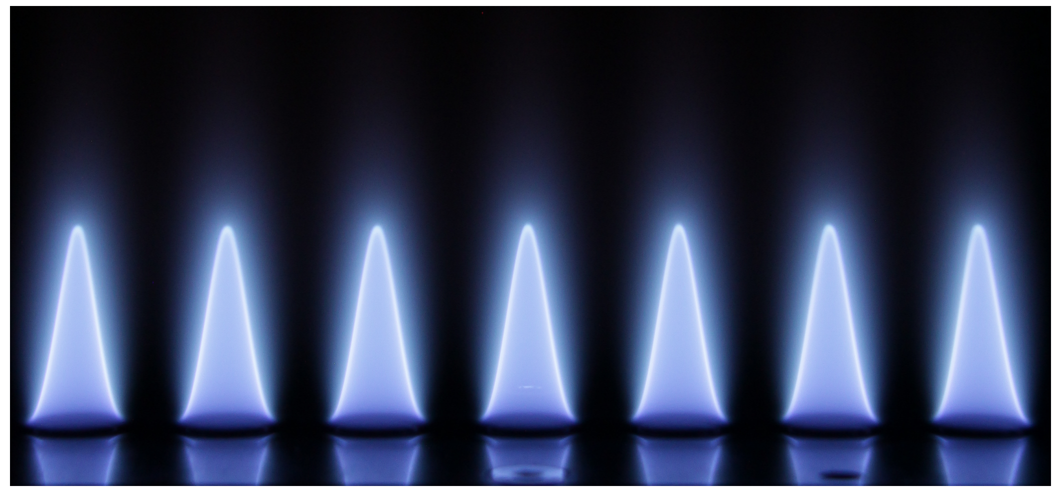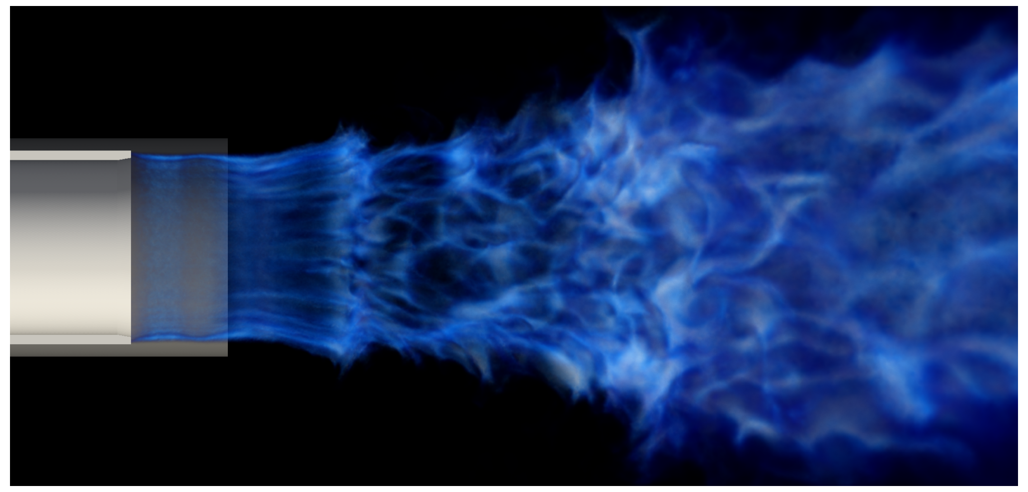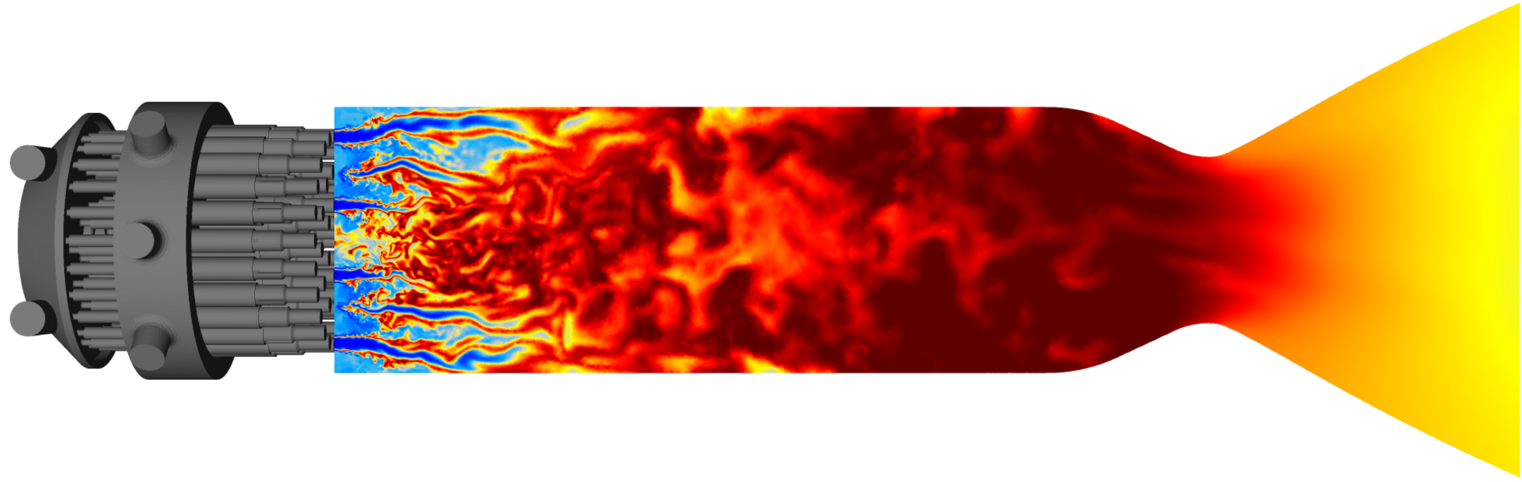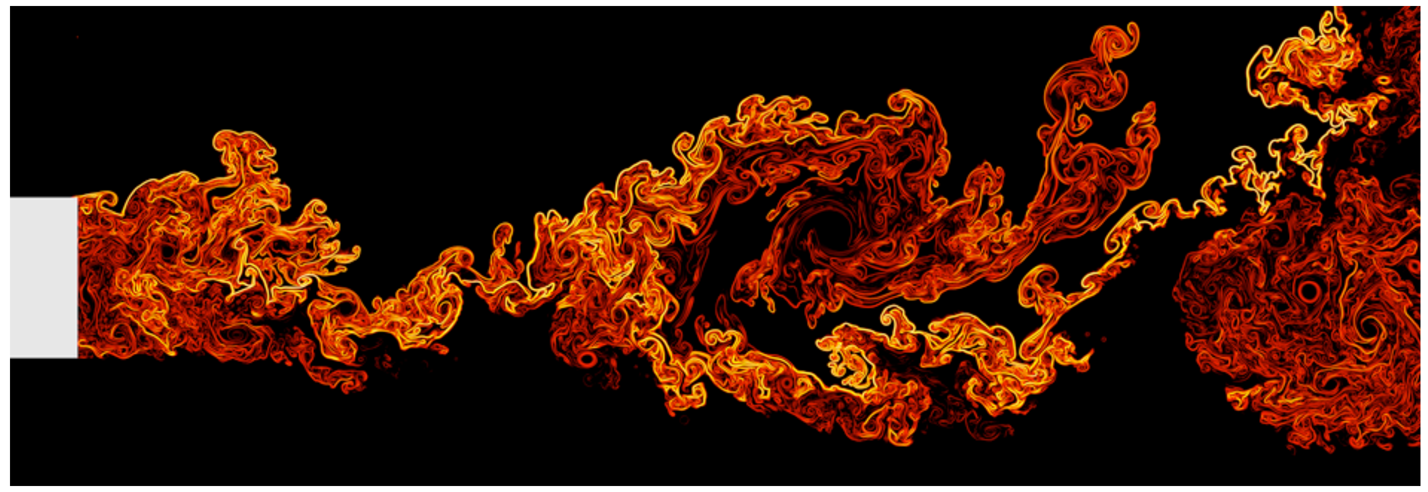

Hydrogen Combustion

Basics and specific features

Laurent Selle - Hydrogen Week @IMFT - Feb. 2024

A peculiar fuel

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- **Diffusion** is much faster than for other fuels (Small molecule) => modelling issues for laminar and turbulent flames.
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Hydrogen kinetics

8 species and 21 reactions

http://web.eng.ucsd.edu/mae/groups/combustion/mechanism.html

Reaction		A^a	n	E^a
$H + O_2 \rightleftharpoons OH + O$		3.52×10^{16}	-0.7	71.42
$H_2 + O \rightleftharpoons OH + H$		5.06×10^{4}	2.67	26.32
$H_2 + OH \rightleftharpoons H_2O + H$		1.17×10^{9}	1.3	15.21
$H_2O + O \rightleftharpoons 2OH$		7.06×10^{0}	3.84	53.47
$2H + M \rightleftharpoons H_2 + M^b$		1.30×10^{18}	-1.0	0.0
$H + OH + M \rightleftharpoons H_2O + M^b$		4.00×10^{22}	-2.0	0.0
$2O + M \rightleftharpoons O_2 + M^b$		6.17×10^{15}	-0.5	0.0
$H + O + M \rightleftharpoons OH + M^b$		4.71×10^{18}	-1.0	0.0
$O + OH + M \rightleftharpoons HO_2 + M^b$		8.30×10^{14}	0.0	0.0
$H + O_2 + M \rightleftharpoons HO_2 + M^c$	k_0	5.75×10^{19}	-1.4	0.0
	k_∞	4.65×10^{12}	0.44	0.0
$HO_2 + H \rightleftharpoons 2OH$		7.08×10^{13}	0.0	1.23
$HO_2 + H \rightleftharpoons H_2 + O_2$		1.66×10^{13}	0.0	3.44
$HO_2 + H \rightleftharpoons H_2O + O$		3.10×10^{13}	0.0	7.20
$HO_2 + O \rightleftharpoons OH + O_2$		2.00×10^{13}	0.0	0.0
$HO_2 + OH \rightleftharpoons H_2O + O_2$		2.89×10^{13}	0.0	−2.08
$2OH + M \rightleftharpoons H_2O_2 + M^d$	k_0	2.30×10^{18}	-0.9	−7.12
	k_∞	7.40×10^{13}	-0.37	0.0
$2HO_2 \rightleftharpoons H_2O_2 + O_2$		3.02×10^{12}	0.0	5.8
$H_2O_2 + H \rightleftharpoons HO_2 + H_2$		4.79×10^{13}	0.0	33.3
$H_2O_2 + H \rightleftharpoons H_2O + OH$		1.00×10^{13}	0.0	15.0
$H_2O_2 + OH \rightleftharpoons H_2O + HO_2$		7.08×10^{12}	0.0	6.0
$H_2O_2 + O \rightleftharpoons HO_2 + OH$		9.63×10^{6}	2.0	16.7

A peculiar fuel

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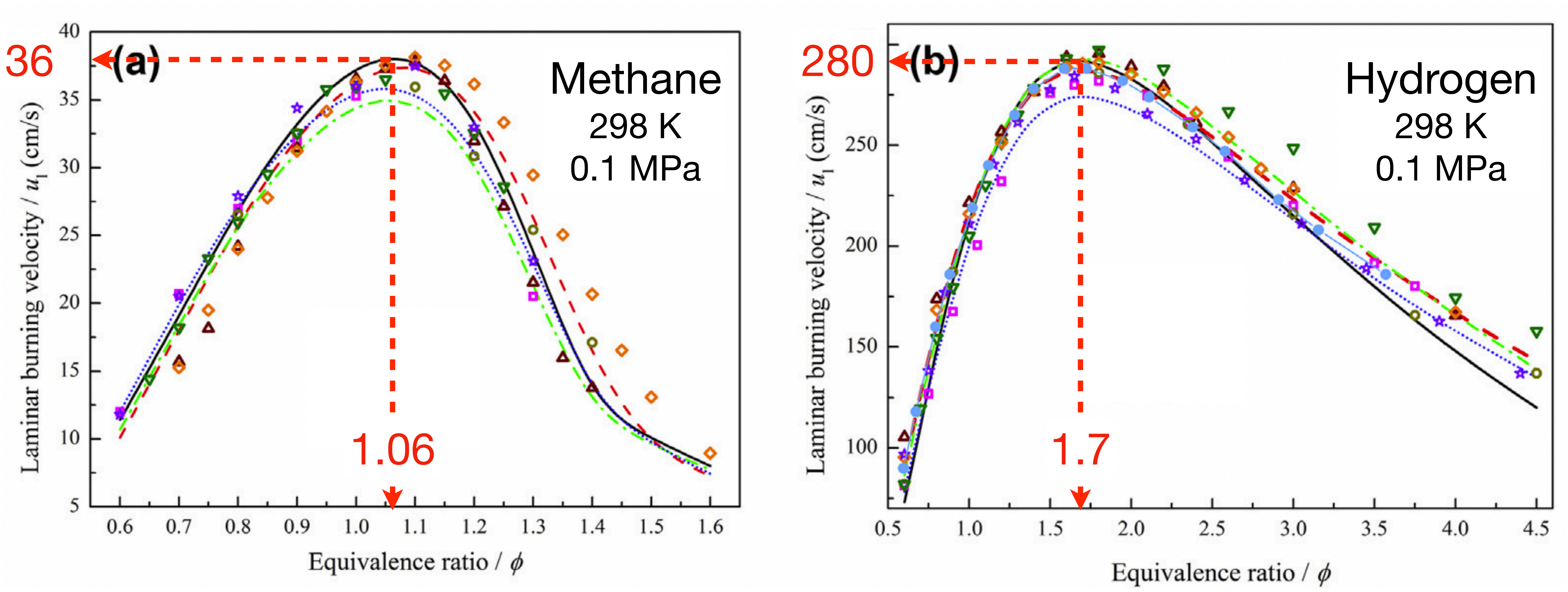
Flame speed



(a)
36
1.06
Methane
298 K
0.1 MPa
Laminar burning velocity / u_l (cm/s)
Equivalence ratio / ϕ
(b)
280
1.7
Hydrogen
298 K
0.1 MPa
Laminar burning velocity / u_l (cm/s)
Equivalence ratio / ϕ

Comparison with methane

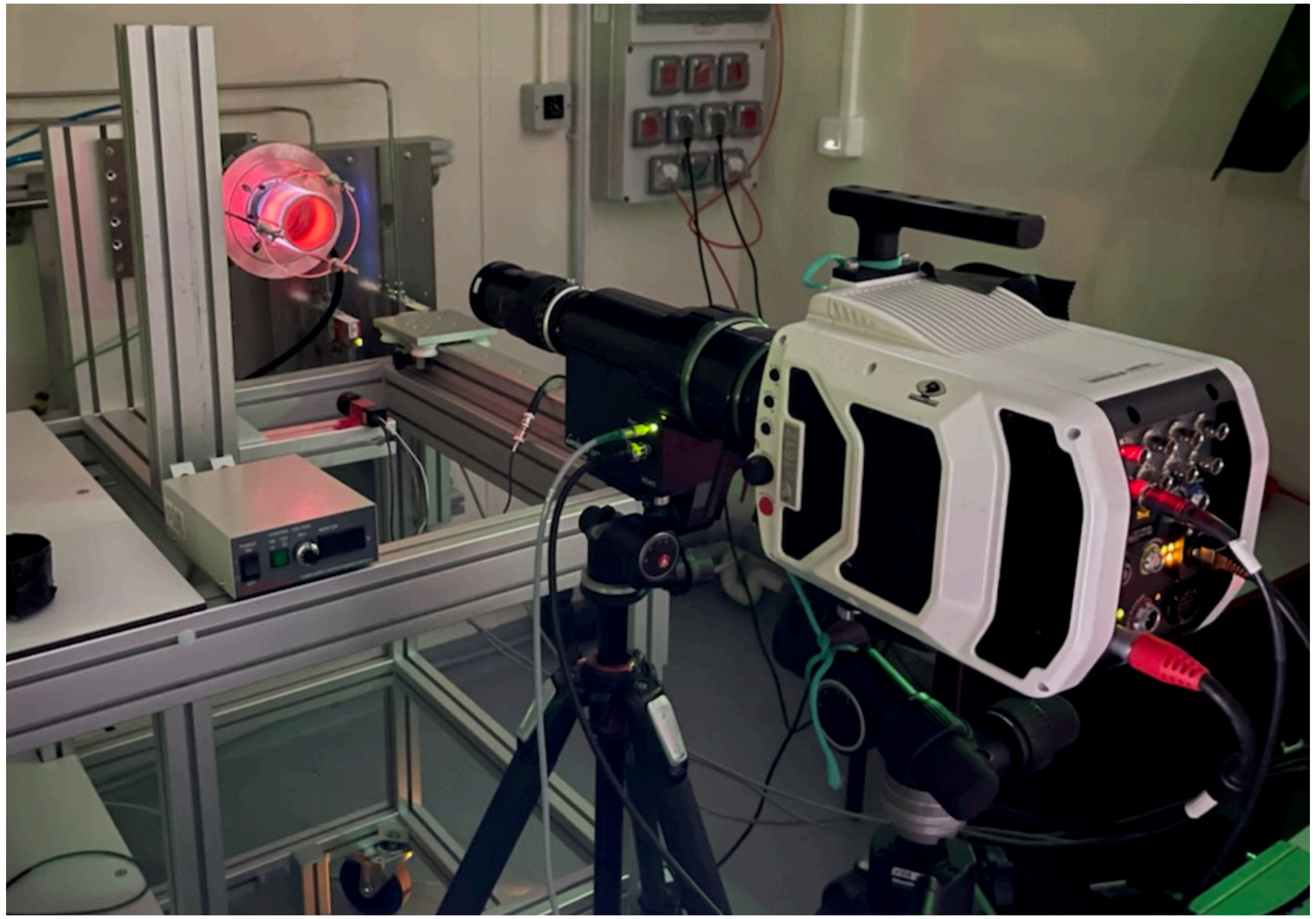
Table 1 — Physical properties of hydrogen and natural gas (293.15 K/101.325 kPa).

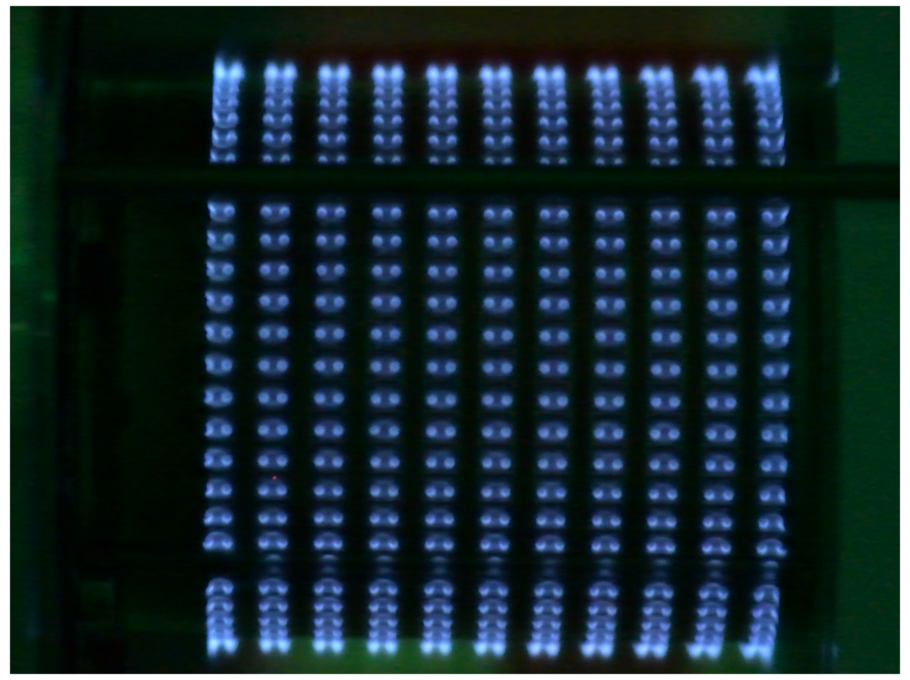
Parameter	Hydrogen	Natural gas (85%/CH_4)
Density (STP, g/L)	0.089	0.717
MIE (in air, mJ)	0.017	0.31
Flammable limits (in air, %)	4–75	5–15
Energy density (LHV, MJ/kg)	119.96	50.07
Boiling point (°C)	−253	−162
Ignition temperature (°C)	574	650
Burning velocity (m/s)	2.65–3.25	0.38

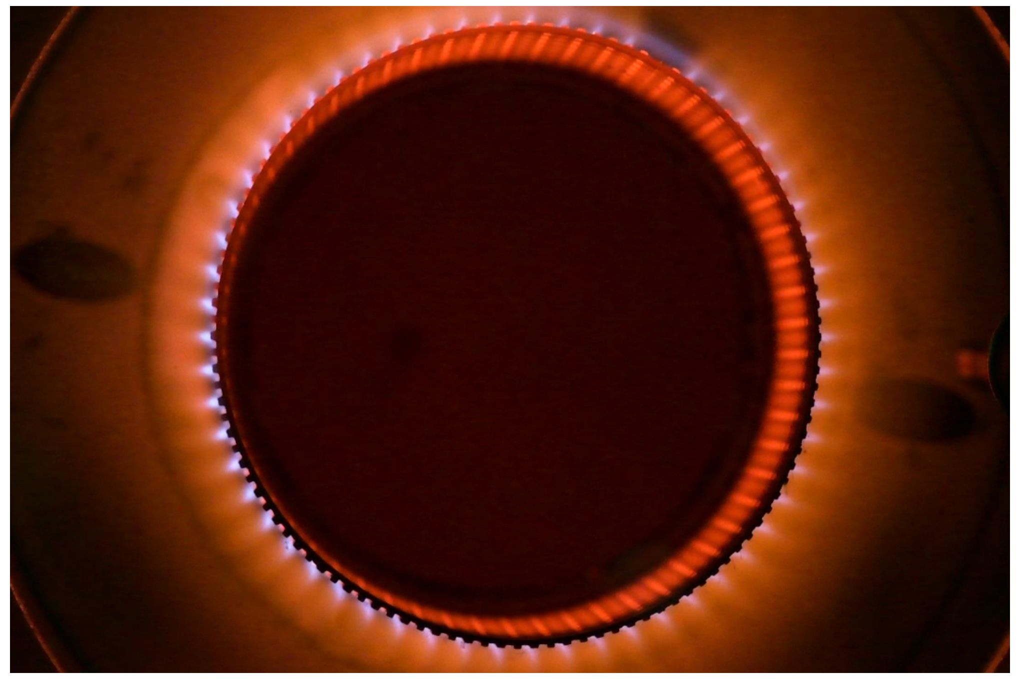
https://doi.org/10.1016/j.ijhydene.2021.07.005

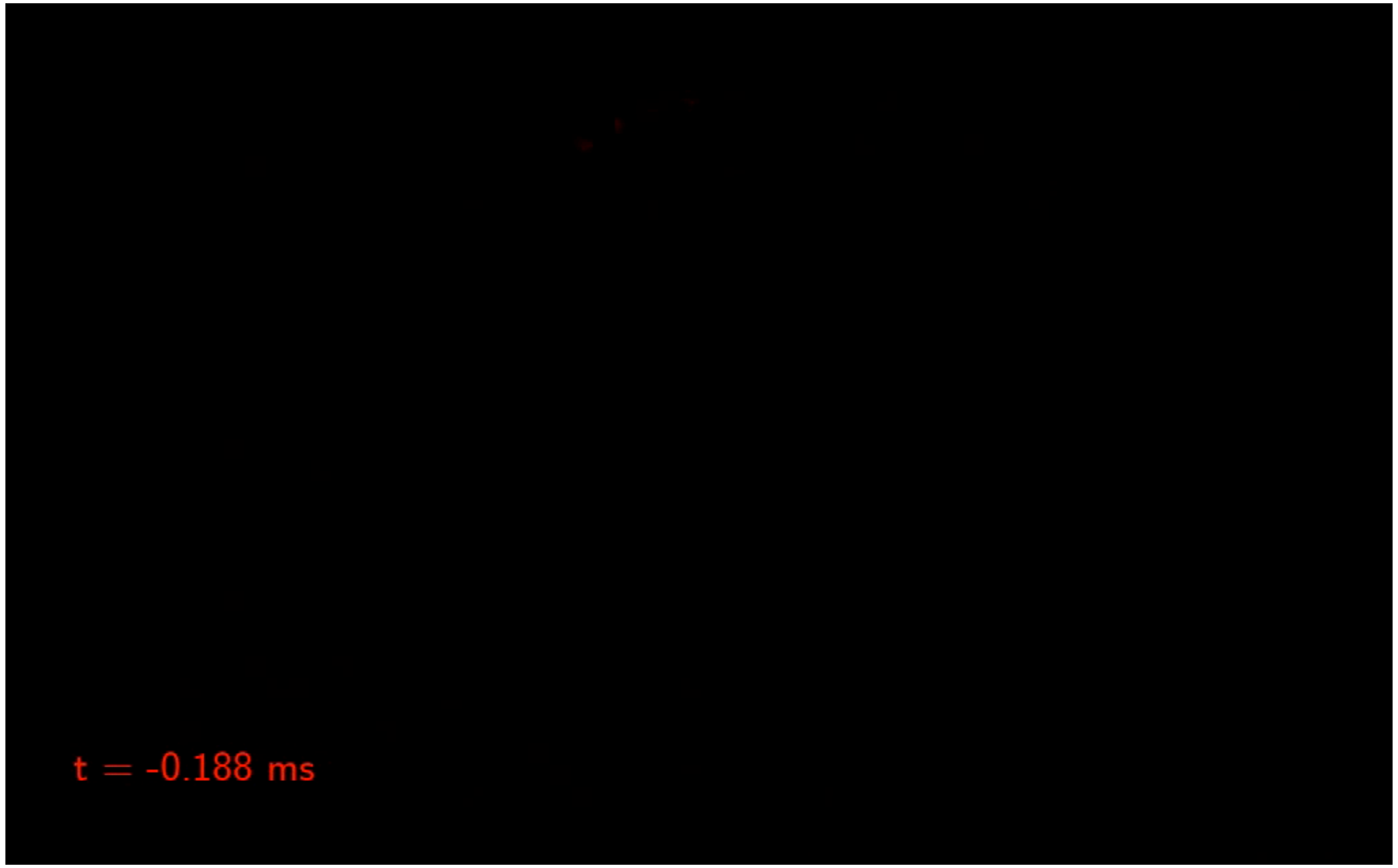
Flashback

INSTITUT DE MECANIQUE DES FLUIDES DE TOULOUSE

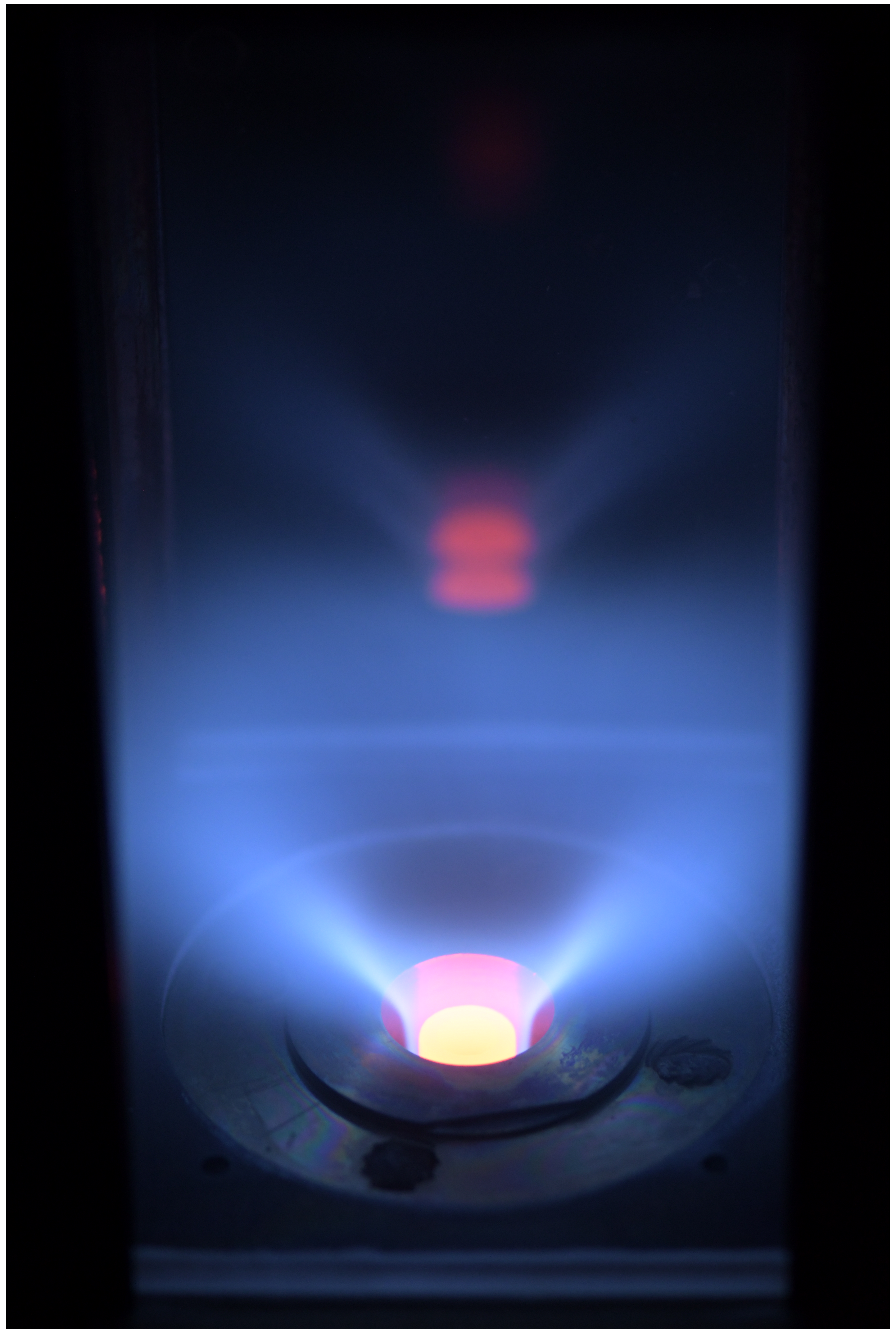




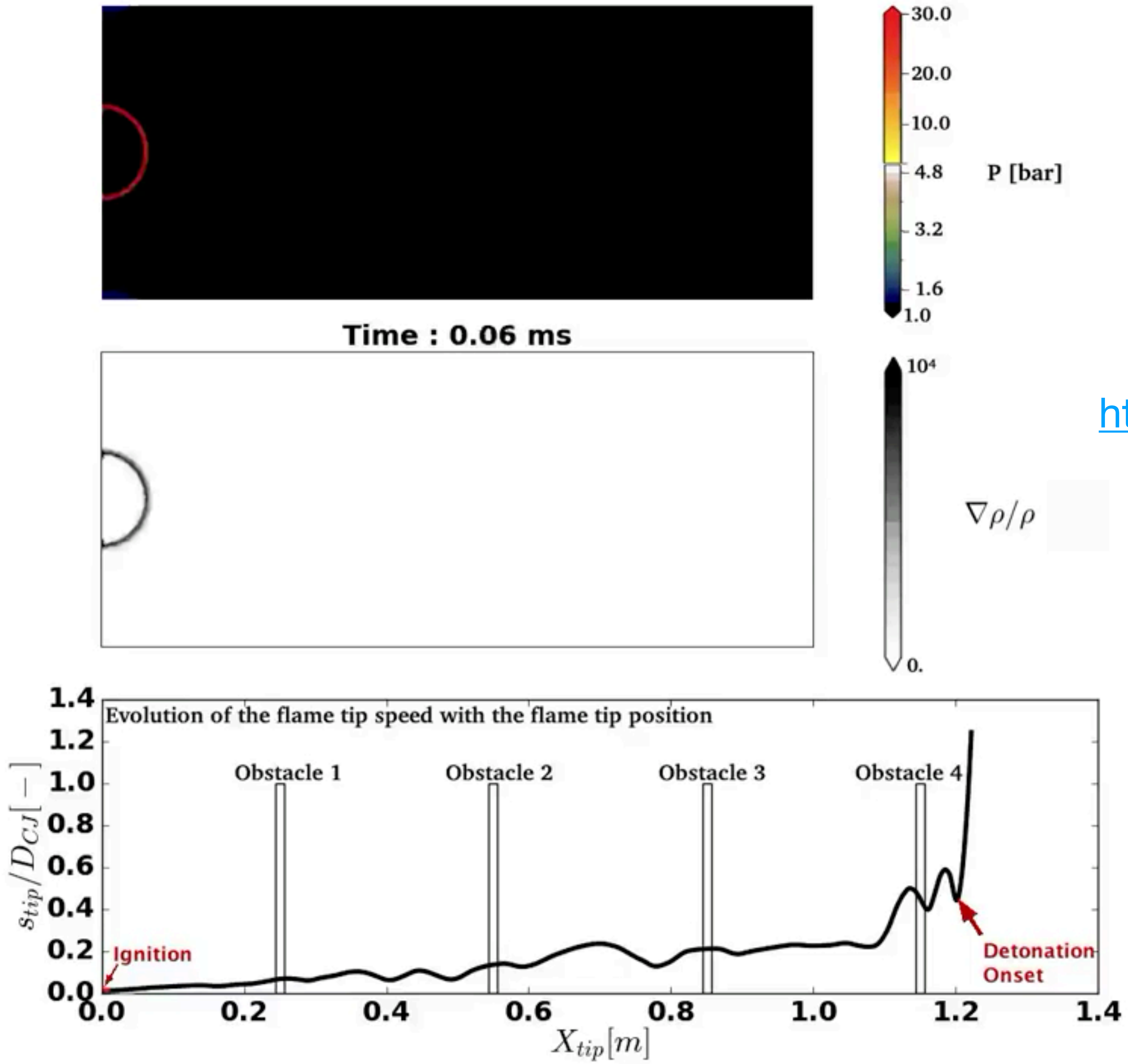




Heat fluxes



Transition to detonation



https://youtu.be/s_unWtCE_Jo

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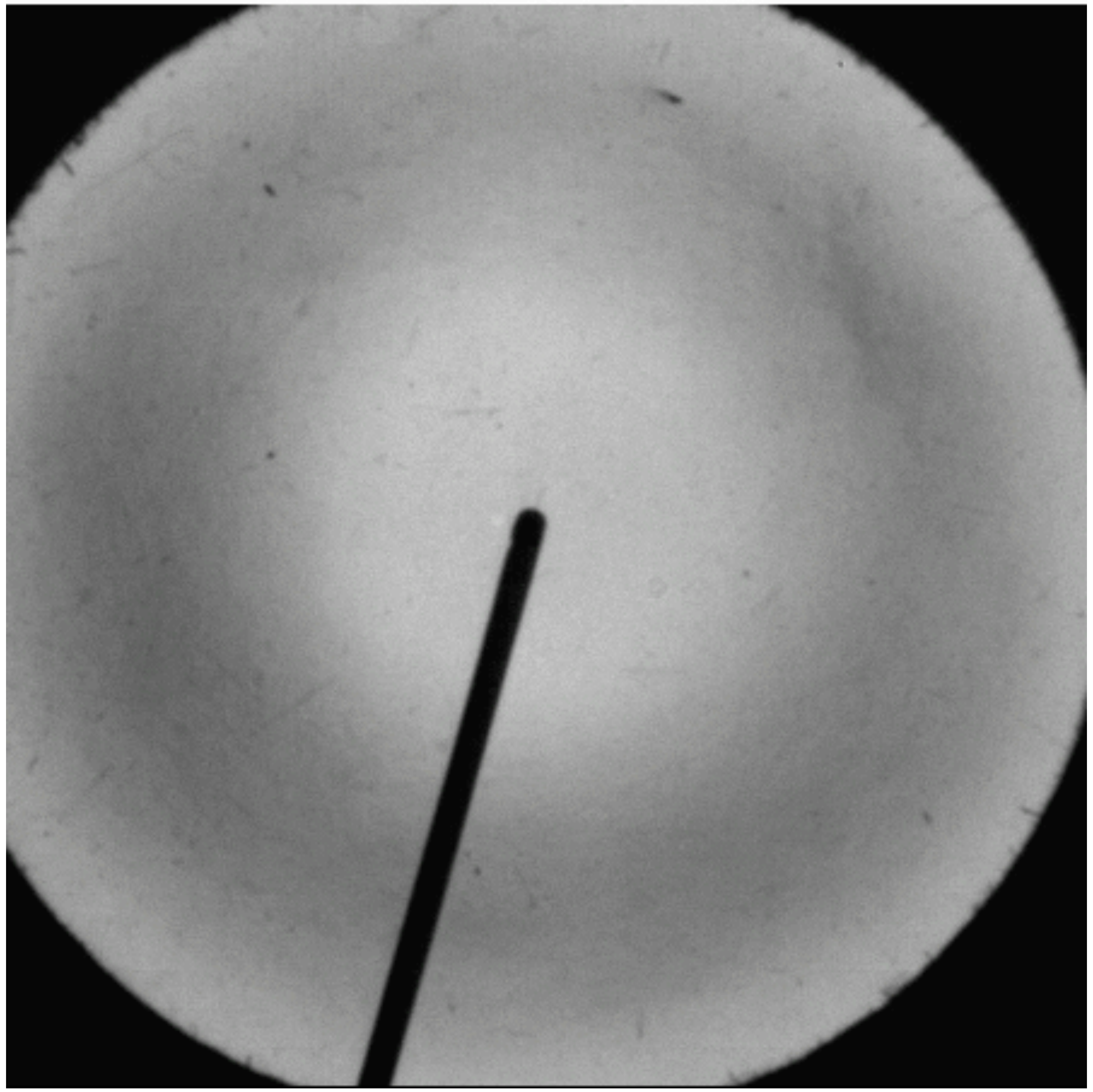
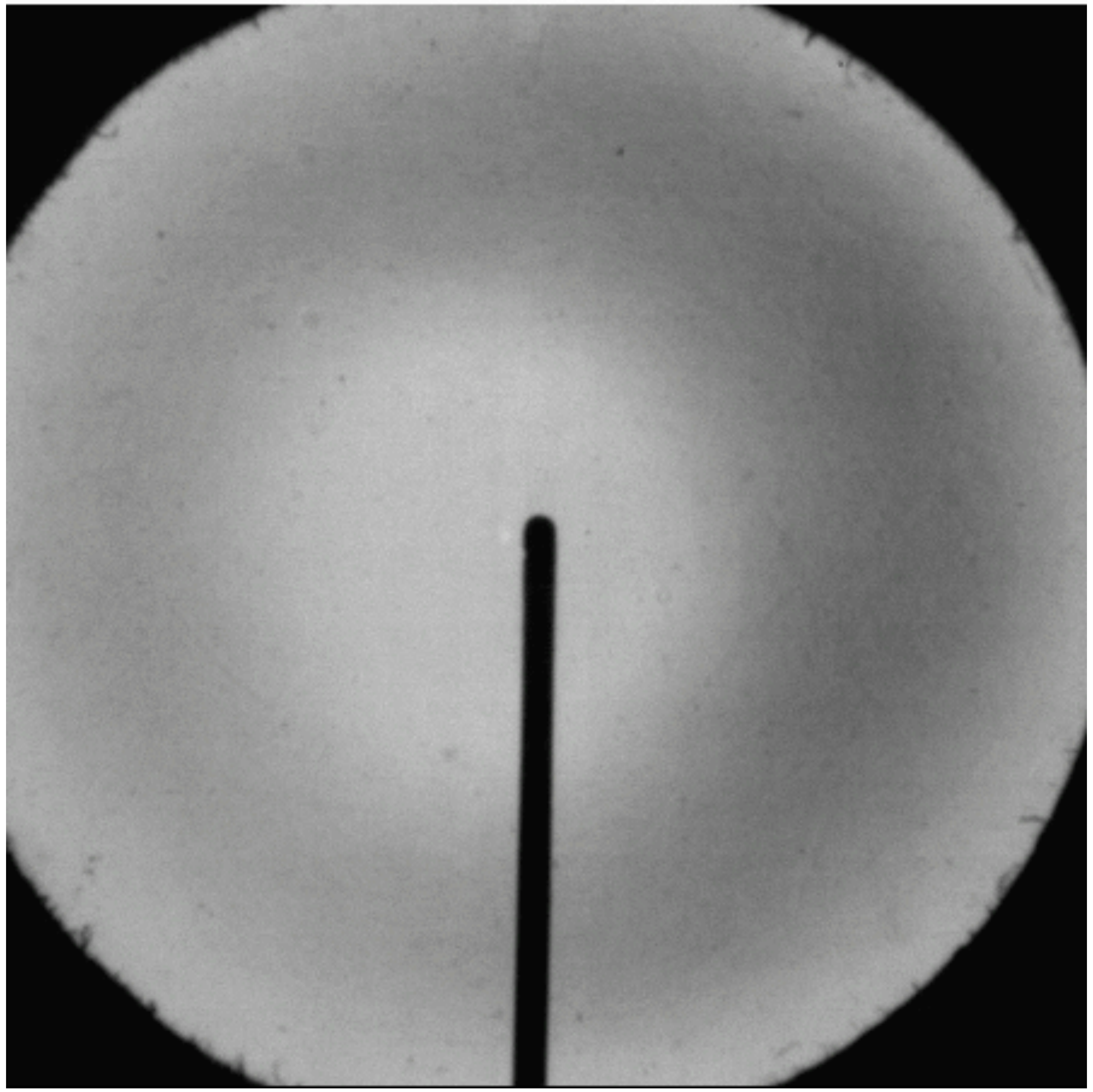
Thermodiffusive instabilities

CH_4 @ $\phi = 0.8$ - Duration 30 ms

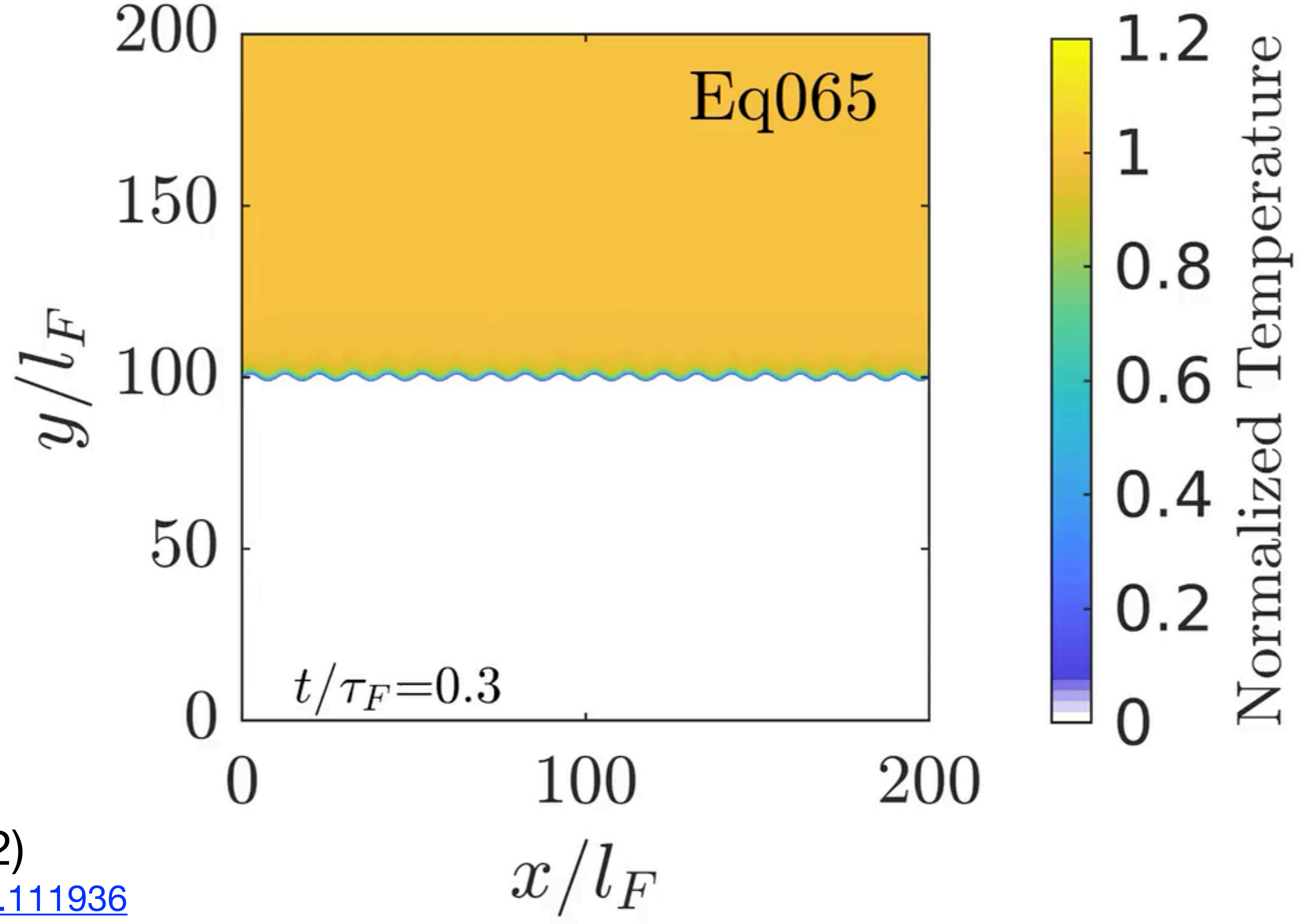


H_2 @ $\phi = 0.6$ - Duration 4 ms



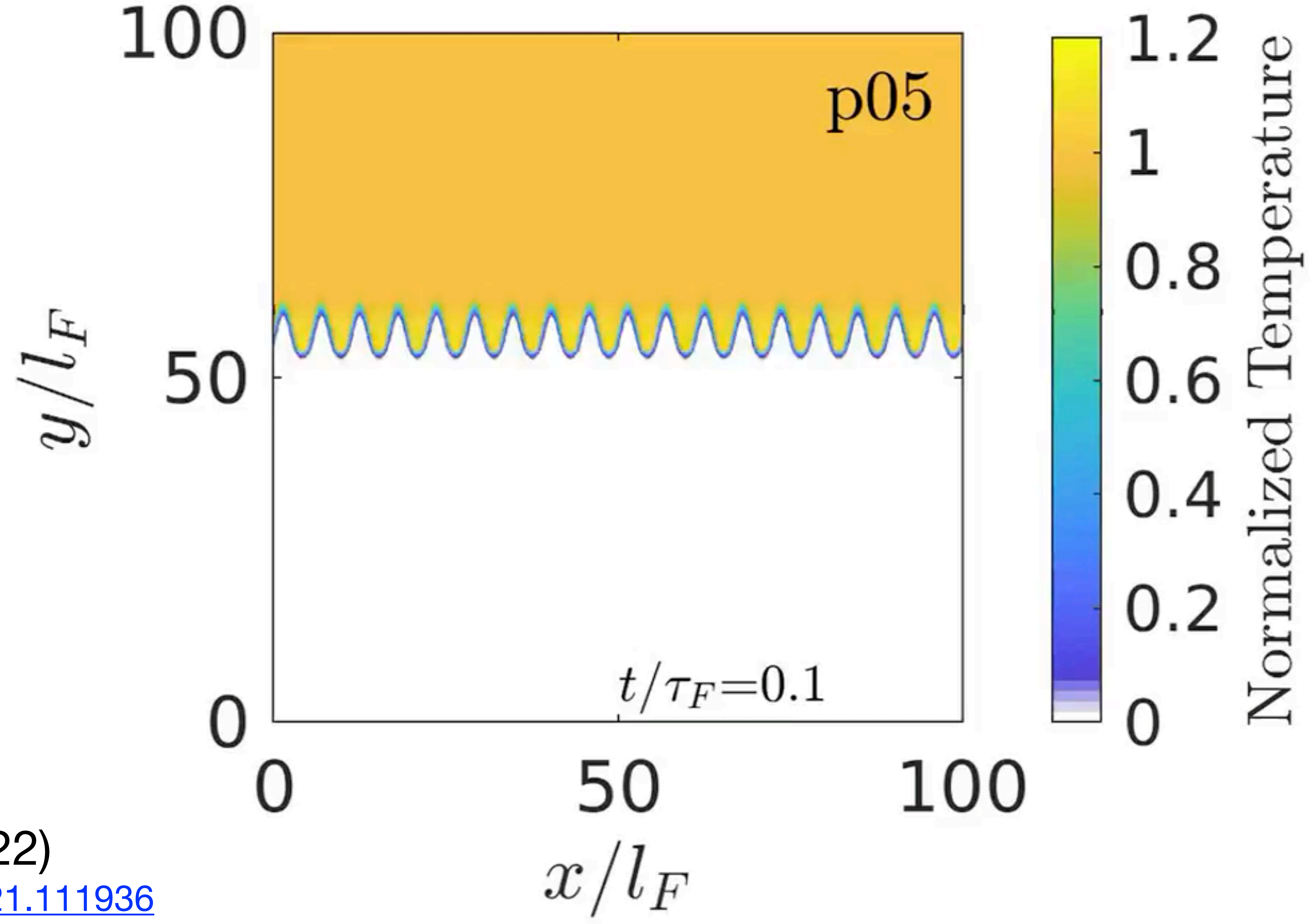
Movies courtesy of H. Pitsch: Beeckmann et al. (2017) (10.1016/j.proci.2016.06.194)

Thermodiffusive instabilities



Berger et al. (2022)
10.1016/j.combustflame.2021.111936

Thermodiffusive instabilities



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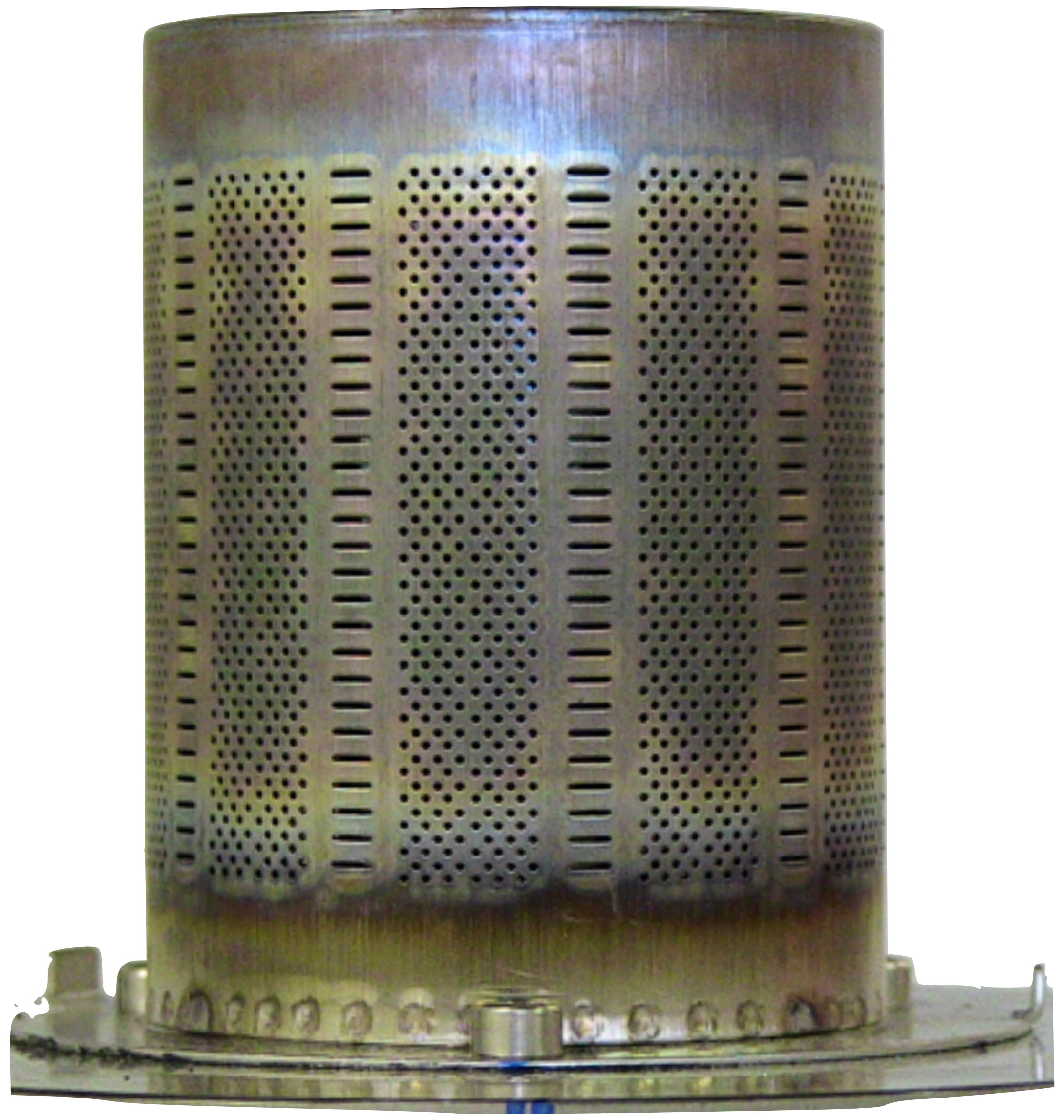
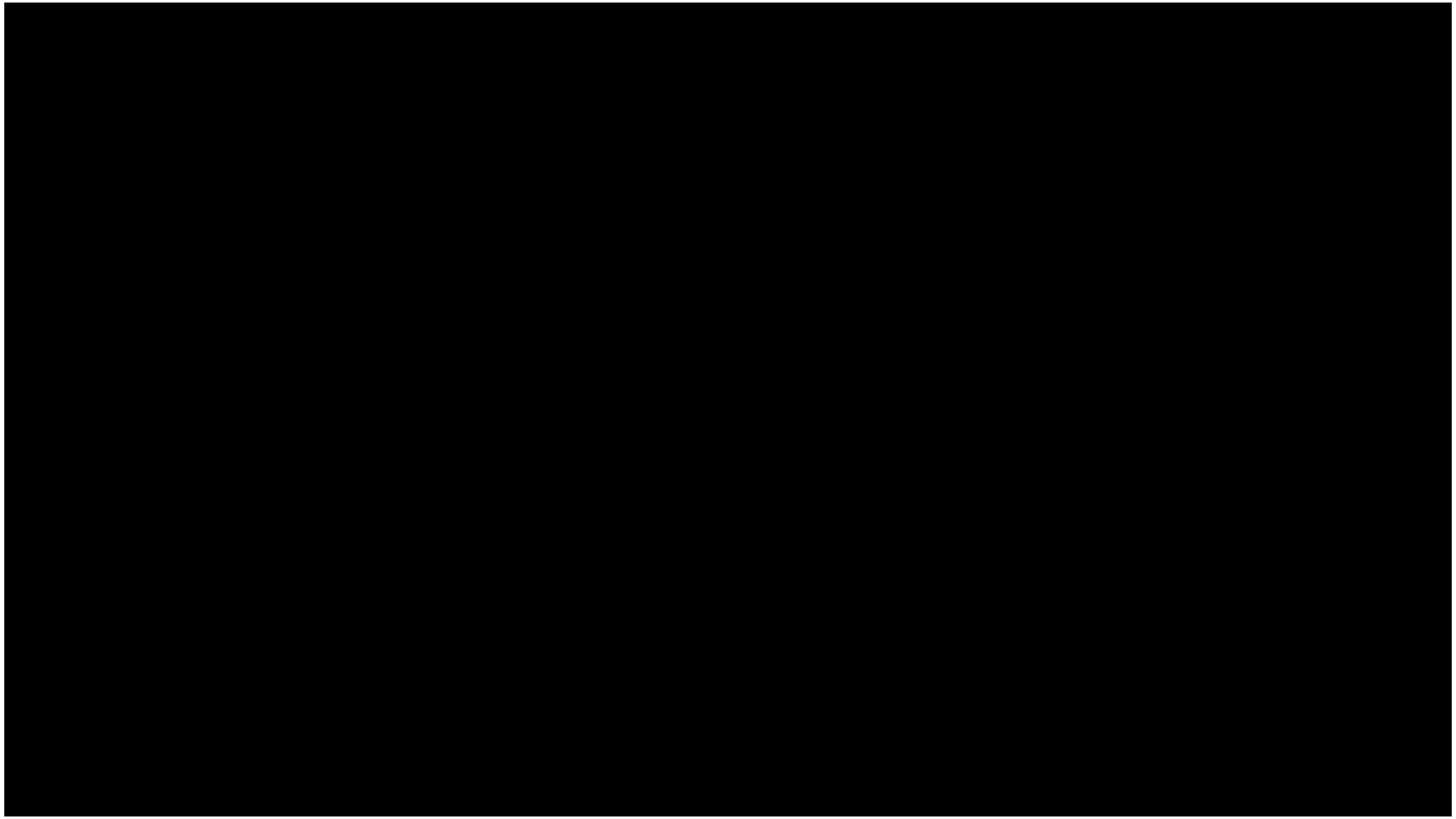
Light emission



Domestic heater burner
(Furipat)



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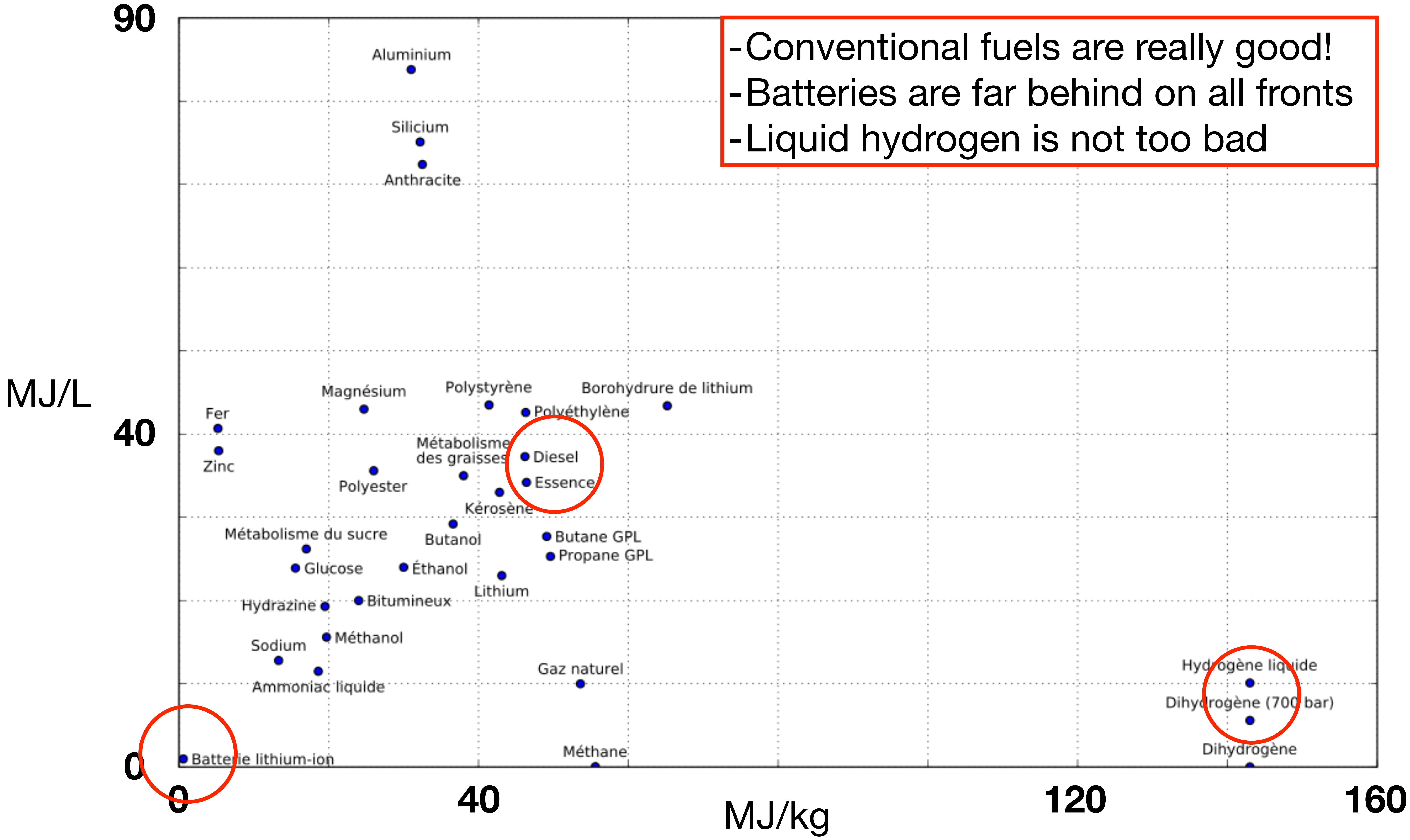
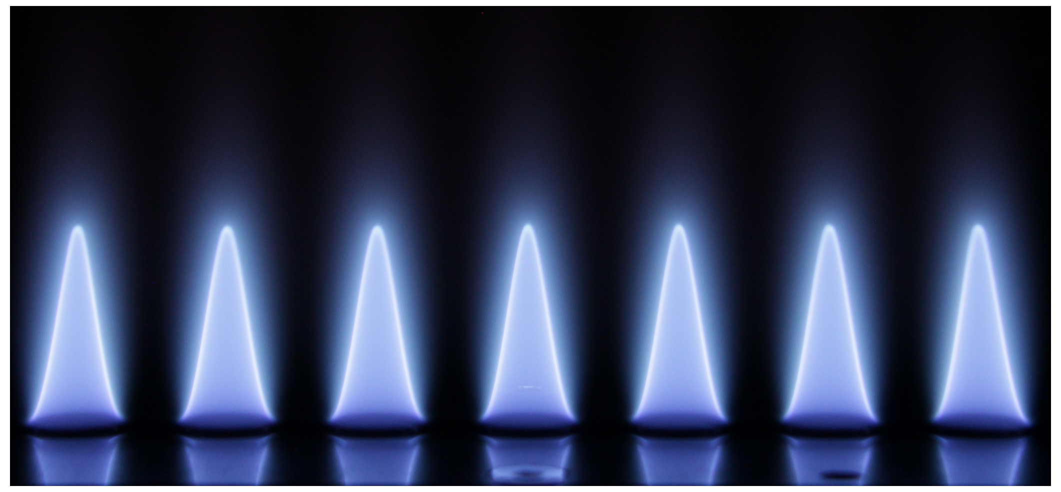
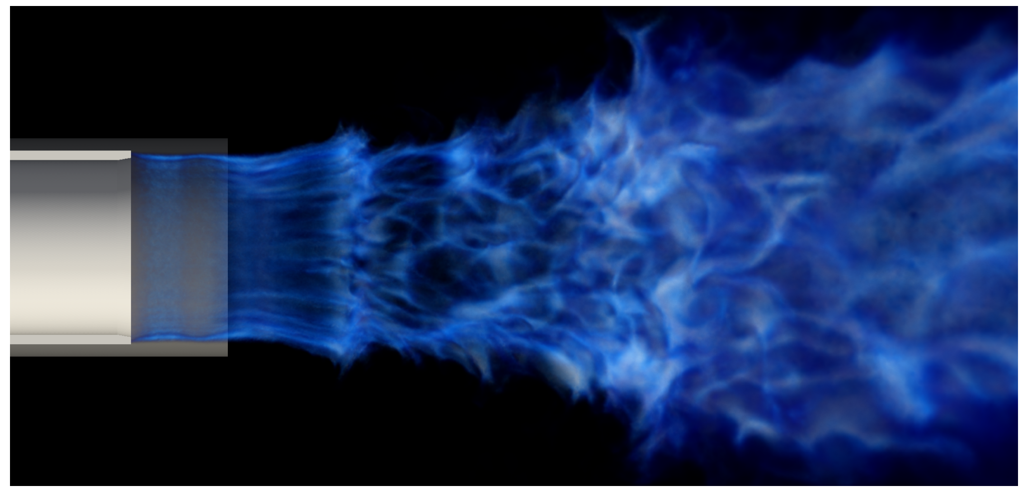
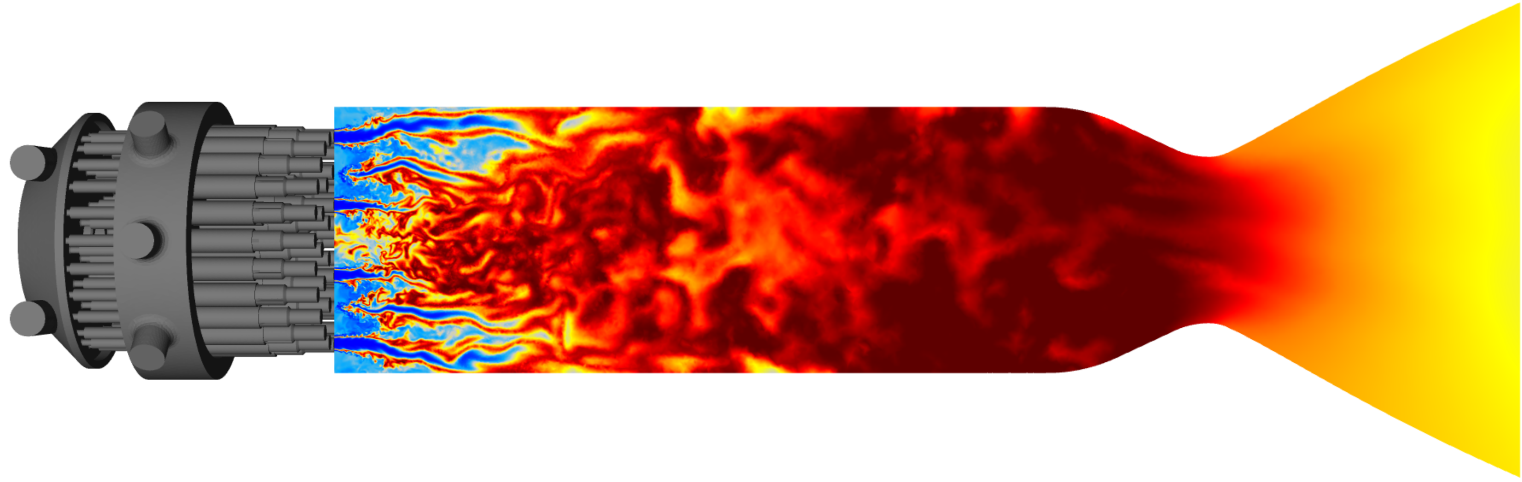
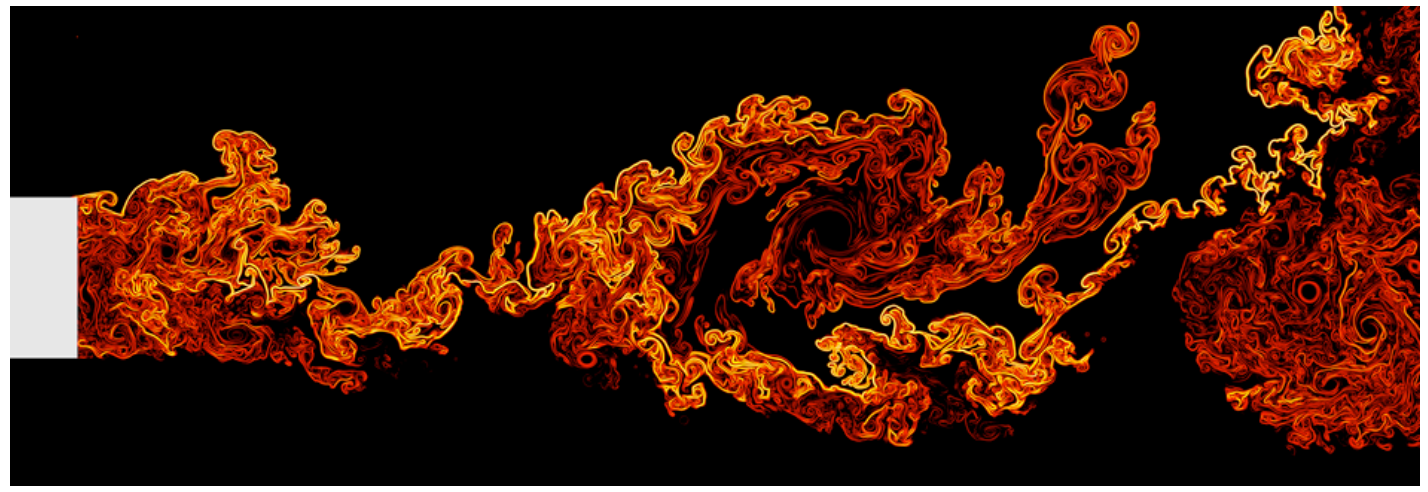
Energy density



- Conventional fuels are really good!
- Batteries are far behind on all fronts
- Liquid hydrogen is not too bad

Hydrogen Combustion

H_2 in gas turbines

Laurent Selle - Hydrogen Week @IMFT - Feb. 2024

In the lab - Micromix

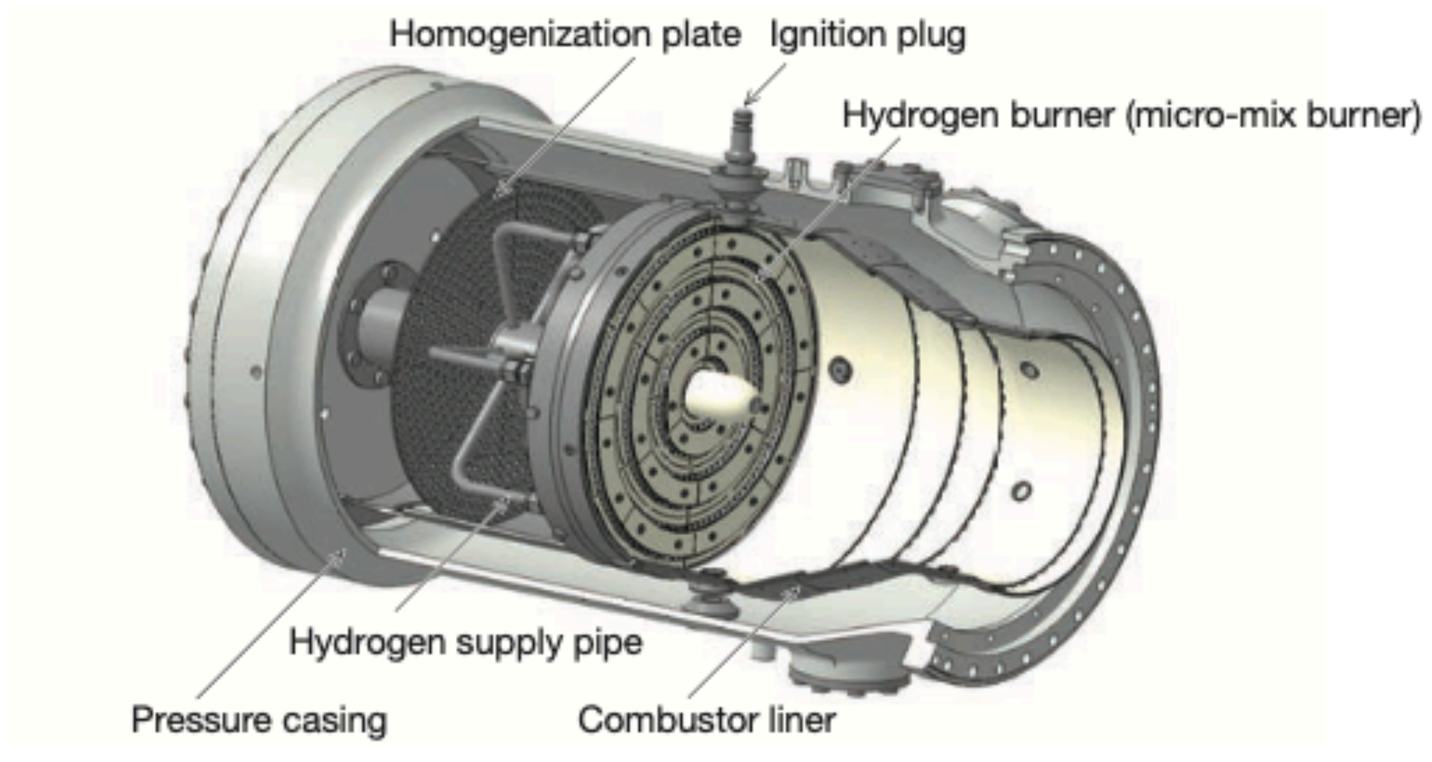
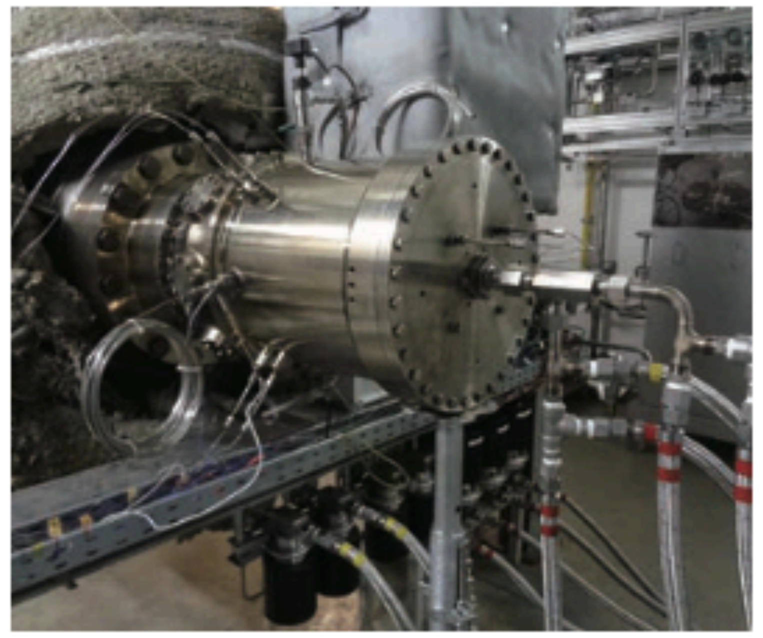


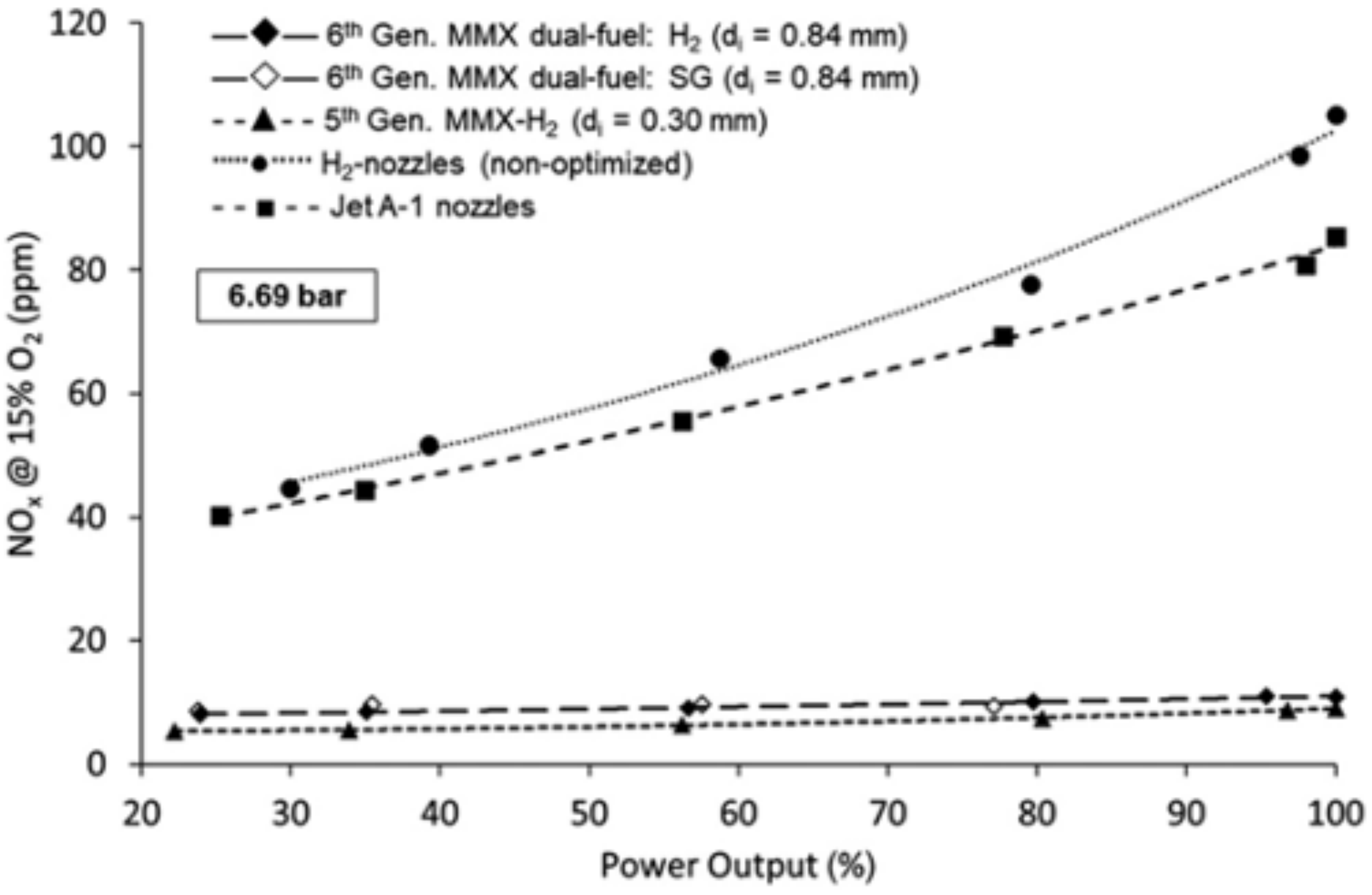
Fig. 7 Hydrogen dry low NOx combustor for 2MW class gas turbine



(a) Trial combustor

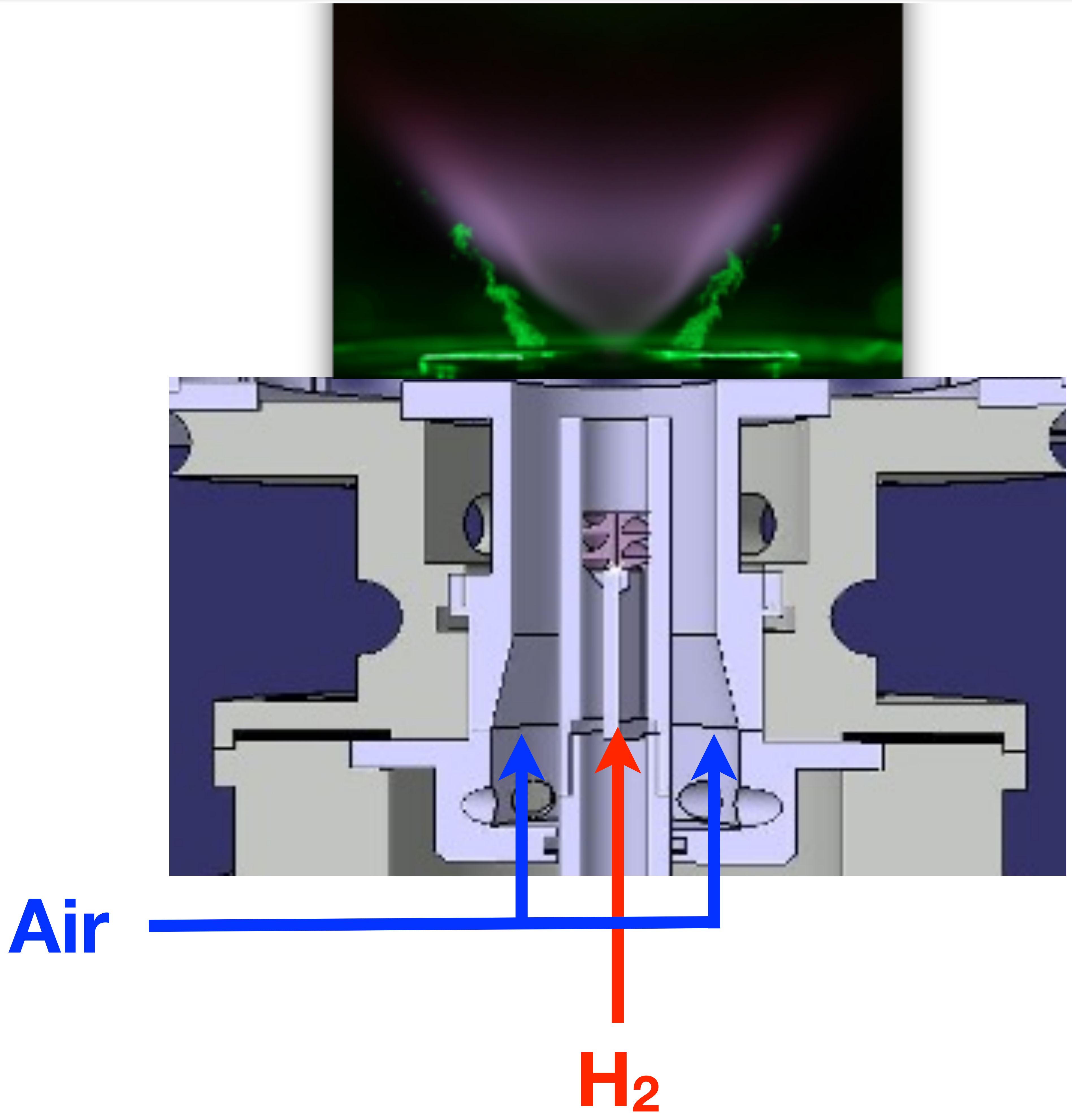
(b) Inside of combustor in design condition equivalent

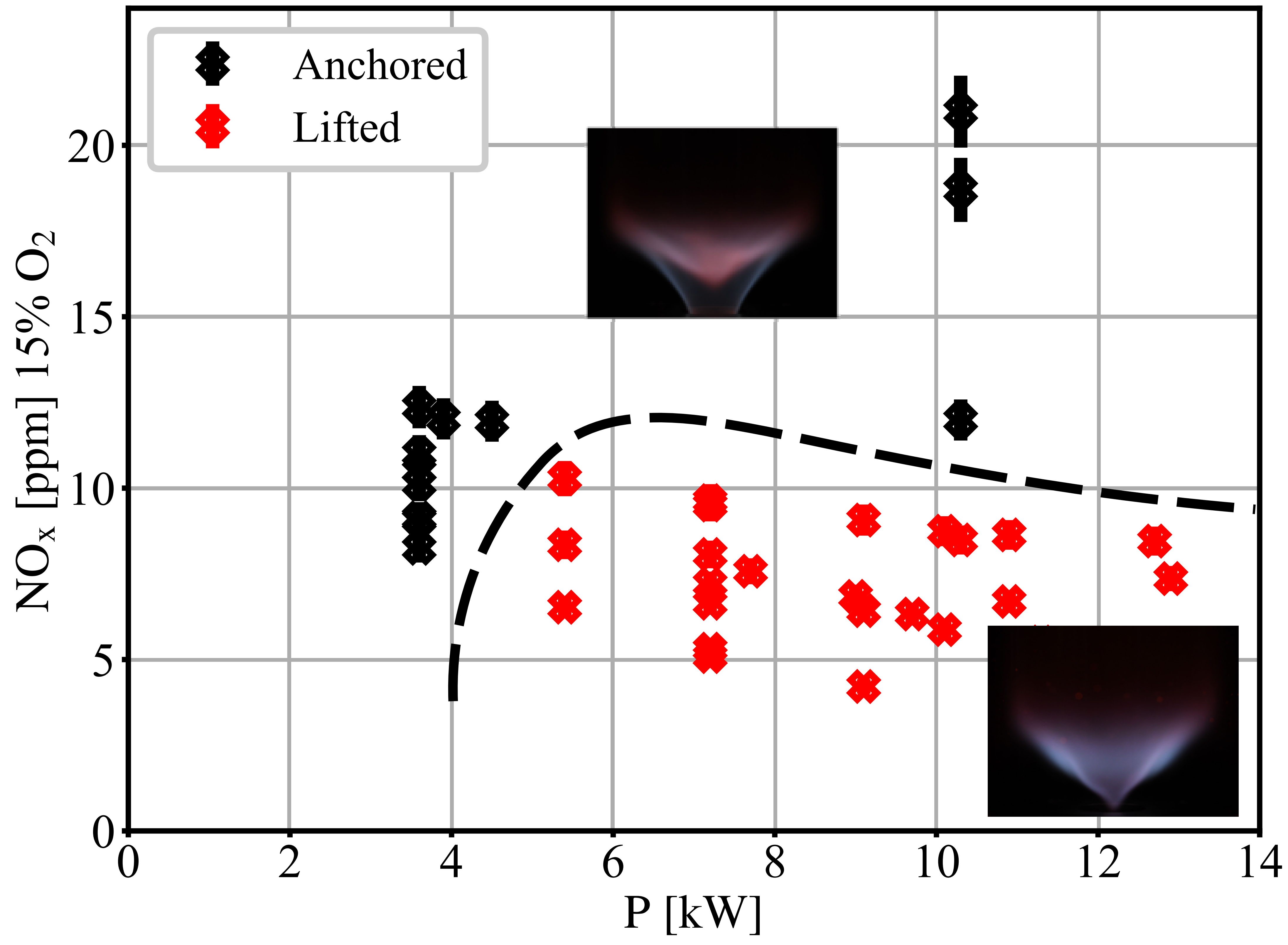
Micromix concept: Kawasaki prototype for power generation



NOx < 20 ppm

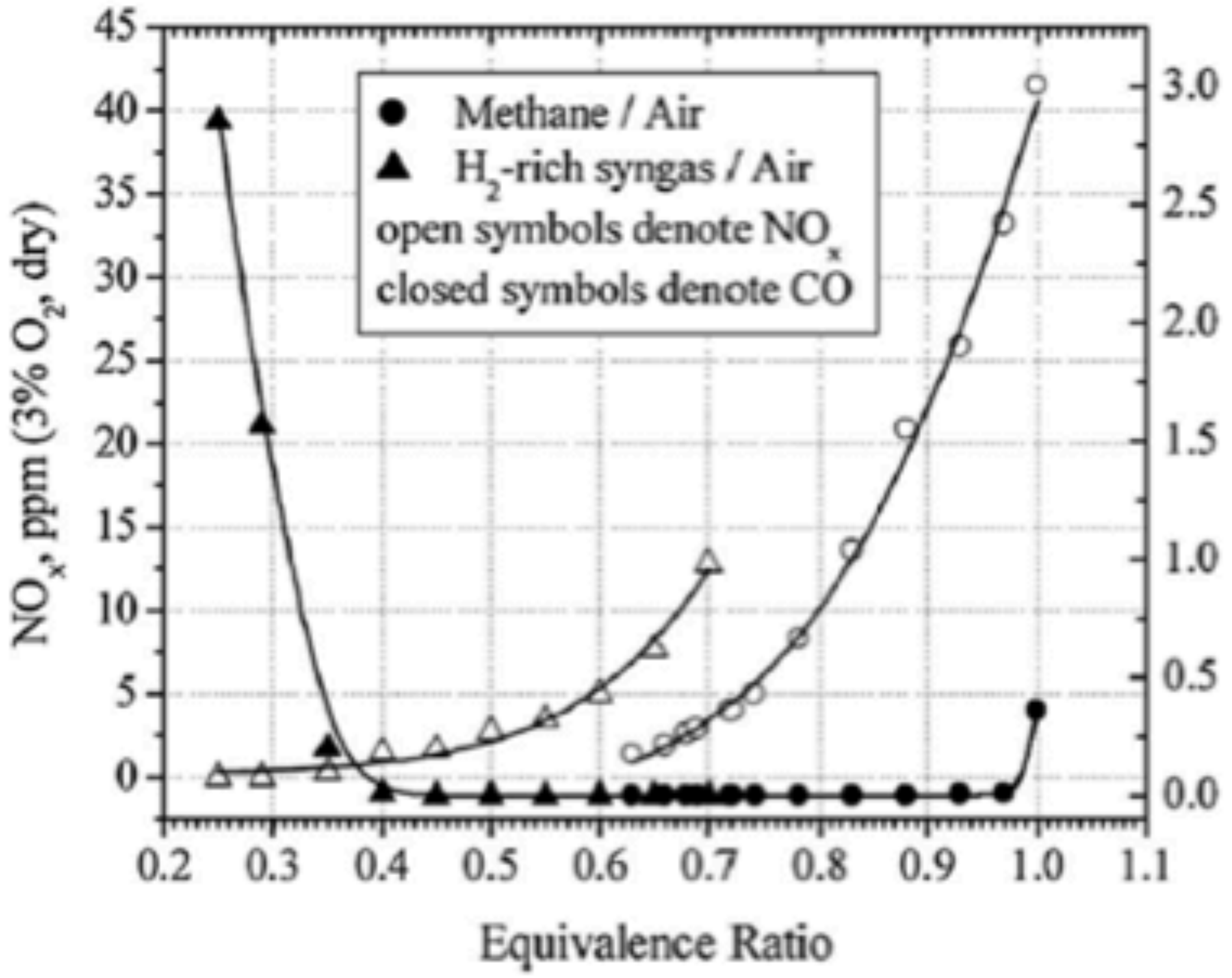
In the lab - Hylon





Hylon burner developed @IMFT (Patented with Safran)

In GT - NOx control



Generally speaking, three methods have been used to reduce NOx emissions from gas turbine power plants:

- **premixed combustion**, including catalytic combustion,
- **fuel dilution**, mostly by **steam**, water or **nitrogen**,
- **removal** from exhaust gases.

For natural gas applications, the first technique is the preferred one: at present, the "dry low-emission" combustors are proposed by manufacturers for virtually any gas turbine model. Their basic principle is to **achieve a moderate flame temperature** by forcing more air than stoichiometric in the primary zone; this is obtained by mixing air to fuel before the combustion.

https://doi.org/10.1115/1.1787513

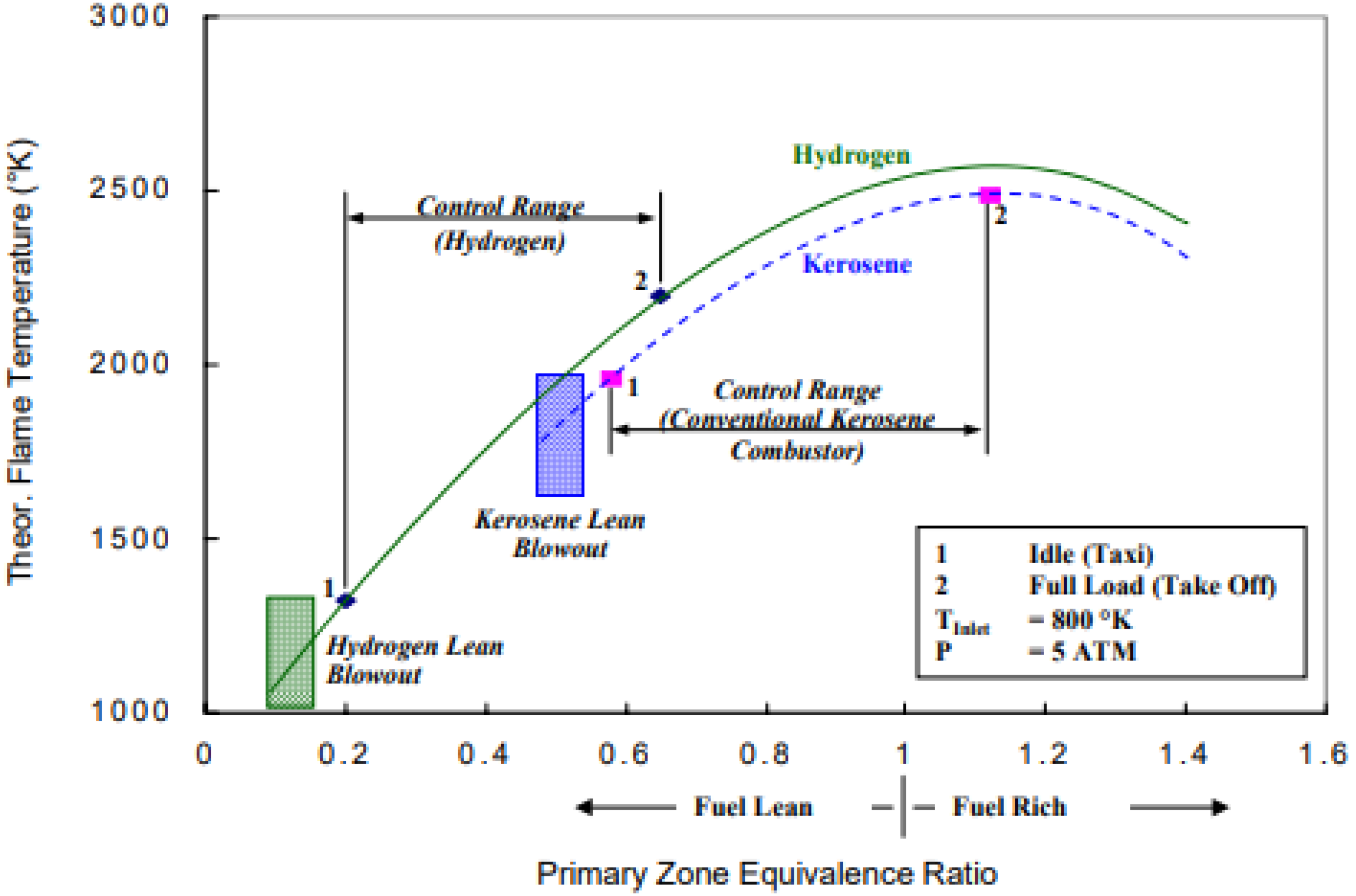
In GT - Effect on turbomachinery

Compared to natural gas, **hydrogen combustion leads to a lower mass flow rate and to a different composition of the product gases**, with an higher water content that in turn influences the molecular weight and the specific heat of the mixture. The most relevant effects on the operation of a gas turbine are:

- a variation of the **enthalpy drop** in the expansion,
- a variation of the **flow rate** at the turbine inlet which, in turn, affects the turbine/compressor matching,
- a variation of the **heat-transfer** coefficient on the outer side of the turbine blades, affecting the **cooling** system performance.

https://doi.org/10.1115/1.1787513

In GT - Temperature



https://doi.org/10.3390/app11093873

Tupolev TU-155


КОМПОНОВКА
ЭКСПЕРИМЕНТАЛЬНОГО САМОЛЕТА ТУ-155

Вариант чистого неба

April 15th 1988

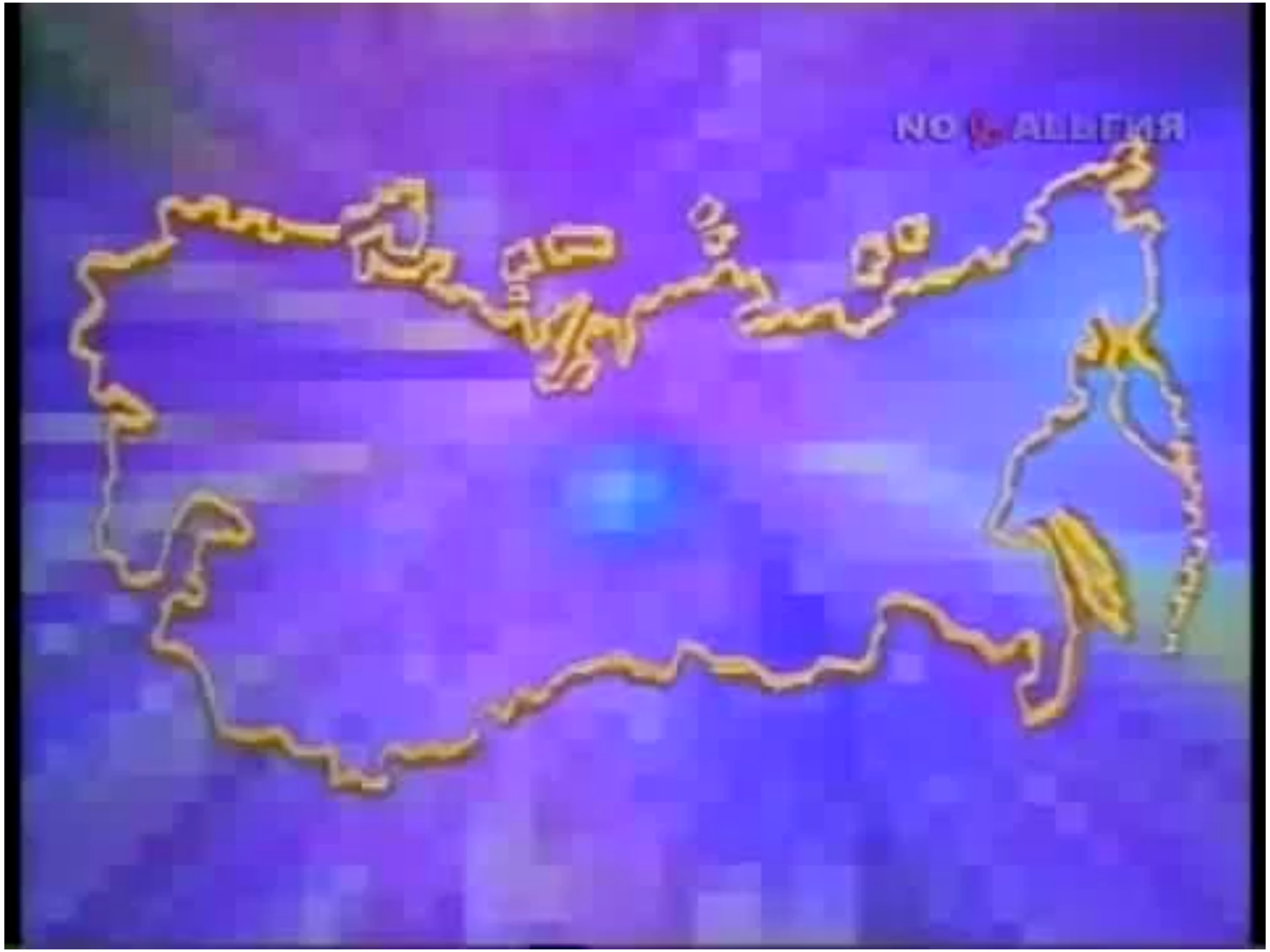
One of the 3 Kuznetsov NK-8 engines ran on H_2 (modified version NK-88)

Production version (Tu-156): 1/3 of the cabin = H_2 tank (cf. photos)

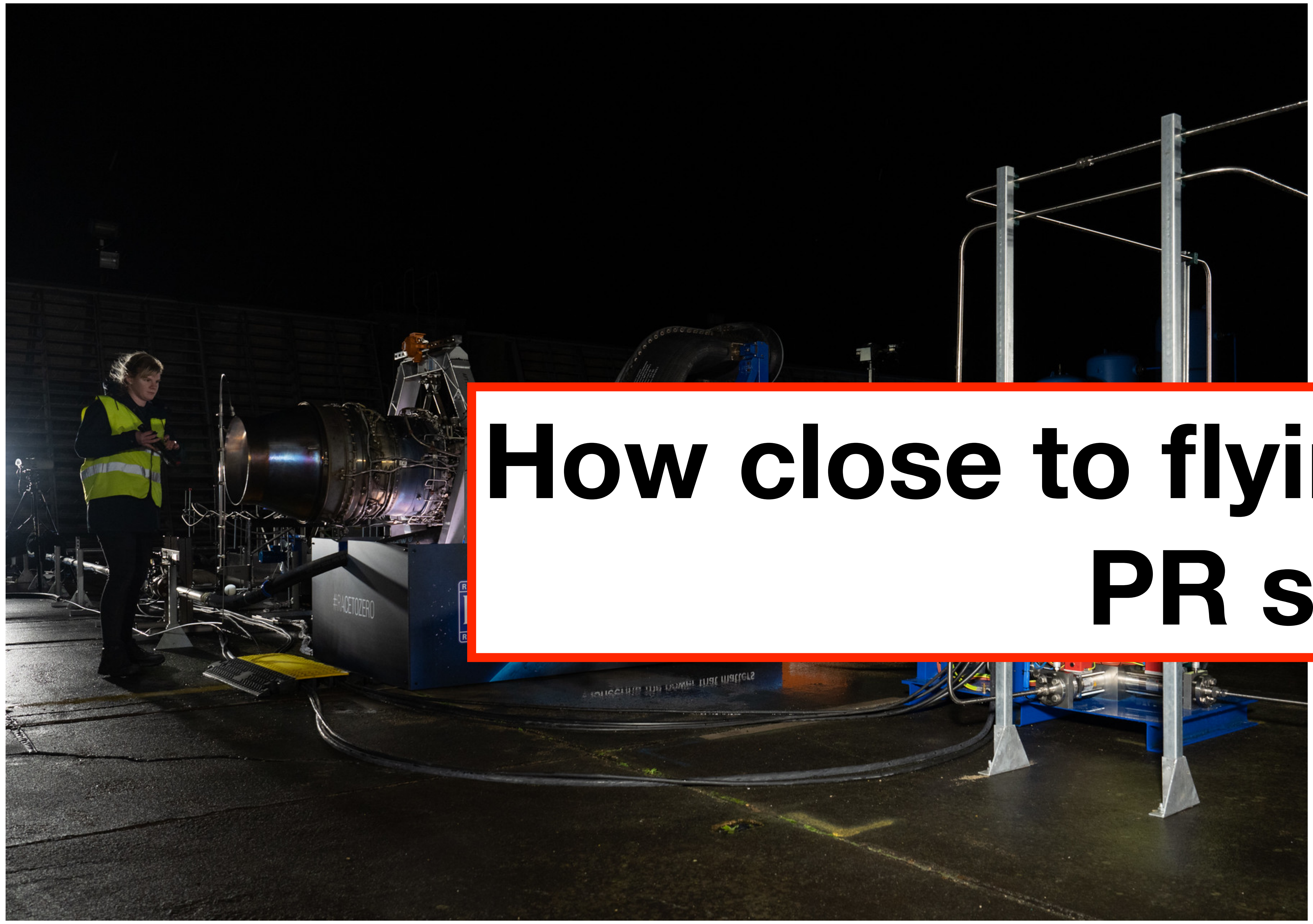
Problem: look where the fuel was stored (cf. video)

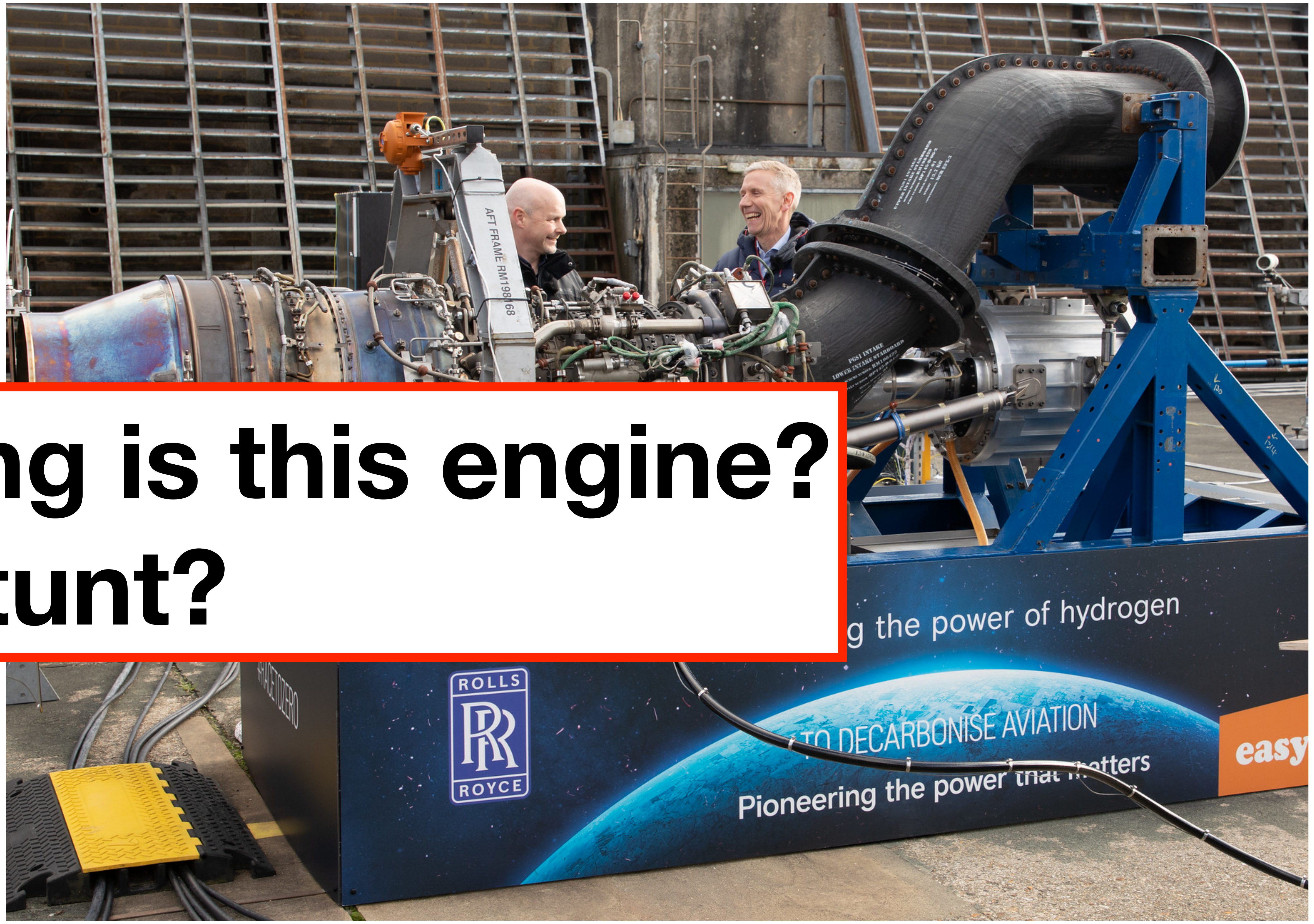
http://blog.privatejetfinder.com/tu-155-hydrogen/

Tupolev TU-155



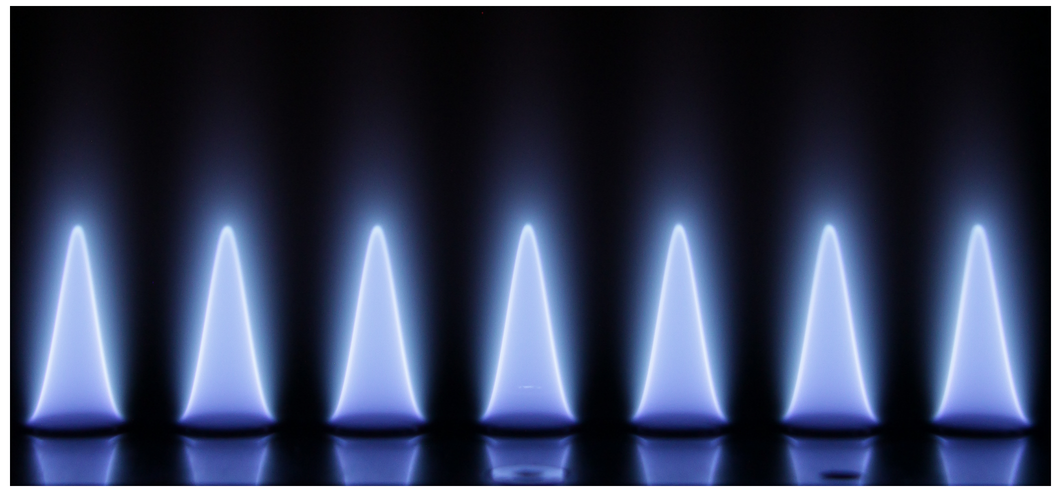
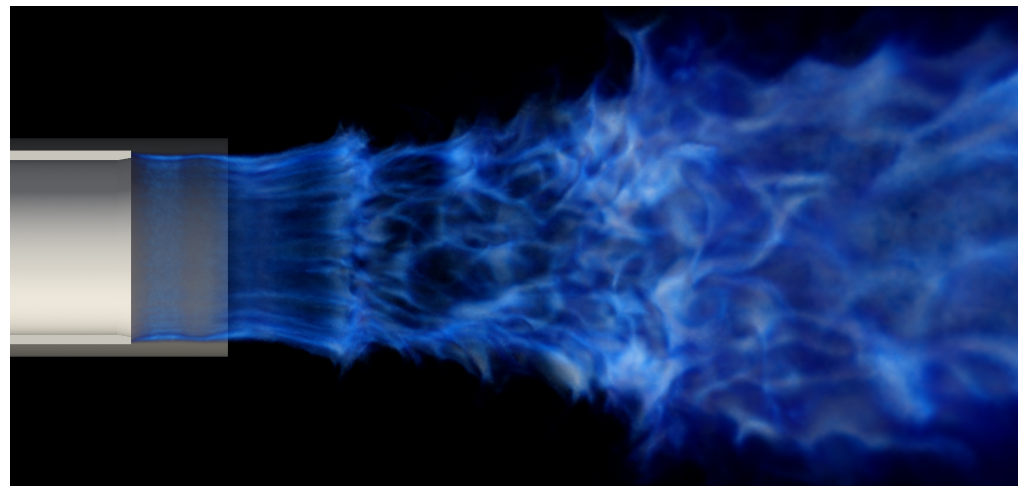
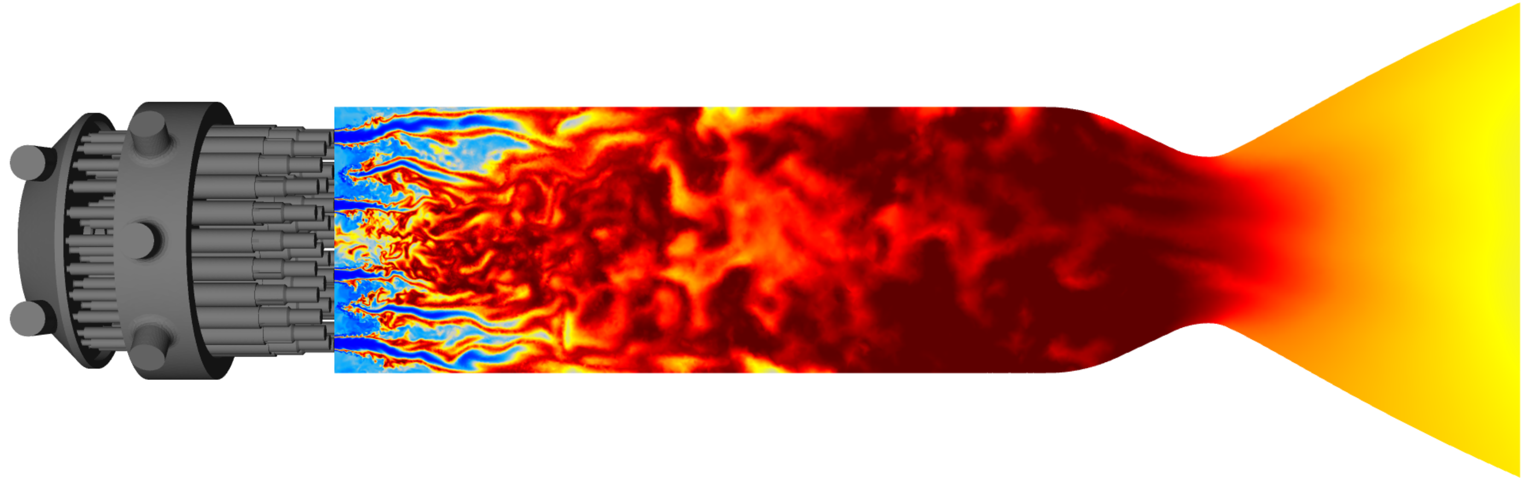
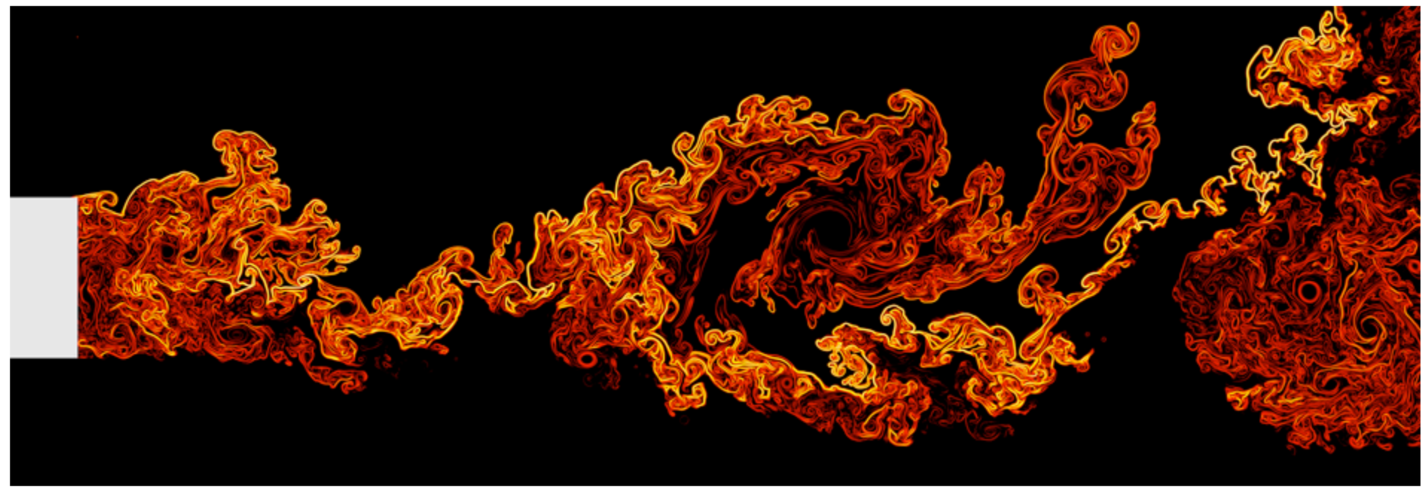
Rolls-Royce and EasyJet





How close to flying is this engine?
PR stunt?

https://www.rolls-royce.com/media/press-releases/2022/28-11-2022-rr-and-easyjet-set-new-aviation-world-first-with-successful-hydrogen-engine-run.aspx

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