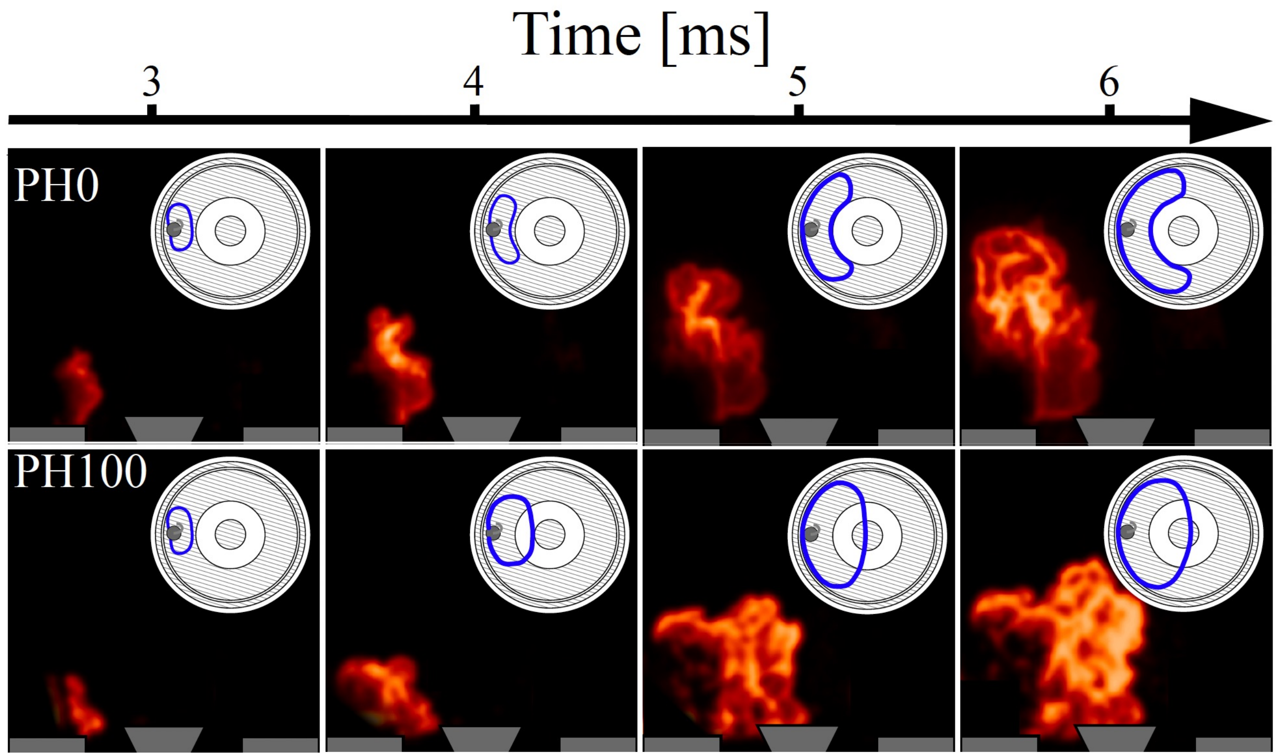
Strong tonal noise emission at high at f=1.8 kHz!

Ignition dynamics

T. Yahou PhD IMFT/NTNU

Fully premixed non-swirling jet burner U_b= 5 m/s, S_L=0.25 m/s, U_b/S_L=20

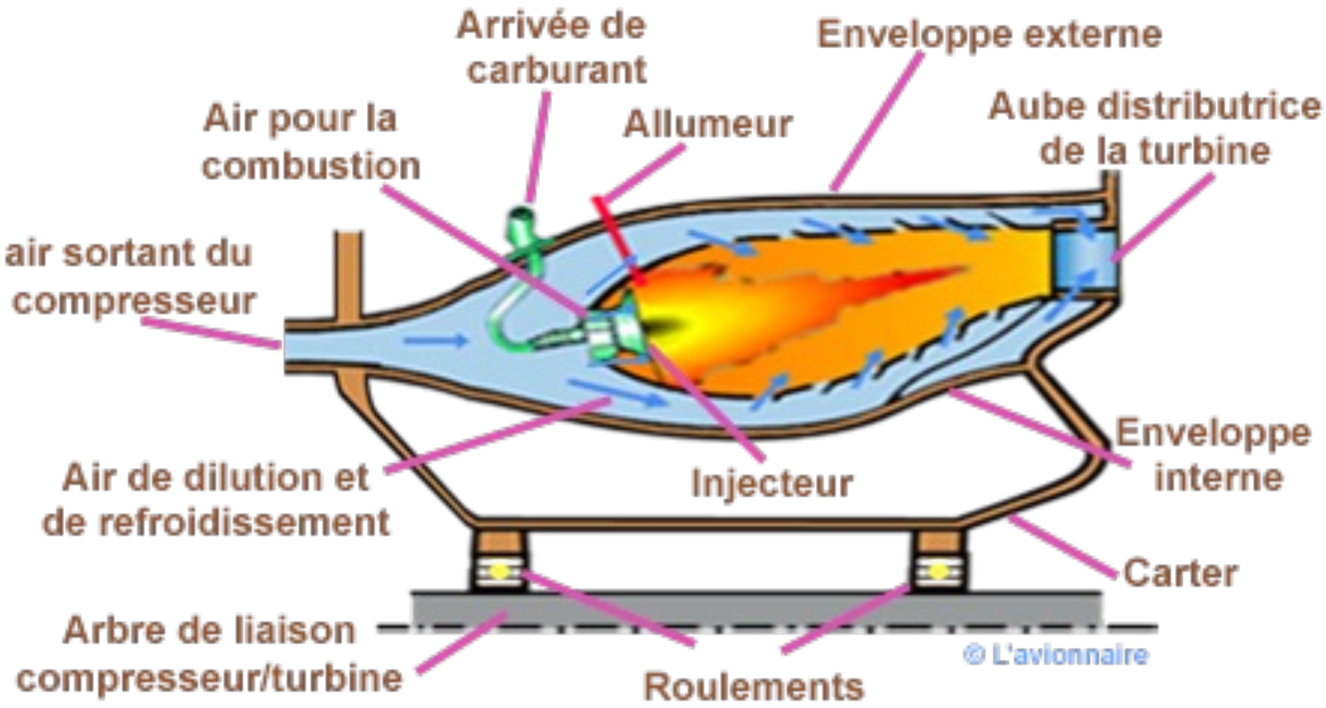




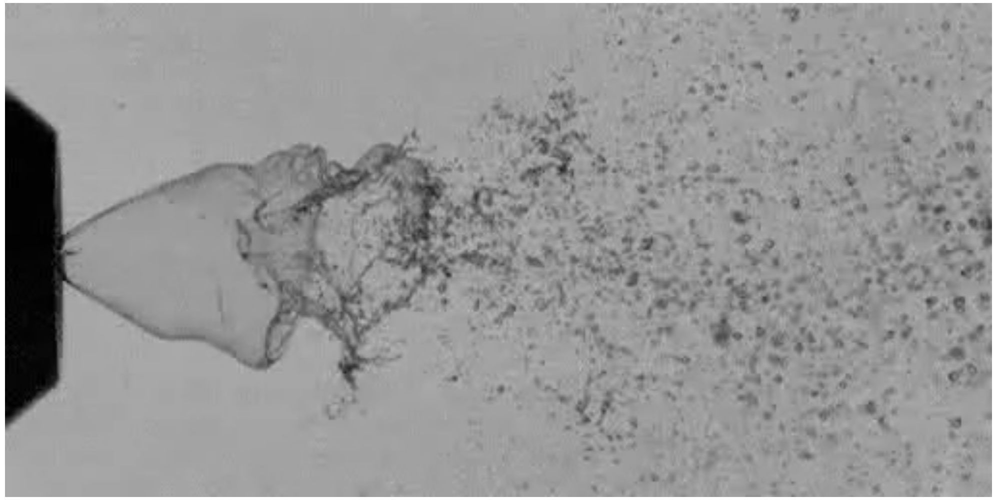
Hydrogen powered systems have violent ignition dynamics possibly leading to a temporary reversal flow (flashback)

Aerojet engine gas turbine

…… are powered by kerosene



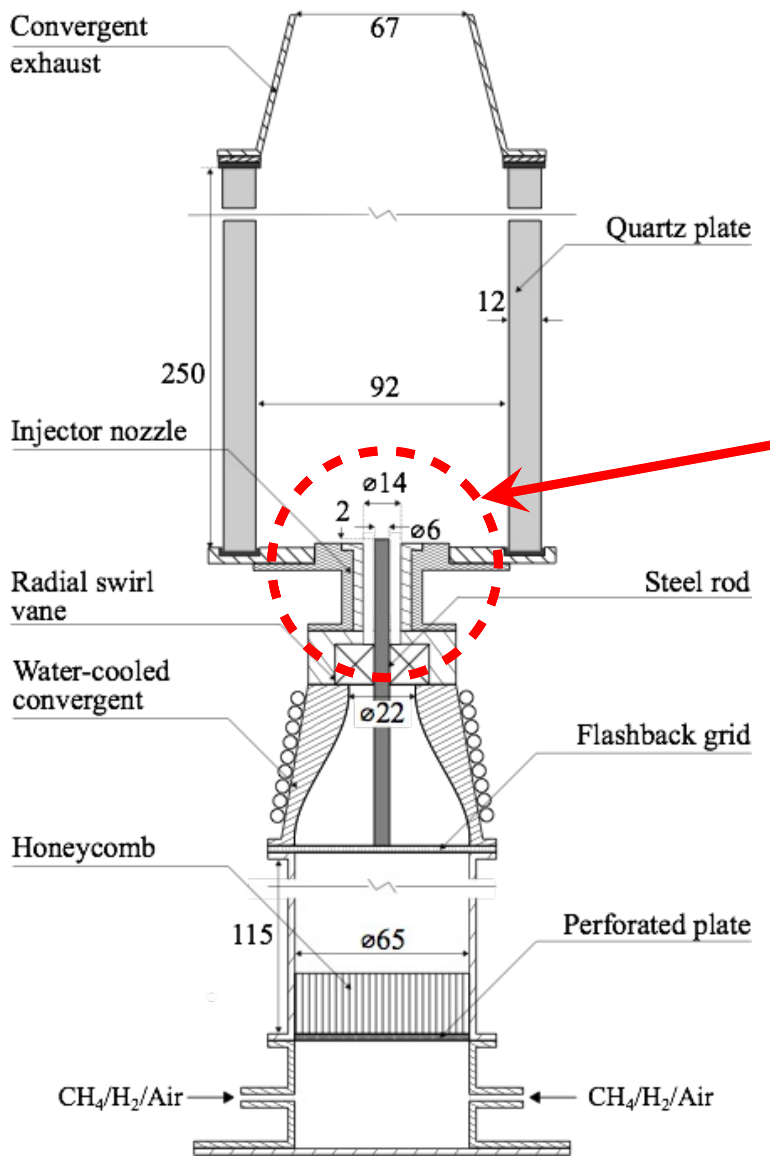
Hollow cone fuel spray injector



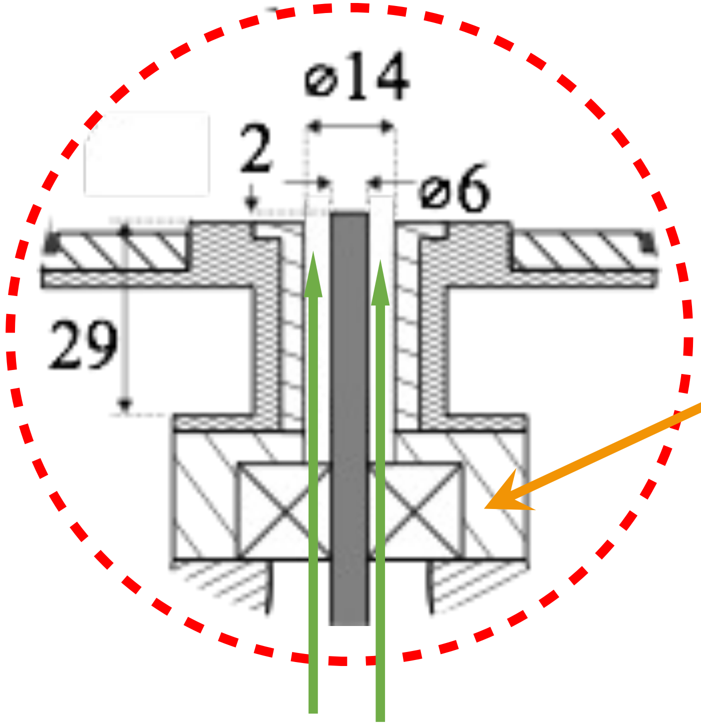
$2x10^5$ frames/s T. Morinière PhD IMFT

How to switch to hydrogen?

Premixed swirled CH4/H2-air flames

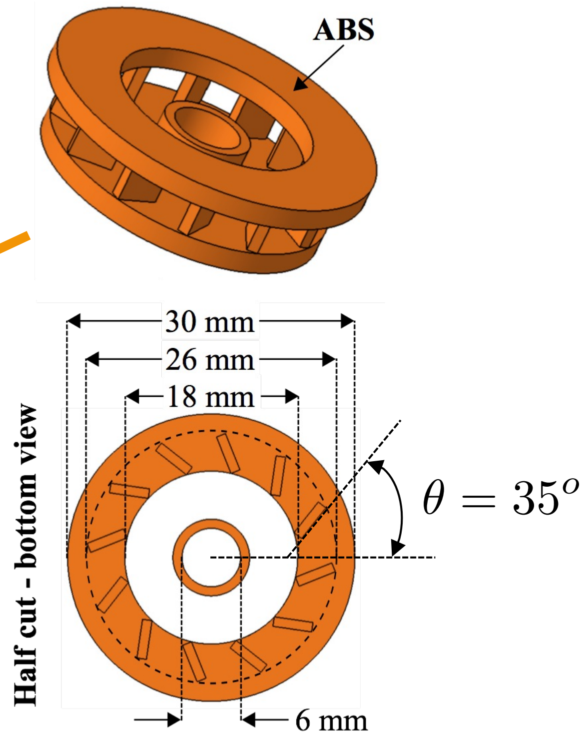


Swirled injector



CH4/H2/air mixture

Radial swirl vane



Swirl number : S=0.4

Guiberti et al. (2015) PCI, 35:1385
Mercier et al. (2016) CNF, 171:42

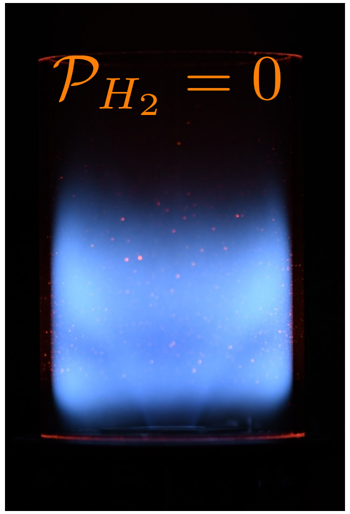
Flame stabilization

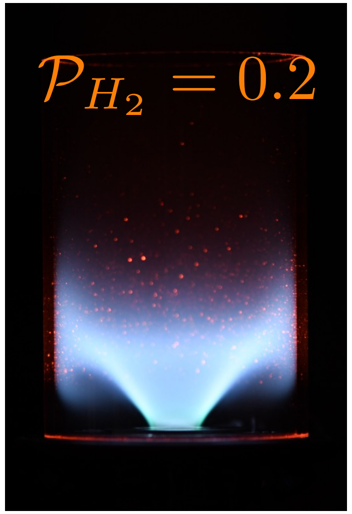
P=10 kW S_i=0.9 S_e=0.7

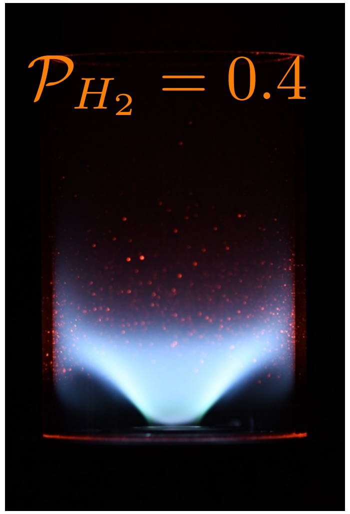
$$J = \frac{\rho_e u_e^2}{\rho_i u_i^2}$$

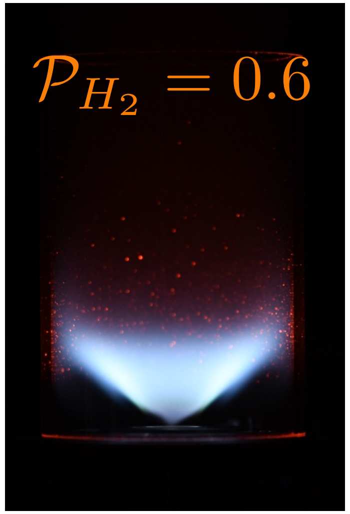
← CH_4/Air mixture (ϕ_e)

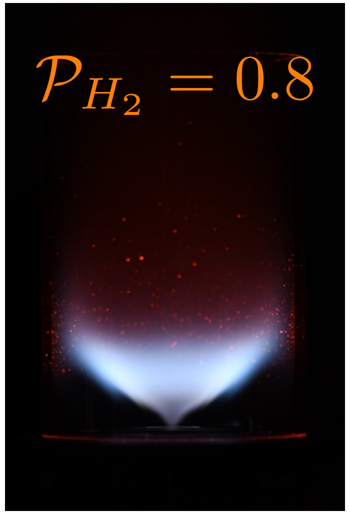
← H_2

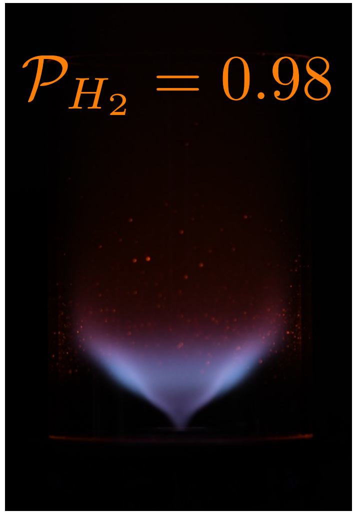










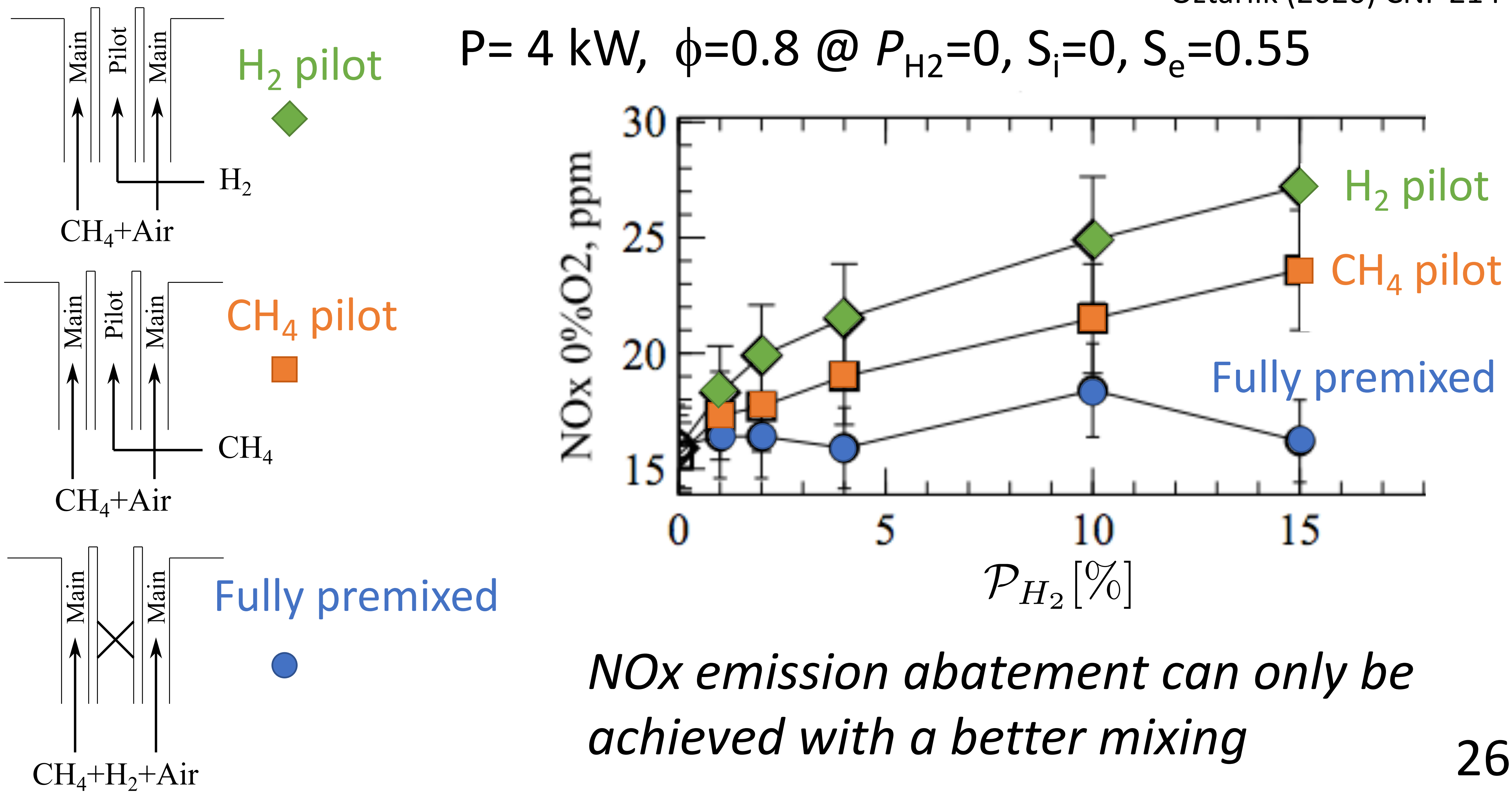


$\phi = 0.70$	$\phi = 0.67$	$\phi = 0.65$	$\phi = 0.62$	$\phi = 0.60$	$\phi = 0.58$
$\phi_e = 0.70$	$\phi_e = 0.56$	$\phi_e = 0.42$	$\phi_e = 0.28$	$\phi_e = 0.14$	$\phi_e \sim 0.01$
$J = \text{inf}$	$J = 172$	$J= 42$	$J=18$	$J=10$	$J=7$
$u_e = 26$ m/s	$u_e = 26$ m/s	$u_e = 25$ m/s	$u_e = 25$ m/s	$u_e = 24$ m/s	$u_e = 24$ m/s
$u_i = 0$ m/s	$u_i = 7$ m/s	$u_i = 15$ m/s	$u_i = 22$ m/s	$u_i = 30$ m/s	$u_i = 36$ m/s

Effect of pilot jet injection on NOx emissions

Oztarlik (2020) CNF 214

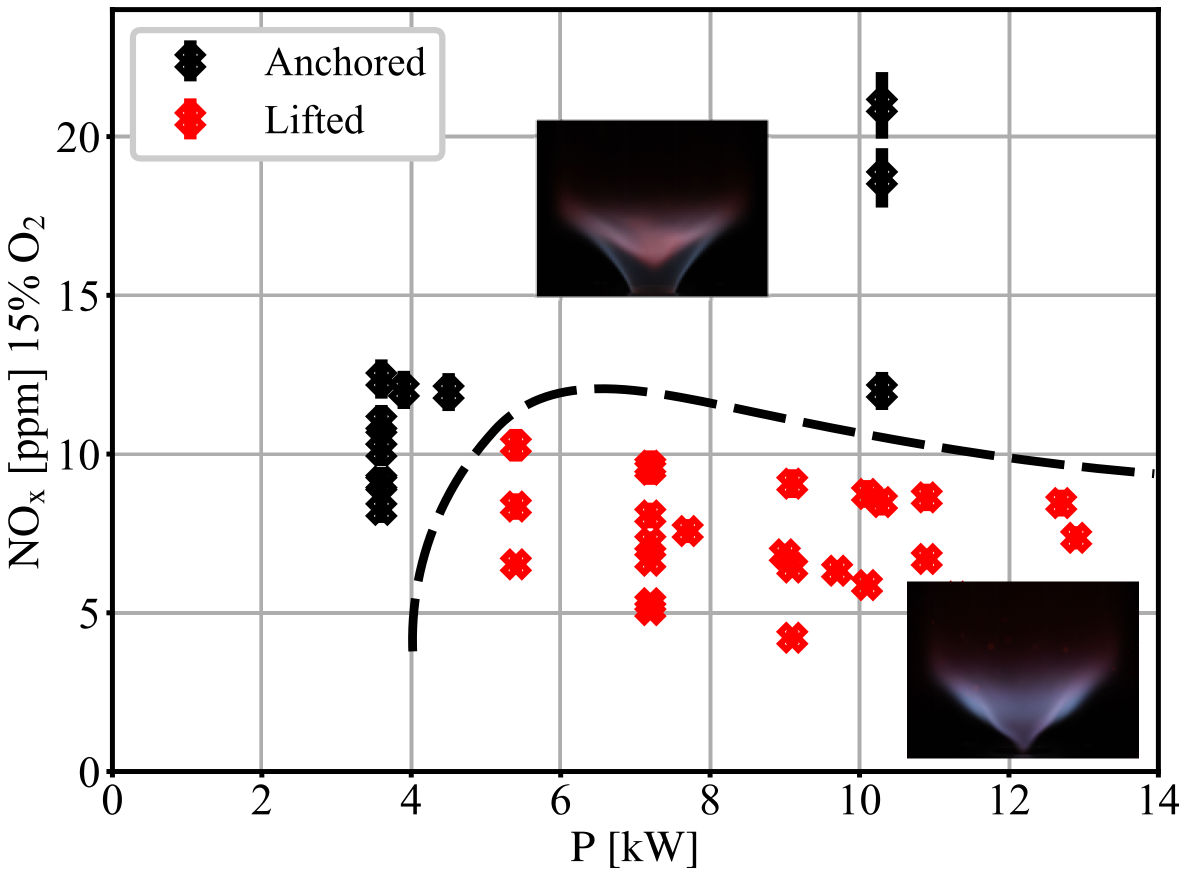
P= 4 kW, ϕ=0.8 @ P_{H2}=0, S_i=0, S_e=0.55

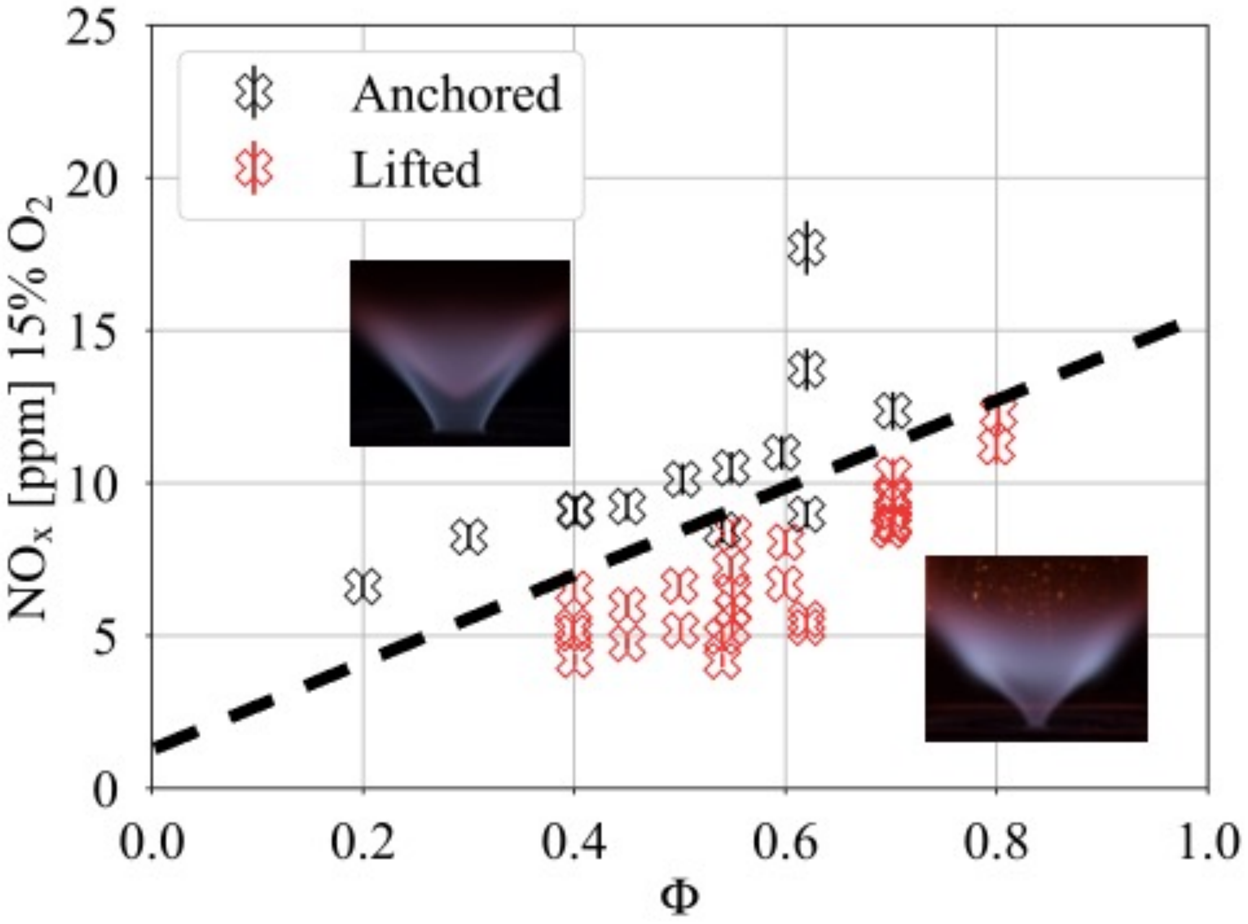


NOx emission abatement can only be achieved with a better mixing

HYLON : NOx emissions

Marragou et al. (2022) IJHE 47: 19275--19288

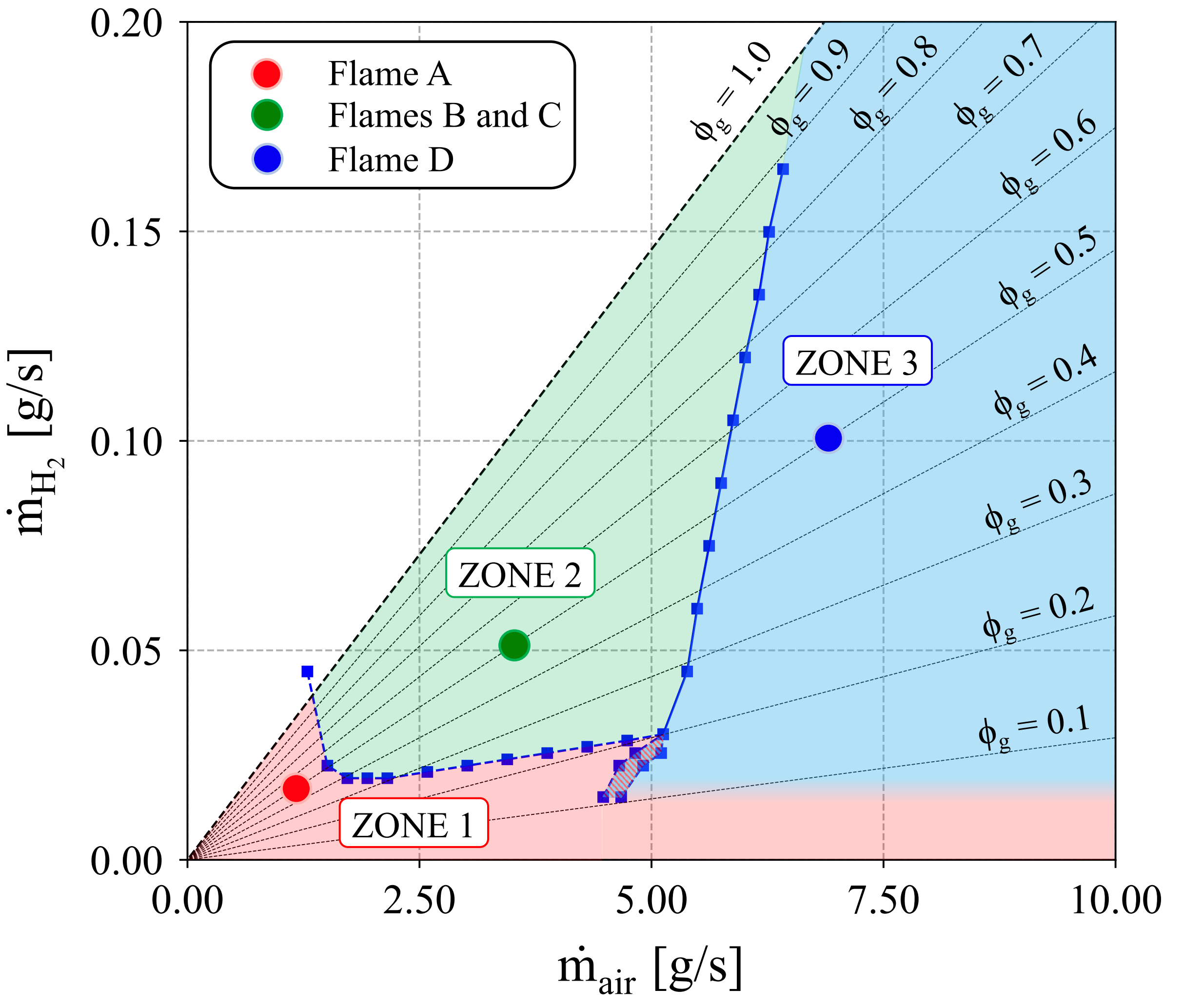


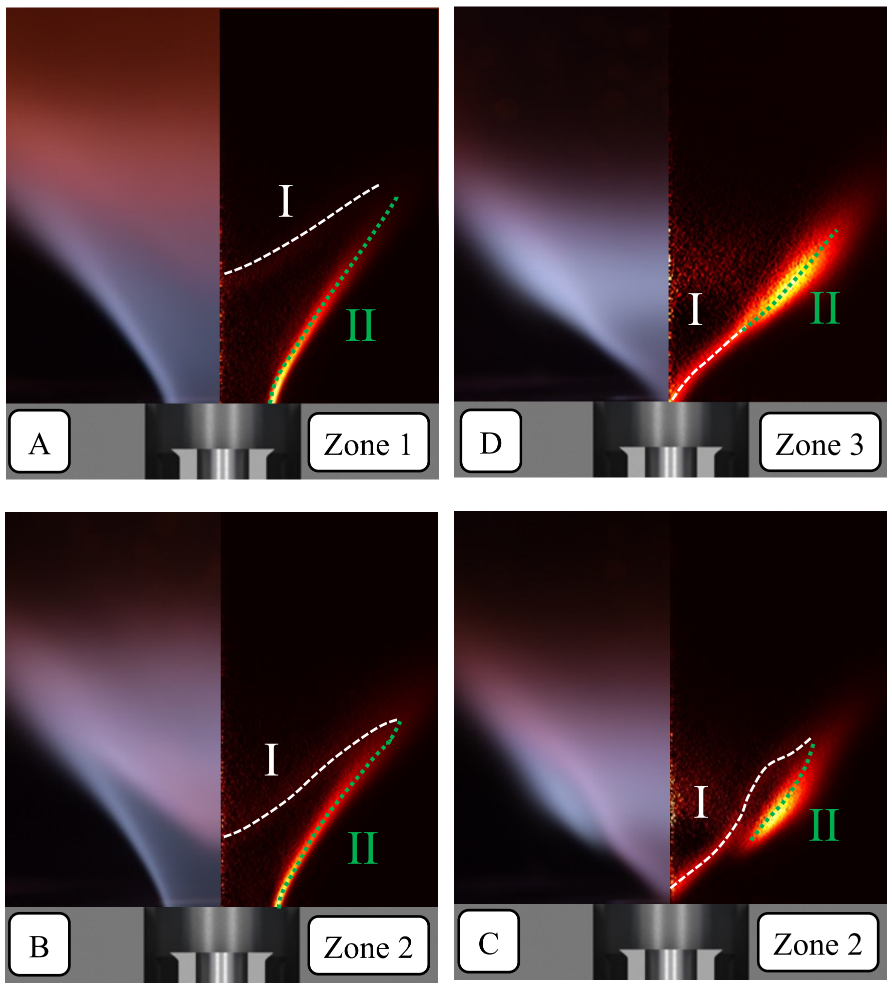


Lifted flames lead to reduced NOx emissions

Stabilization chart @ p=1 bar, T=300 K

Magnes et al. GT2023-103192

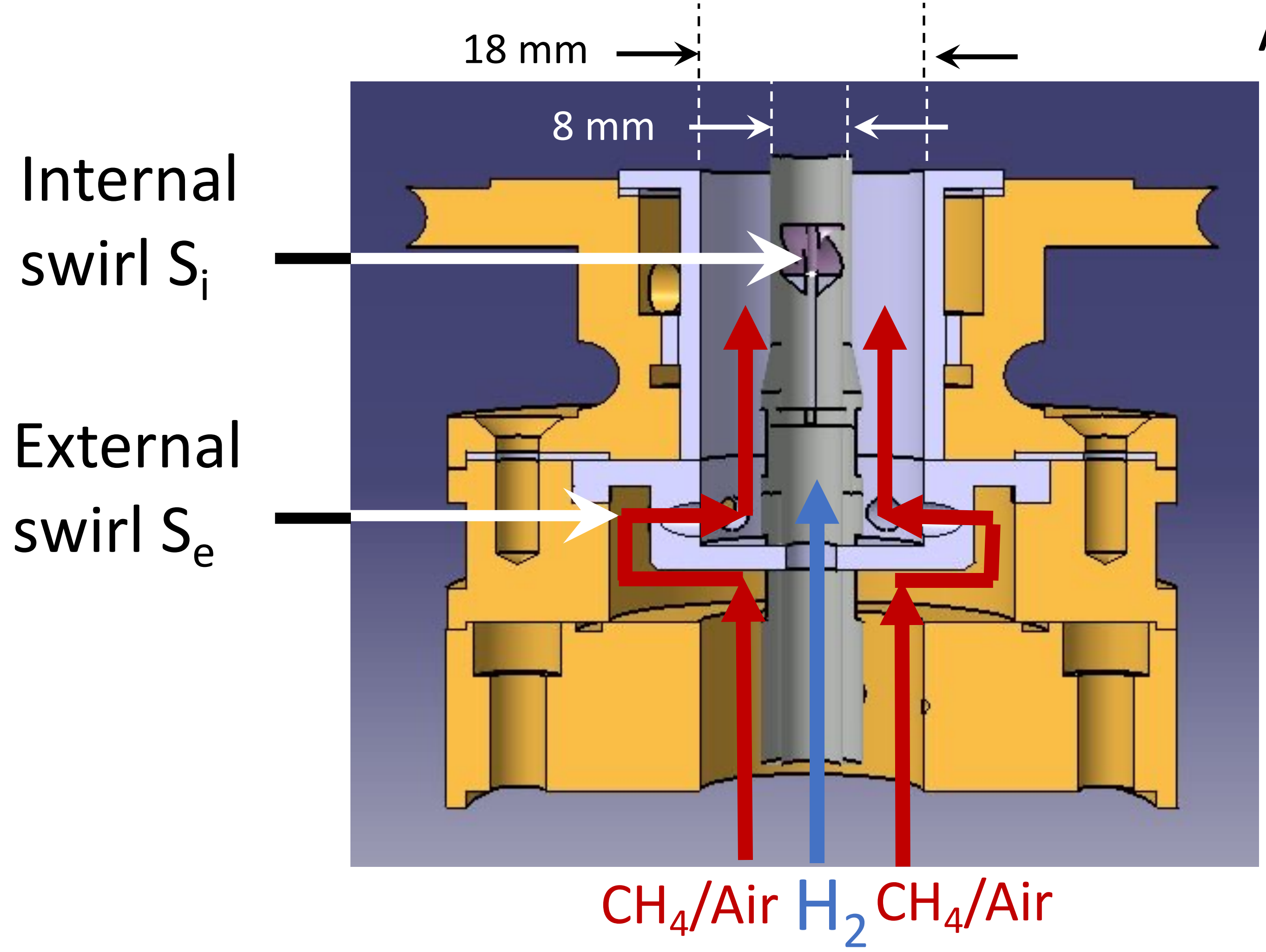




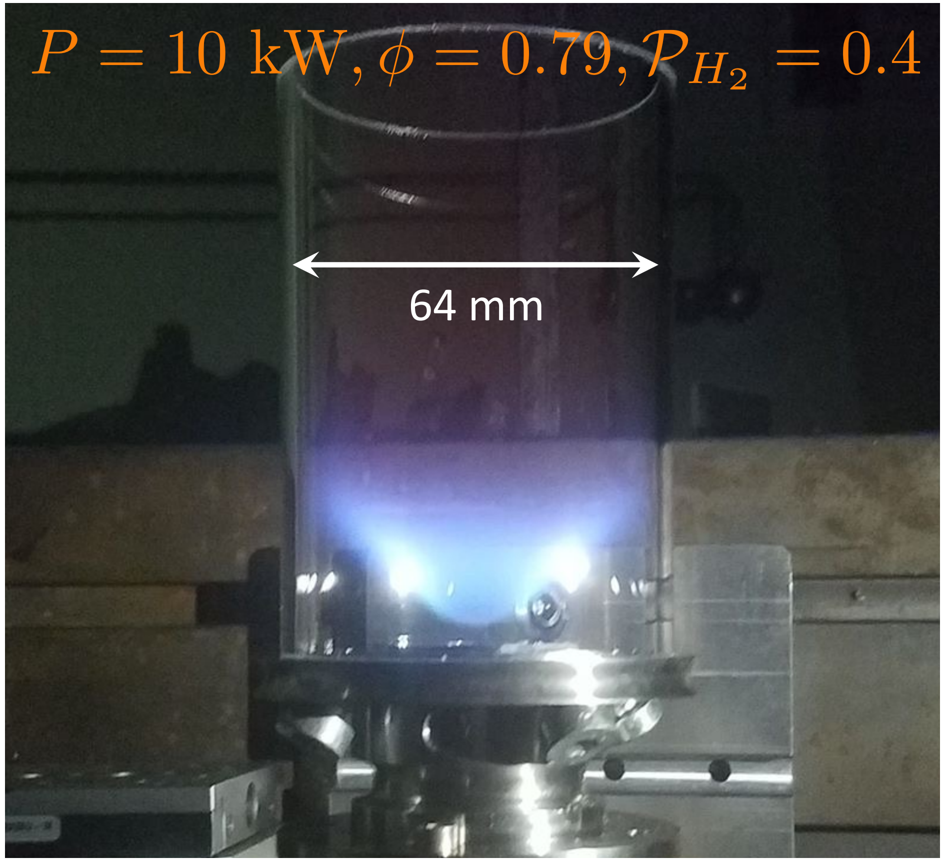
Dual fuel dual swirl non-premixed injector

Swirling the fuel yields compact and lifted flames

Degenève et al. (2019) JEGTP 141:121018



Aerodynamically stabilized flame



S. Marragou's iphone picture