Hydrogen combustion in gas turbines

Sikke Klein, November, 26th 2021
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TUDelft

Agenda

- Hydrogen FOR gas turbine applications
- Hydrogen IN gas turbine applications
- Flashback theory and observations
- Flashback modeling
- Application for hydrogen in gas turbines
- Conclusions and next steps
- Questions

Hydrogen FOR gas turbine applications

Why Hydrogen in gas turbines ?

H_2

~~CO_2~~

Green hydrogen : no CO_2

Why hydrogen in gas turbines ?

H_2

- ☐ Transport/Aviation
  - ☐ liquidH_2 : 10 MJ/l   Kerosene: 33 MJ/l
  - ☐ liquidH_2 : 145 MJ/kg   Kerosene: 45 MJ/kg
  - ☐ No infrastructure for cryogenic liquid H2

?√

- ☐ Baseload Combined heat and power
  - ☐ Overall efficiency losses: power => H_2 => CHP
  - ☐ Baseload operation => high impact of losses

??

- ☐ Balancing power
  - ☐ Round trip efficiency: “only” 40%
  - ☐ Retrofit potential => low costs
  - ☐ High H_2 to power efficiency: 55-60%

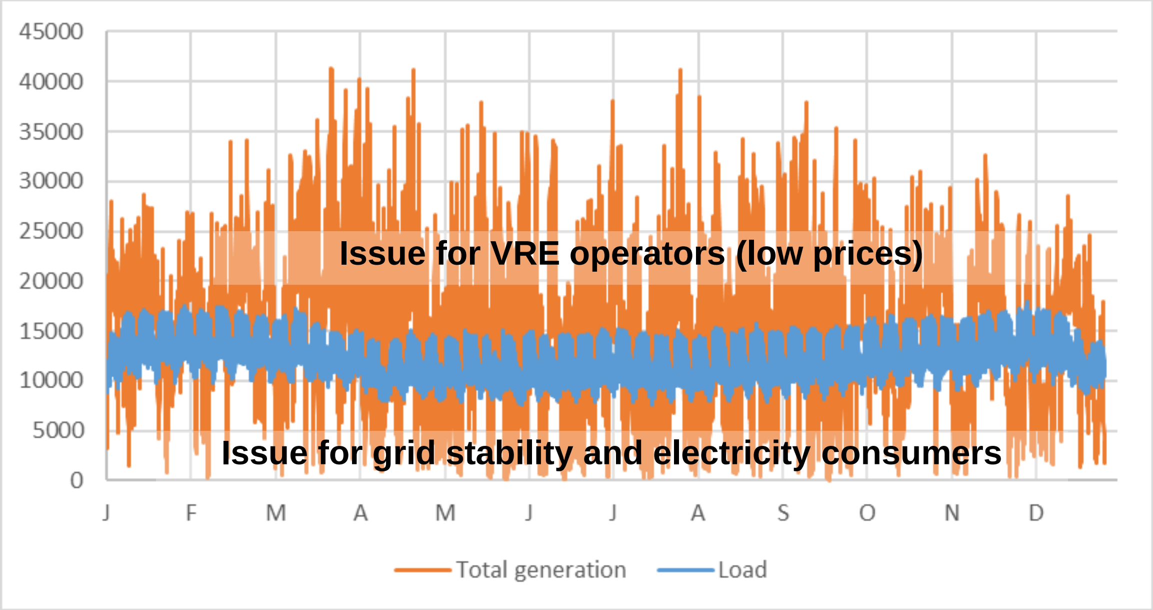
√?

For all cases: current availability of green hydrogen is zero to very limited

Electricity supply : Assume a fossil free electricity system ….

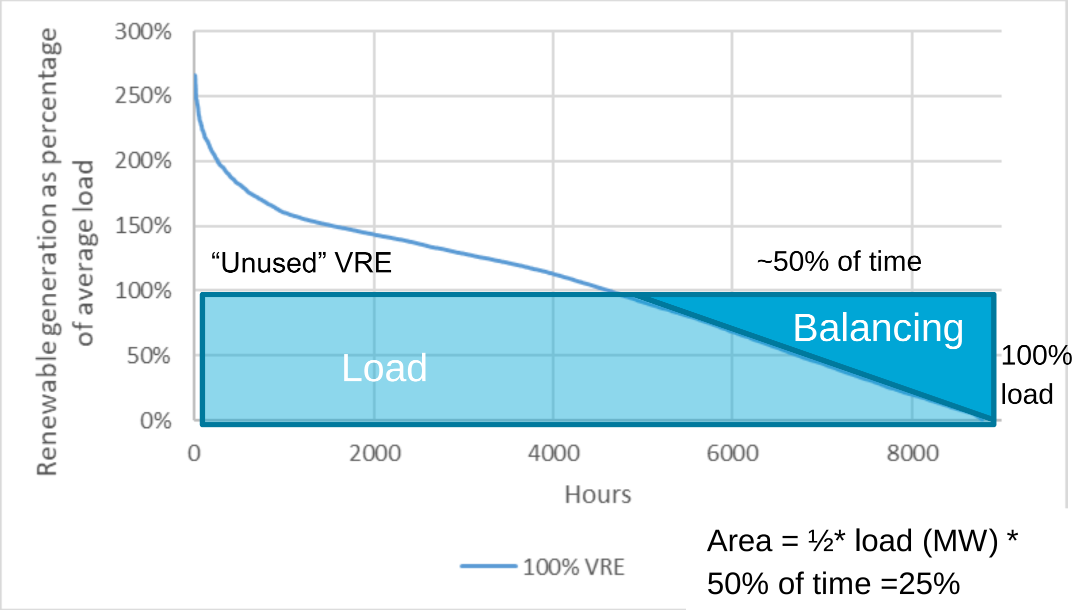
- Generation by Variable Renewable Energy (VRE): solar, wind on shore and wind off shore

- Balancing of supply and demand required: about 25% of the non flexible load



Issue for VRE operators (low prices)

Issue for grid stability and electricity consumers



“Unused” VRE

~50% of time

Load

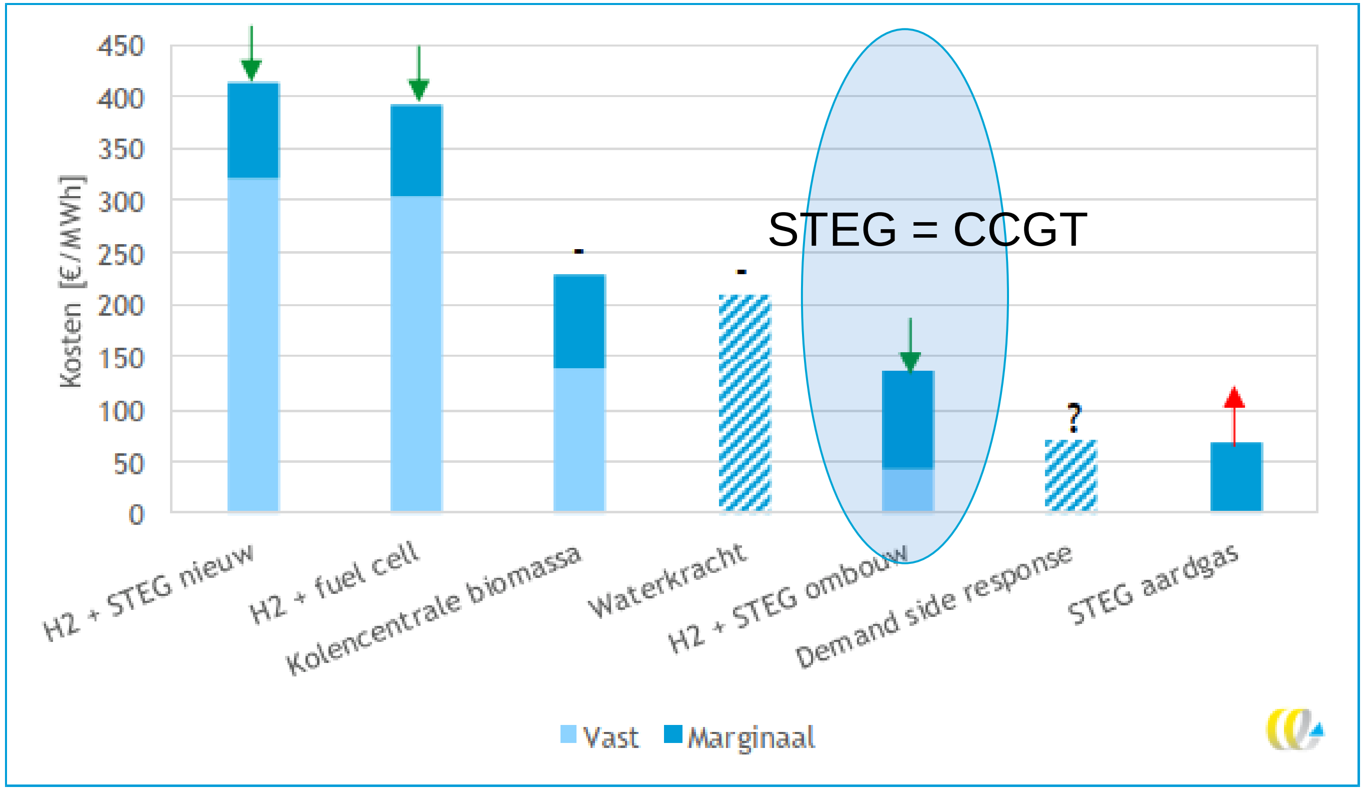
Balancing

100% load

Area = ½* load (MW) * 50% of time =25%

2020 CE Delft Study shows that H_2 in **retrofit** gas turbine power plant is attractive for balancing

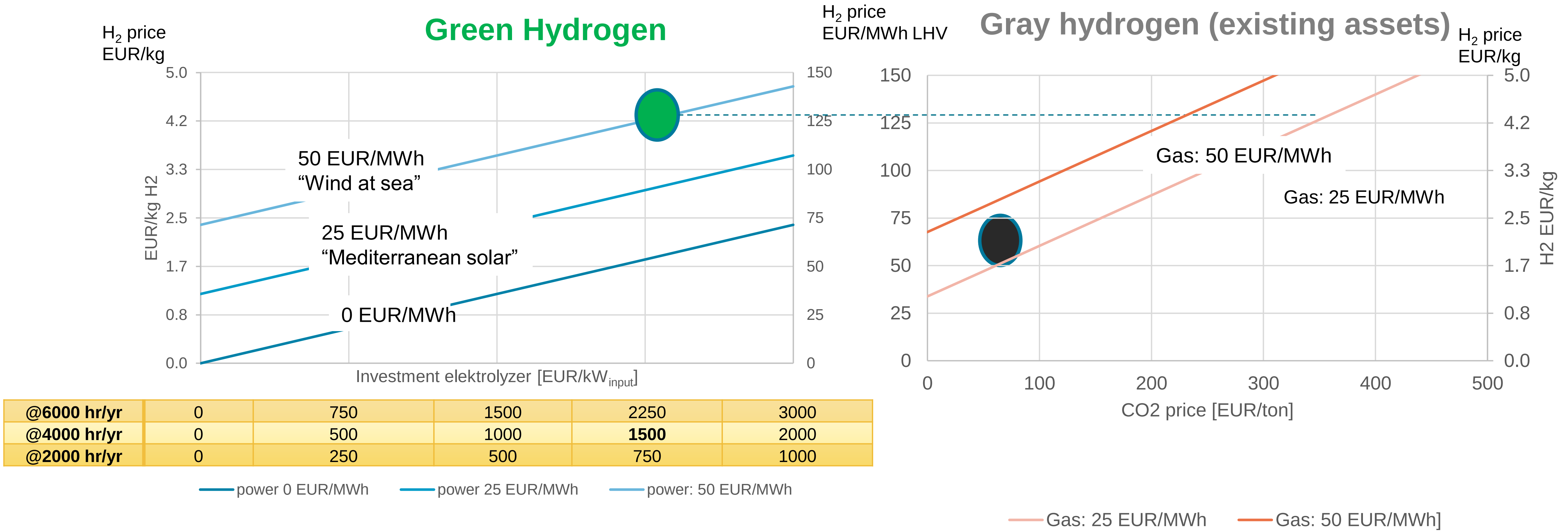
Figuur 5 - Marginale en vaste kosten in 2030 van technieken om tekorten aan te vullen



STEG = CCGT

CE Delft, Verkenning ontwikkeling CO2-vrije flexibele energietechnieken, Publicatienummer: 20.190402.041 , 2020

Hydrogen is however not cheap



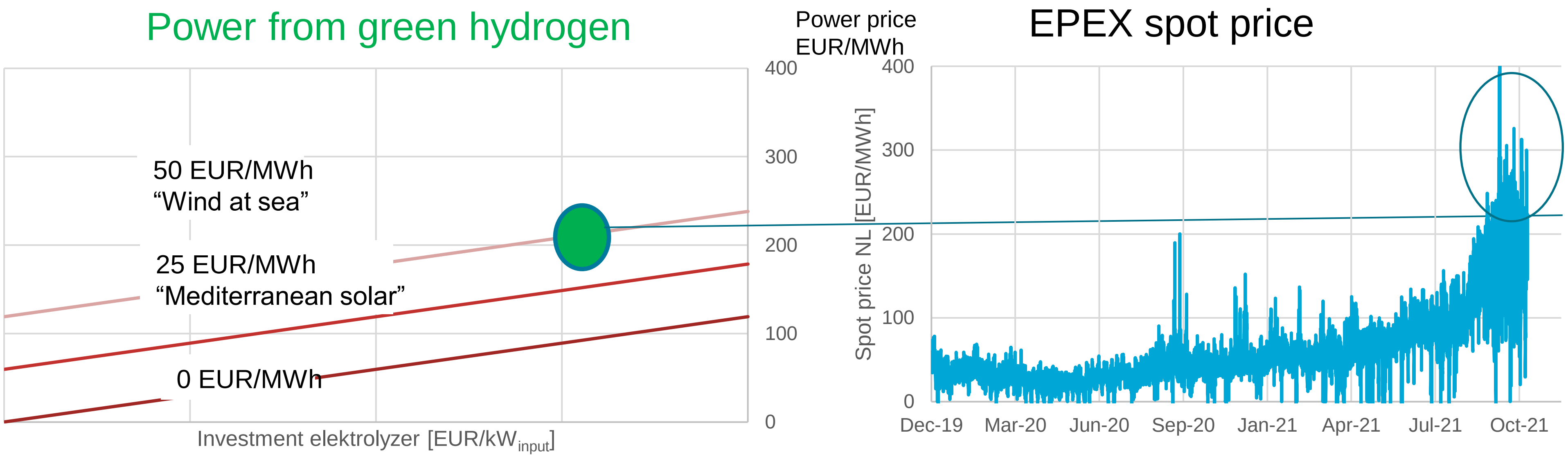
@6000 hr/yr	0	750	1500	2250	3000
@4000 hr/yr	0	500	1000	**1500**	2000
@2000 hr/yr	0	250	500	750	1000

Green H$_2$: investment, annual operational hours & costs of renewable power

Gray H$_2$: gas & CO$_2$

Simplified business cases: Green H$_2$: annual costs : 10% of CAPEX + average power costs (70% LHV efficiency)
Gray H$_2$: only commodity gas & CO$_2$ (81% LHV efficiency)
Both cases: transport & storage excluded

Power from hydrogen is even more expensive



@6000 hr/yr	0	750	1500	2250	3000
@4000 hr/yr	0	500	1000	1500	2000
@2000 hr/yr	0	250	500	750	1000

Current (extreme) price levels could match hydrogen based power

60% H_2 to power conversion

Why Hydrogen for gas turbine applications ?

- CO_2 reduction
- Challenges Green Hydrogen:
  - Availability
  - Price level
  - Intermittency of generation (coupled to wind/solar) => storage
  - Efficiency losses in value chain
- Potential sources:
  - Regional production & storage
  - Import
  - ……

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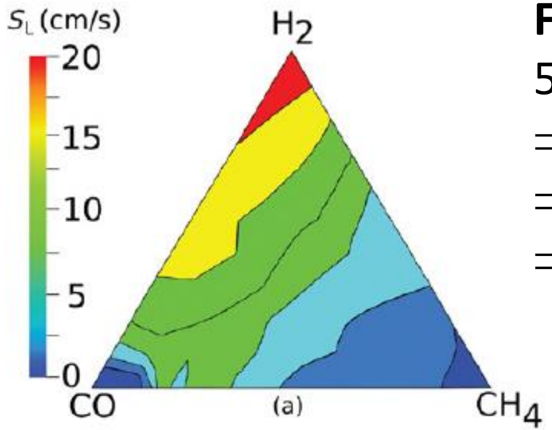
Hydrogen IN gas turbine applications

Challenges for hydrogen in gas turbines: flash back, emissions (NOx), dynamics and leakages

Flashback



Flame speed

5-10x natural gas

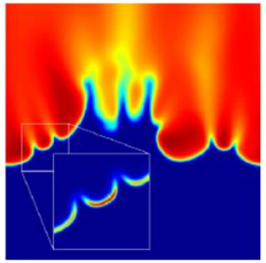
- ⇒ Burner flash back
- ⇒ Stability
- ⇒ Dynamics

Lewis number << 1

H_2 diffusivity >> thermal diffusivity

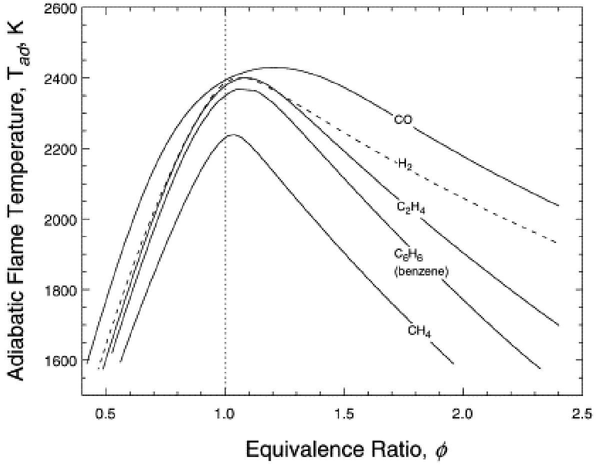
- ⇒ Increased flame speed at lean conditions
- ⇒ Stability, dynamics

Diffusivity



(*)

NOx



Stoich. Flame temperature:

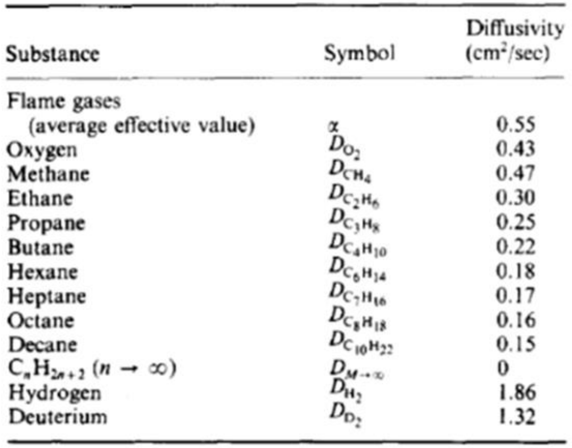
400K above natural gas

=> High NOx with non-premixed combustion

Diffusivity

3-4x higher than natural

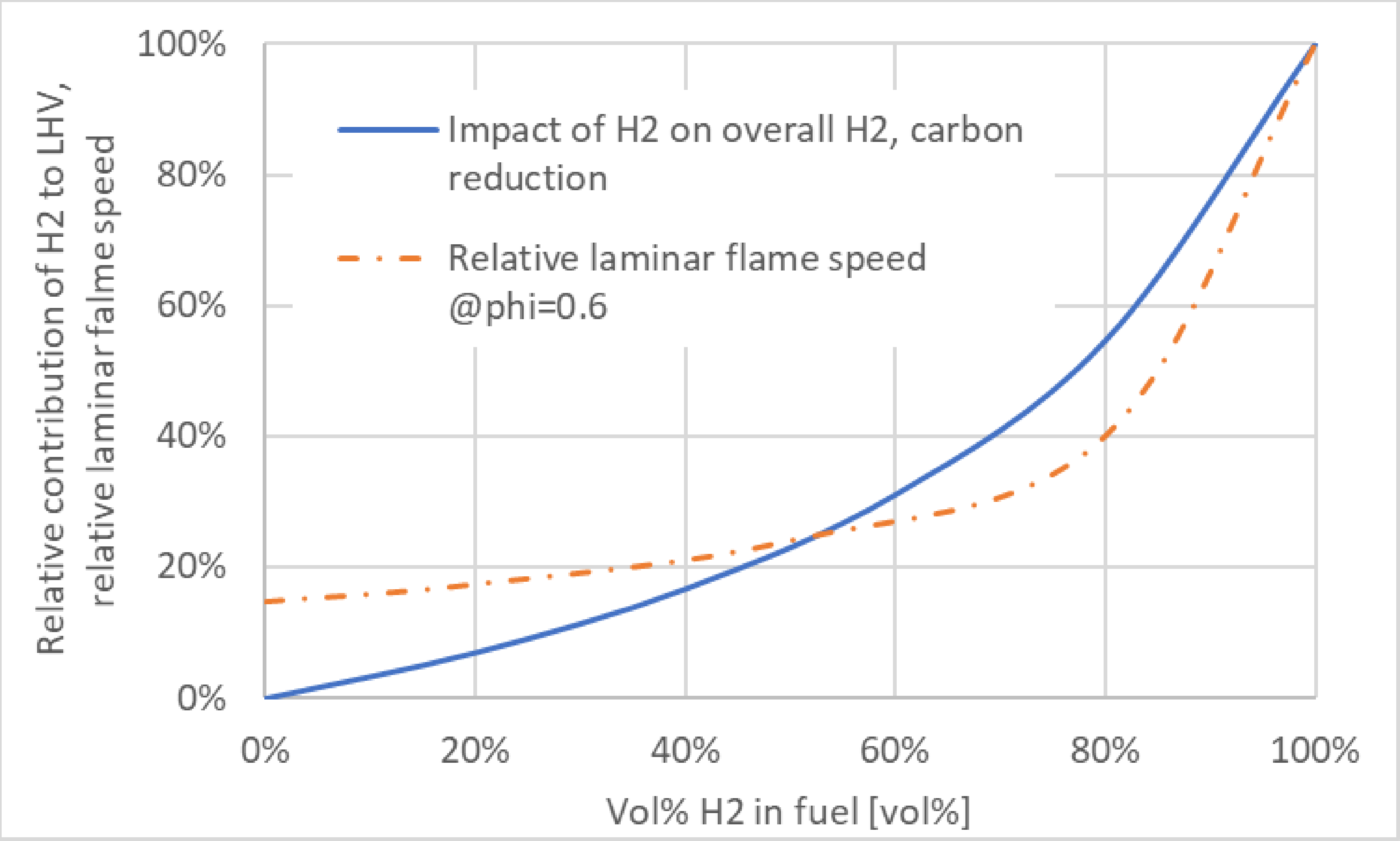
- ⇒ Leakages valves and supply
- ⇒ Preferential diffusion



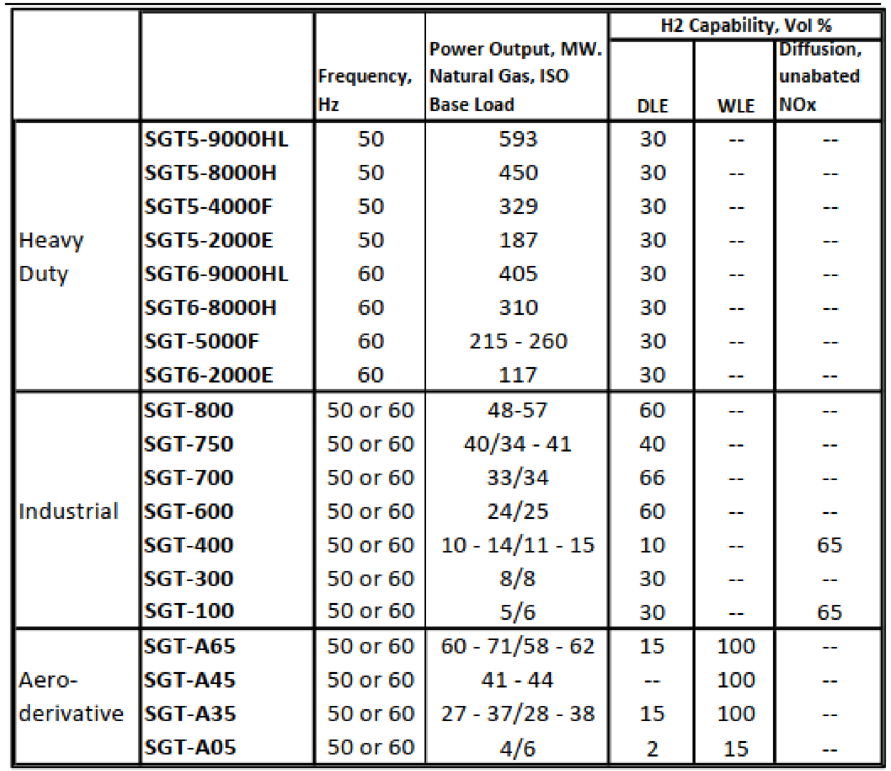
Substance	Symbol	Diffusivity (cm²/sec)
Flame gases (average effective value)	α	0.55
Oxygen	D_{O_2}	0.43
Methane	D_{CH_4}	0.47
Ethane	$D_{C_2H_6}$	0.30
Propane	$D_{C_3H_8}$	0.25
Butane	$D_{C_4H_{10}}$	0.22
Hexane	$D_{C_6H_{14}}$	0.18
Heptane	$D_{C_7H_{16}}$	0.17
Octane	$D_{C_8H_{18}}$	0.16
Decane	$D_{C_{10}H_{22}}$	0.15
C_nH_{2n+2} $(n \to \infty)$	$D_{M \to \infty}$	0
Hydrogen	D_{H_2}	1.86
Deuterium	D_{D_2}	1.32

(*) Why hydrogen flames are different: Effects of preferential diffusion on dynamics and stabilization
Prof. Jeroen van Oijen. WEBINAR DUTCH SECTION OF THE COMBUSTION INSTITUTE, SEPTEMBER 24, 2021

Main impact for hydrogen at higher volume percentages



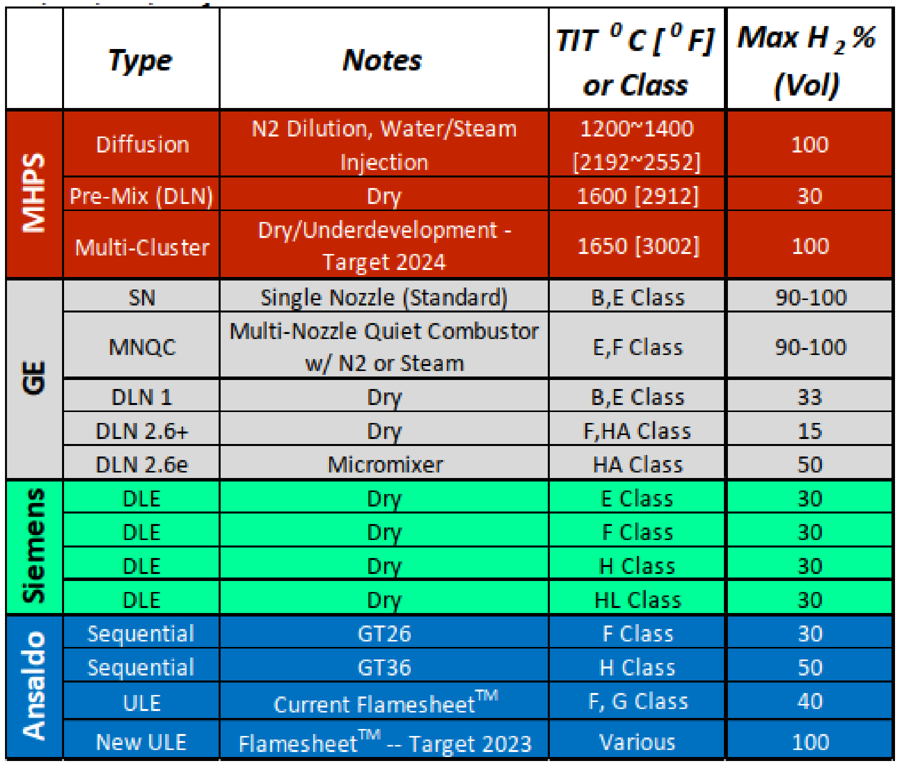
Advertised maximum H_2 vol% for different gas turbine suppliers



		Frequency, Hz	Power Output, MW. Natural Gas, ISO Base Load	H2 Capability, Vol %		
				DLE	WLE	Diffusion, unabated NOx
Heavy Duty	**SGT5-9000HL**	50	593	30	--	--
	SGT5-8000H	50	450	30	--	--
	SGT5-4000F	50	329	30	--	--
	SGT5-2000E	50	187	30	--	--
	SGT6-9000HL	60	405	30	--	--
	SGT6-8000H	60	310	30	--	--
	SGT-5000F	60	215 - 260	30	--	--
	SGT6-2000E	60	117	30	--	--
Industrial	**SGT-800**	50 or 60	48-57	60	--	--
	SGT-750	50 or 60	40/34 - 41	40	--	--
	SGT-700	50 or 60	33/34	66	--	--
	SGT-600	50 or 60	24/25	60	--	--
	SGT-400	50 or 60	10 - 14/11 - 15	10	--	65
	SGT-300	50 or 60	8/8	30	--	--
	SGT-100	50 or 60	5/6	30	--	65
Aero-derivative	**SGT-A65**	50 or 60	60 - 71/58 - 62	15	100	--
	SGT-A45	50 or 60	41 - 44	--	100	--
	SGT-A35	50 or 60	27 - 37/28 - 38	15	100	--
	SGT-A05	50 or 60	4/6	2	15	--

Siemens "Hydrogen Combustion in Siemens Gas

Turbines: Sales Information v 3.0," July 2019



	Type	***Notes***	***TIT ^{0}C [^{0}F] or Class***	***Max H_2% (Vol)***
MHPS	Diffusion	N2 Dilution, Water/Steam Injection	1200~1400 [2192~2552]	100
	Pre-Mix (DLN)	Dry	1600 [2912]	30
	Multi-Cluster	Dry/Underdevelopment - Target 2024	1650 [3002]	100
GE	SN	Single Nozzle (Standard)	B,E Class	90-100
	MNQC	Multi-Nozzle Quiet Combustor w/ N2 or Steam	E,F Class	90-100
	DLN 1	Dry	B,E Class	33
	DLN 2.6+	Dry	F,HA Class	15
	DLN 2.6e	Micromixer	HA Class	50
Siemens	DLE	Dry	E Class	30
	DLE	Dry	F Class	30
	DLE	Dry	H Class	30
	DLE	Dry	HL Class	30
Ansaldo	Sequential	GT26	F Class	30
	Sequential	GT36	H Class	50
	ULE	Current Flamesheet^{TM}	F, G Class	40
	New ULE	Flamesheet^{TM} -- Target 2023	Various	100

Emerson, B.E. et al., "Assessment of Current Capabilities and Near-Term Availability of Hydrogen-Fired Gas

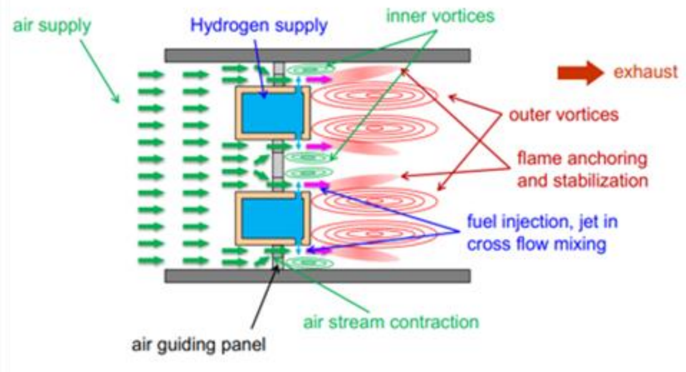
Turbines Considering a Low-Carbon Future", GT2020-15714

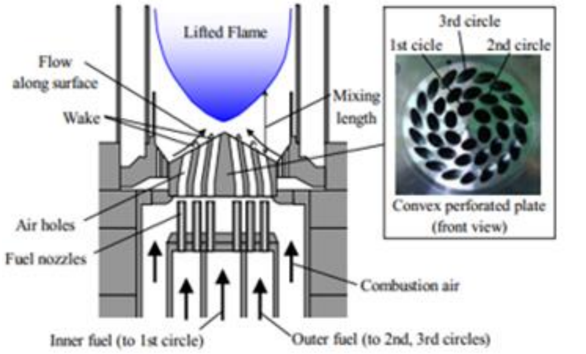
TU Delft

Combustor designs under development for high hydrogen gas turbines

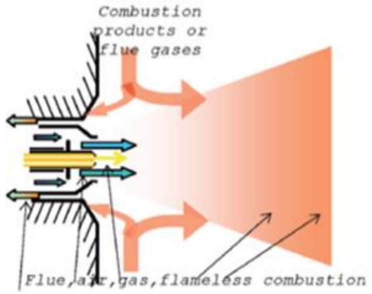
Non premixed combustion => high NOx

(reduction of NOx: flame temperature/residence time)





MicroMixing - Small diffusion flames

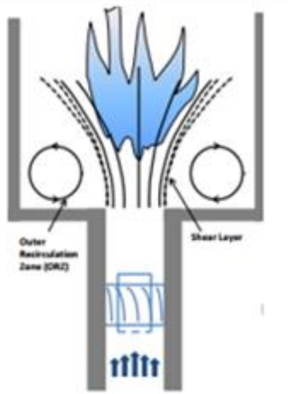


FLOX

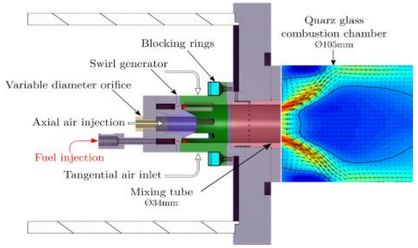
Steam injection

Premixed combustion => low NOx

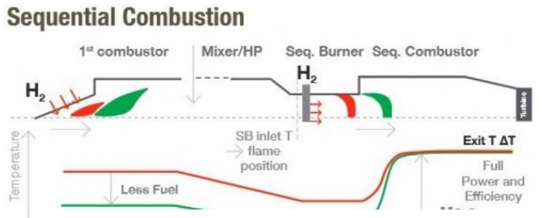
(flashback prevention)



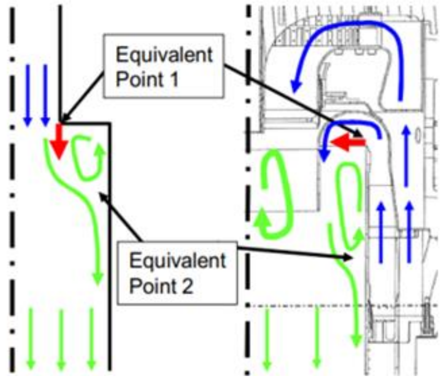
Low Swirl



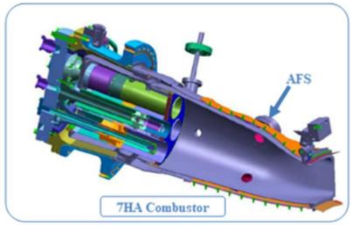
High swirl + axial injection



Sequential combustion



Trapped vortex



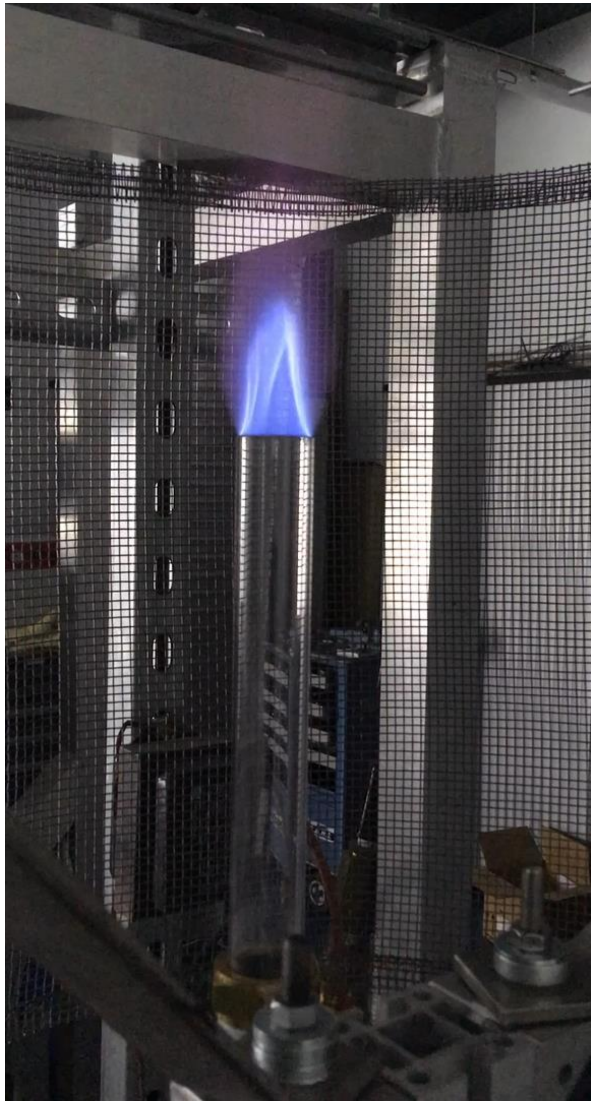
Axial staged combustion

Flashback Theory and Observations

What is Flashback?

Upstream propagation of the flame into the burner, leading to e.g.:

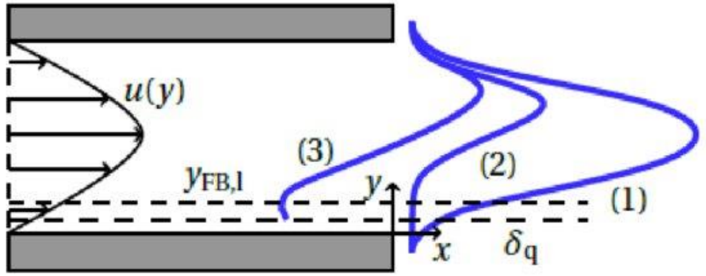
- Local overheating => damage
- Incomplete burning & mixing => emissions, performance etc.
- Shutdown of the engine to prevent (further) damage



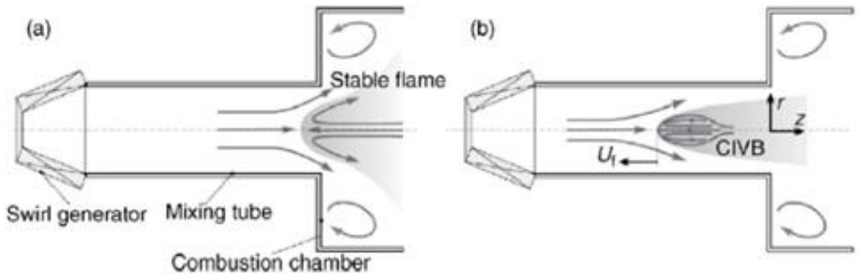
Flashback in premixed flames

Two main types:

1. **Boundary layer flash back**
    a) Unconfined
    b) Confined



2. **Swirling flames:**
   Combustion induced vortex break down

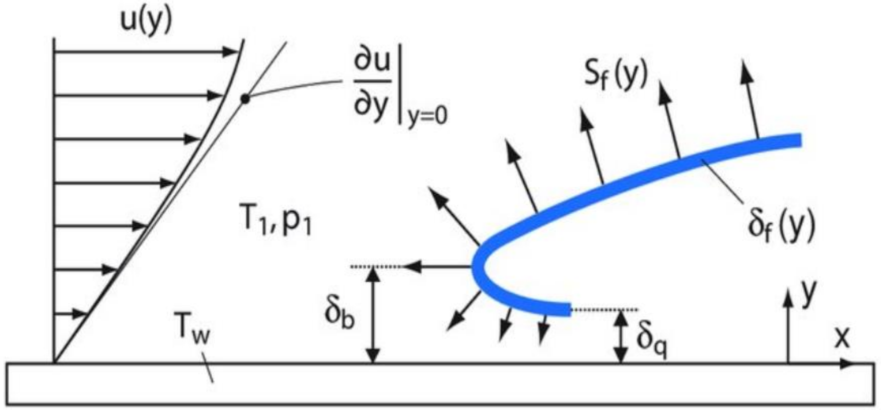


Combustion driven oscillations amplify both cases

Classic flashback theory

- Basis: Lewis and Von Elbe (1943)
- Local velocity in boundary layer below laminar flame speed at penetration distance δ_b :

$$S_L(\delta_b) > u(\delta_b)$$



- δ_b minimum location from wall where flame can persist (penetration depth $\delta_b > \delta_{quench}$)

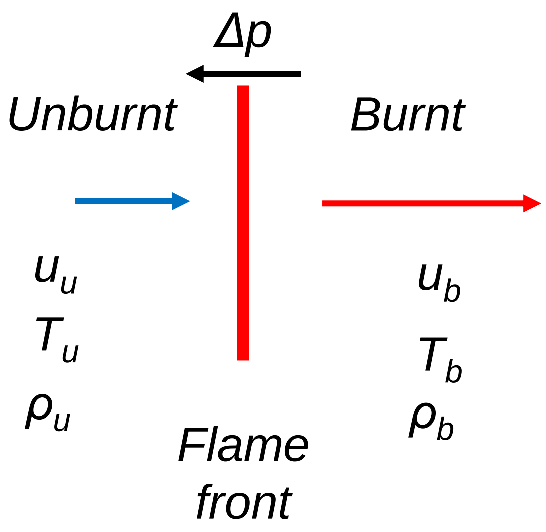
- Critical velocity gradient:
  Flashback when flow velocity (g_f) gradient below critical (g_c):

$$g_f < g_c \longrightarrow \frac{\partial u}{\partial y} < \frac{S_L}{\delta_b}$$

Flame adverse pressure

- Rankine Hugionot conditions across the flame front
- Flow is accelerated in flame front due to expansion/temperature in increase
- Mass conservation: $\rho_u u_u = \rho_b u_b$
- Momentum conservation: $\rho_u u_u^2 + p_u = \rho_b u_b^2 + p_b$
- Pressure jump: $$\Delta p = p_u - p_b = \rho_u u_u^2 \left(\frac{\rho_u}{\rho_b} - 1 \right)$$

$$\Delta p_{flame} = \rho_u S_f^2 \left(\frac{\rho_u}{\rho_b} - 1 \right)$$

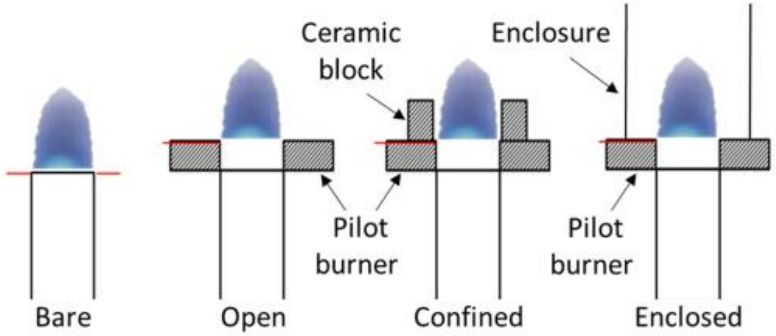


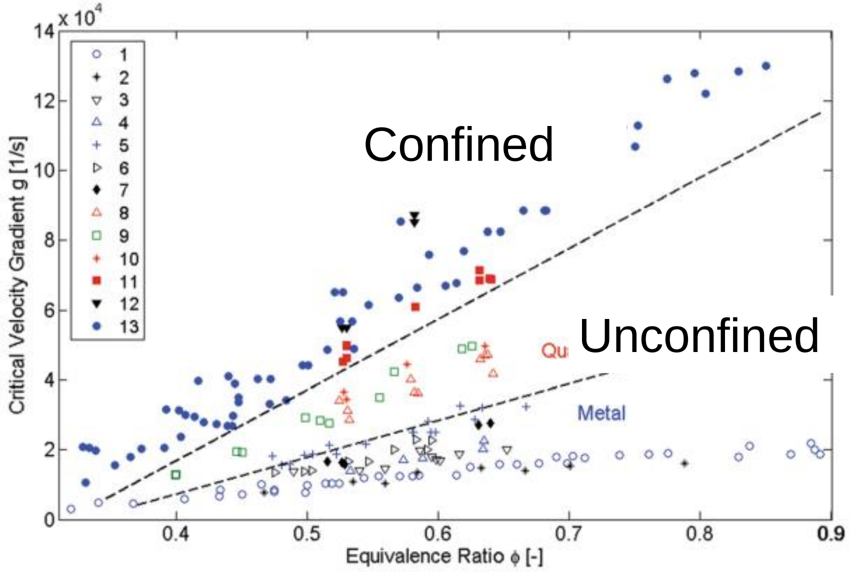
- S_f : Flame speed
- Pressure upstream of flame > down stream of flame => Retardation of incoming flow by flame

TU Delft

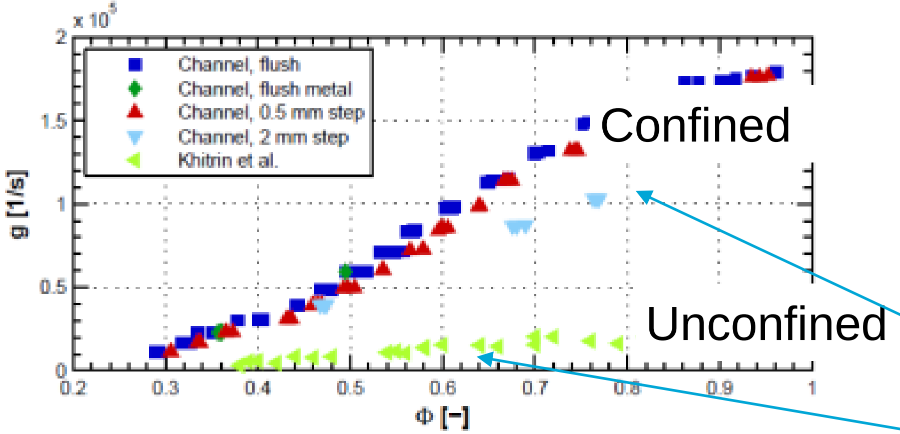
Confined versus unconfined flame

- Confined flames much higher critical velocity gradient
    - “Flashback occurs at lower velocities”
- Effect of flame adverse pressure
    - Unconfined flames: no to little impact on incoming flow in tube
    - Confined flames: adverse pressure creates boundary instability in incoming flow





Baumgartner (2016)



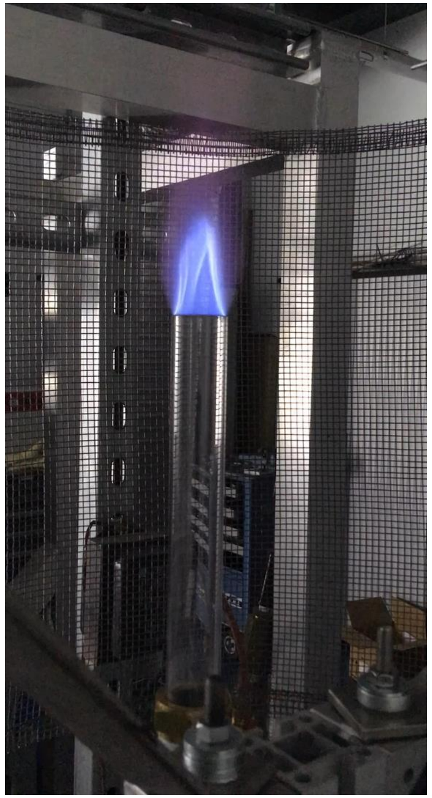
Flashback if $g<g_c$

Eichler (2012)

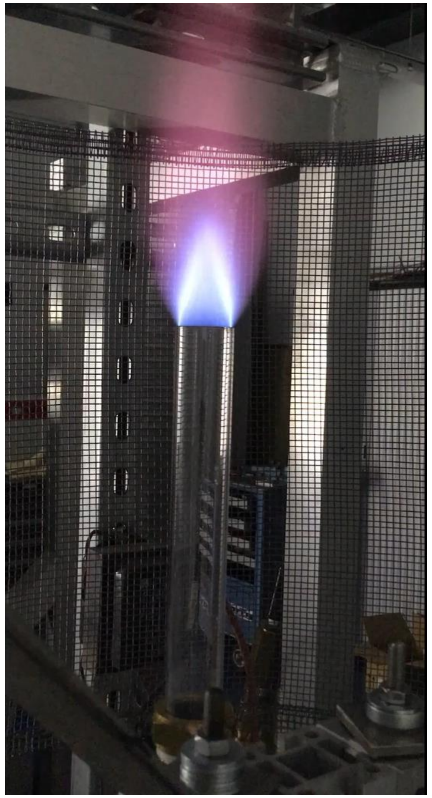
How does flashback look like?

unconfined

confined

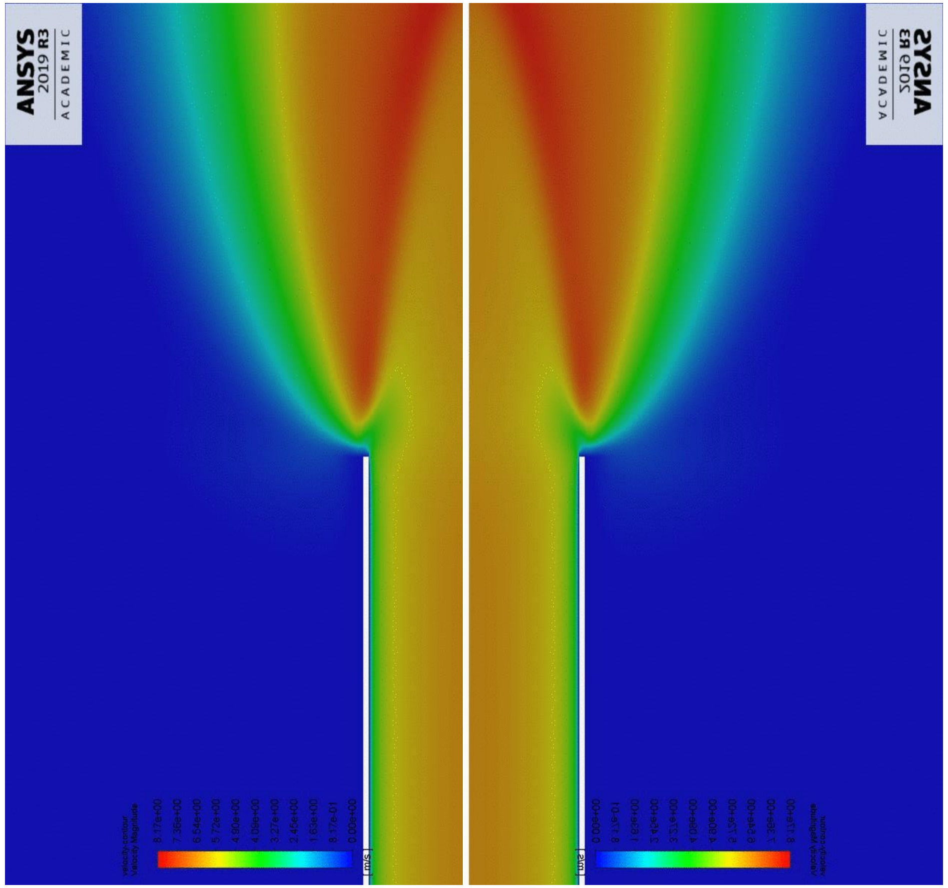


Natural gas



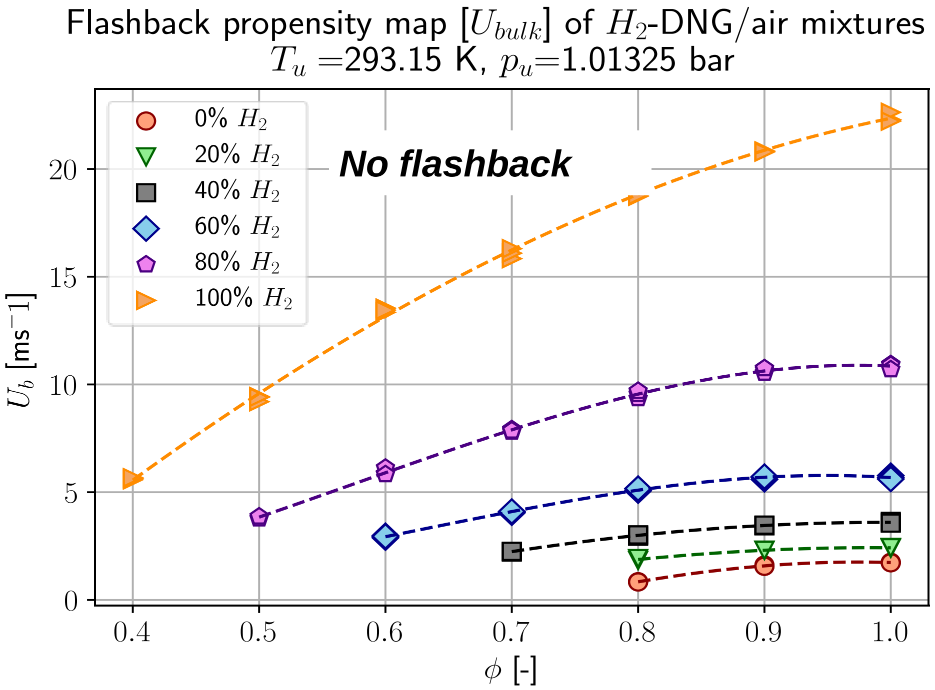
80% Hydrogen

Flame flashback animation

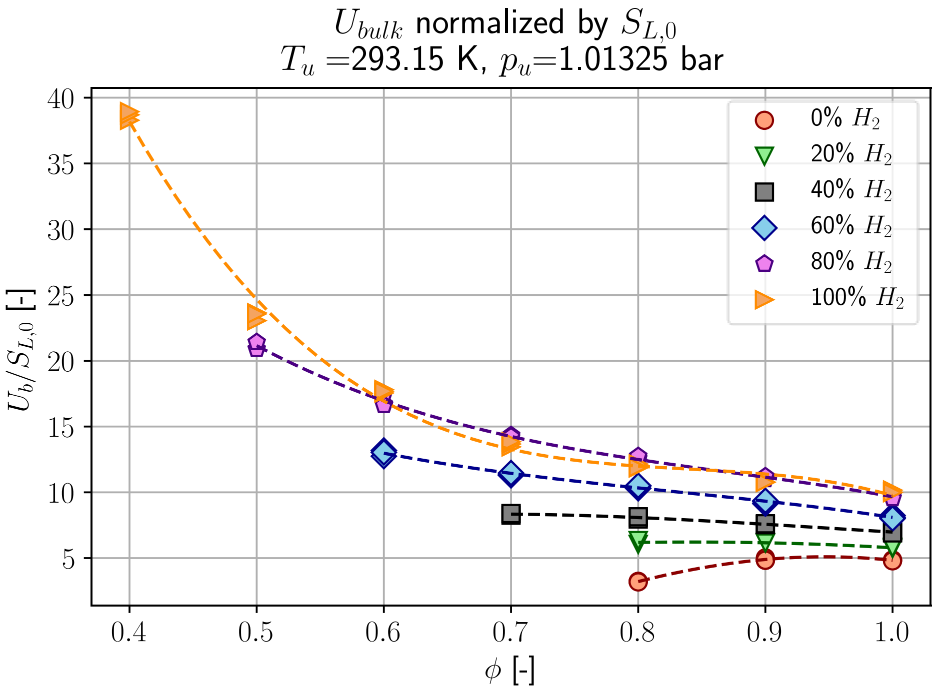


Velocity

Flashback map unconfined flame in TU Delft laboratory



Standard: U_bulk versus equivalence ratio



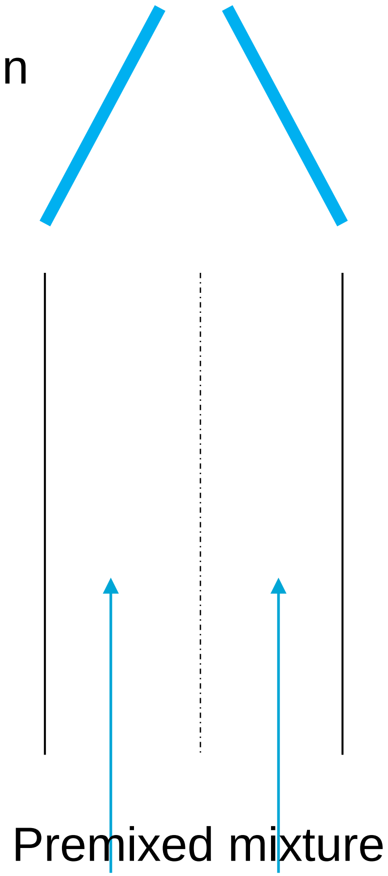
U_bulk normalized with laminar flame speed

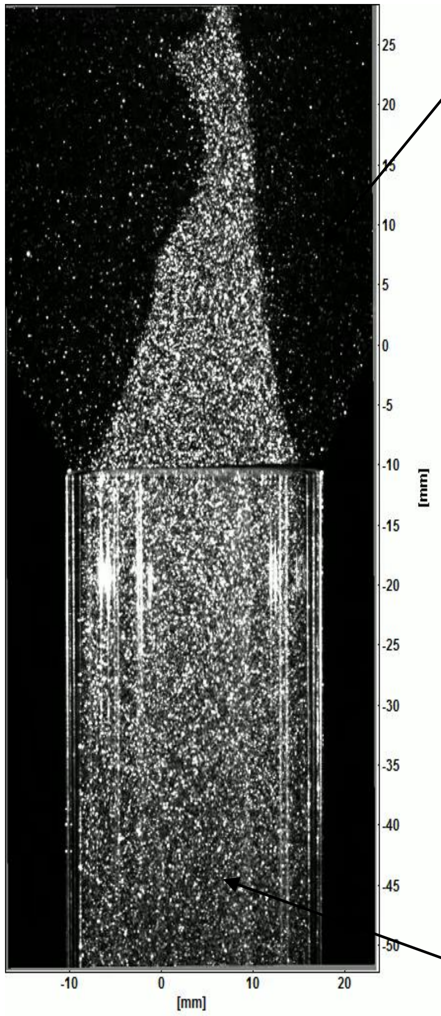
Boundary layer flash back

1. Flame shape modification
(above burner)

2. "Jump into burner"
(*at burner)*

3. Confined flashback
(in burner)





Willems (2021)

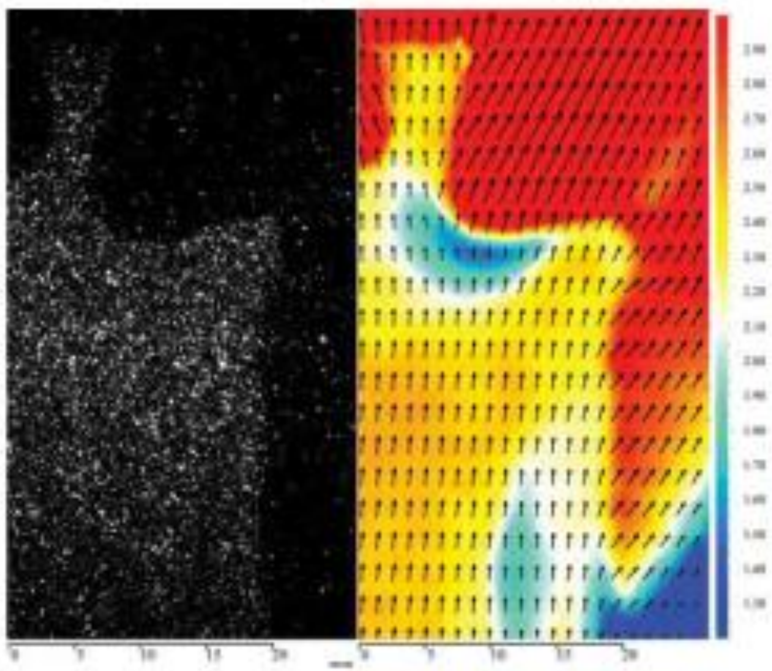
Dark color
- Low seeding density
- High temperature
- Burnt

Experiments:
- Faldella (2020)
- Lambers (2021)
- Willems (in progress)

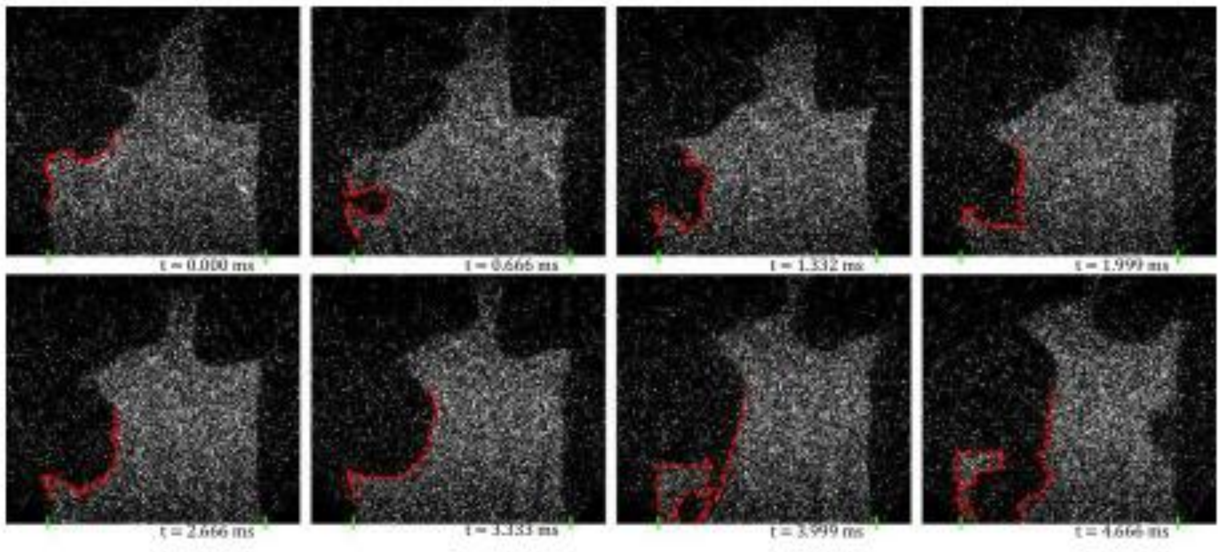
Model development:
- Tober (2018)
- Björnsson (2019)
- Van Put (2021)

White color
- High seeding density
- Low temperature
- Unburnt

Boundary layer flashback: **above burner** (phase 1)



- Cusp formation
- Incoming flow is decelerated by flame front

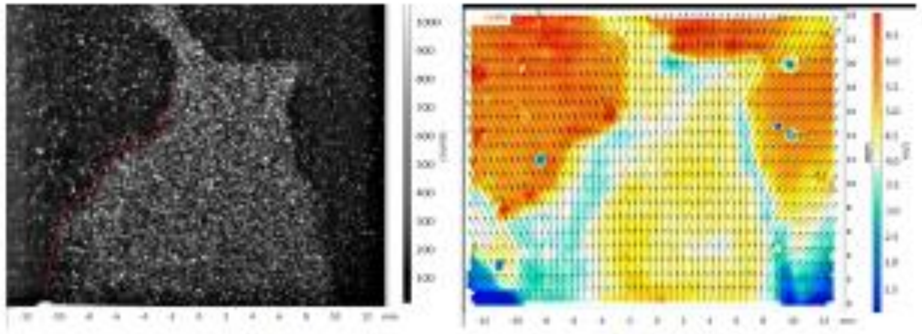


- Flash back sequence for natural gas
- Delta t = 0.666 ms

Faldella (2020)

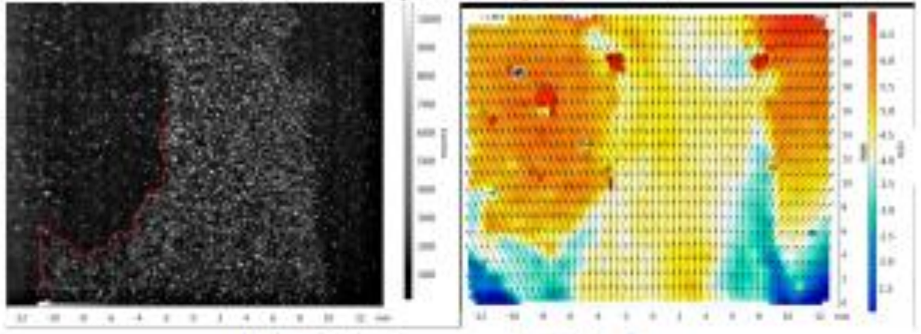
Boundary layer flashback: **above burner** (phase 1)

1



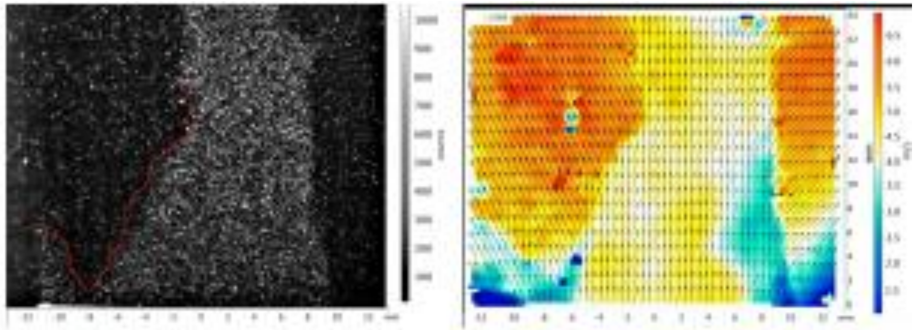
(a) Flashback process step 1, $t = 0$ ms.

2



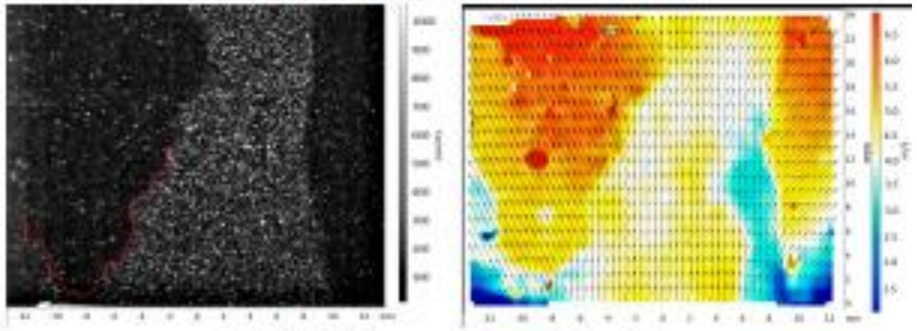
(b) Flashback process step 2, $t = 3$ ms.

3



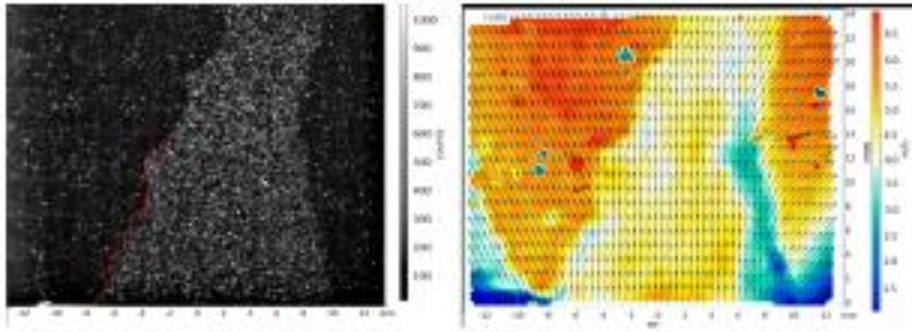
(c) Flashback process step 3, $t = 3.9$ ms.

4



(d) Flashback process step 4, $t = 4.2$ ms.

5



(e) Flashback process step 5, $t = 4.8$ ms.

Lambers (2021)

Adverse gradient increases with flames closer to flashback

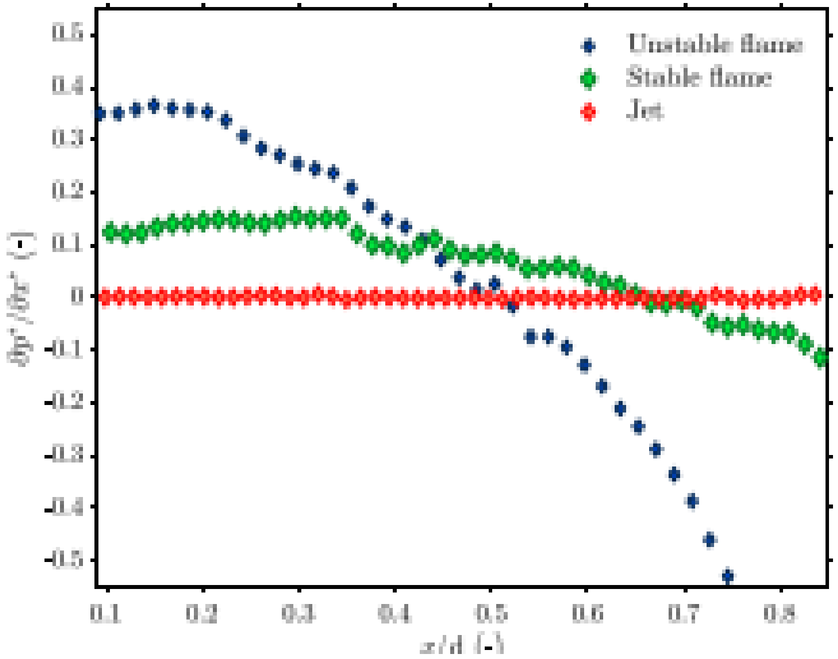
- Averaged Euler equation

$$\frac{\partial \overline{u^*}}{\partial x^*} + \frac{1}{r^*}\frac{\left(\partial r^* \overline{v^*}\right)}{\partial r^*} = 0$$

$$\underbrace{\overline{u^*}\frac{\partial \overline{u^*}}{\partial x^*}}_{\substack{\text{Advection}\\ \text{axial}\\ \text{direction}}} + \underbrace{\overline{v^*}\frac{\partial \overline{u^*}}{\partial r^*}}_{\substack{\text{Advection}\\ \text{radial}\\ \text{direction}}} = -\underbrace{\frac{\partial \overline{p^*}}{\partial x^*}}_{\substack{\text{Pressure}\\ \text{gradient}\\ \text{axial}\\ \text{directon}}} - \underbrace{\frac{\partial \overline{u'^* u'^*}}{\partial x^*}}_{\substack{\text{Reynolds}\\ \text{stress}\\ \text{gradient}\\ \text{axial}\\ \text{direction}}} - \underbrace{\frac{1}{r^*}\frac{\partial\left(r^* \overline{u'^* v'^*}\right)}{\partial x^*}}_{\substack{\text{Reynolds}\\ \text{shear stress}\\ \text{gradient}\\ \text{radial}\\ \text{direction}}}.$$

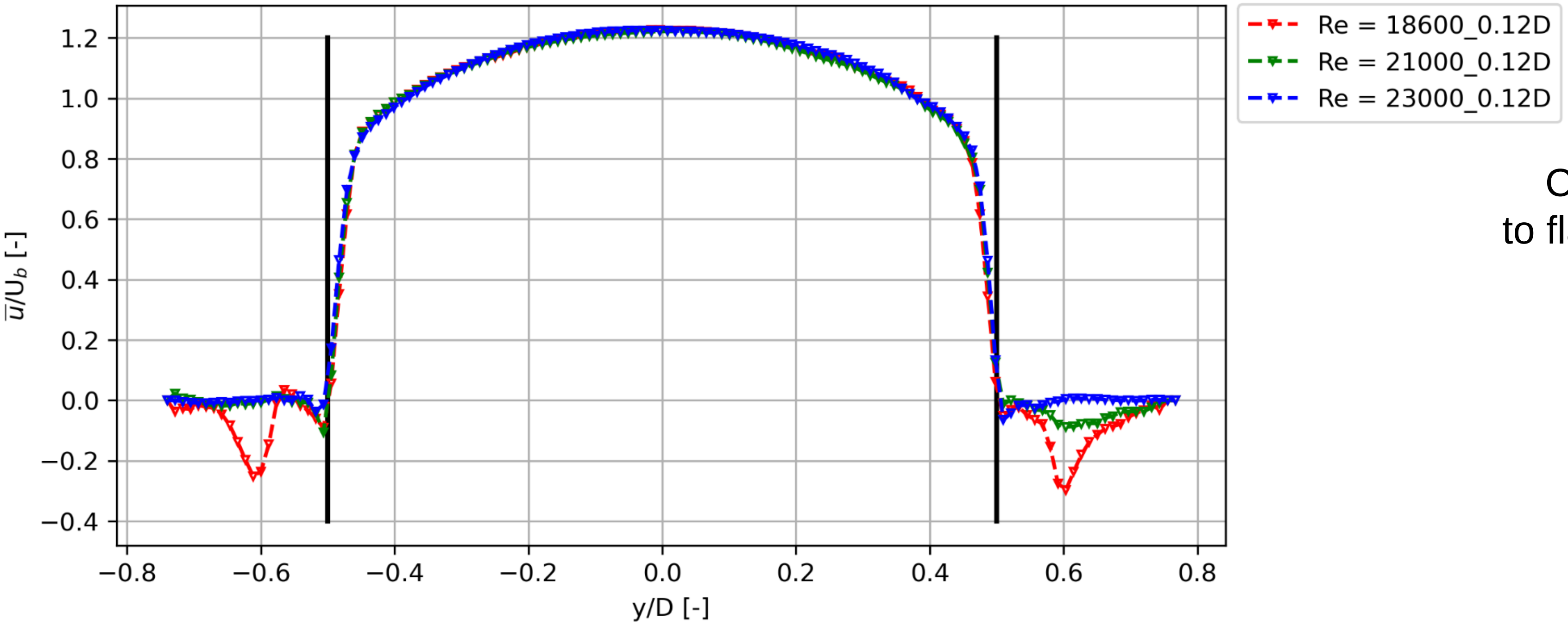
- At central axis simplifies to:

$$\overline{u^*}\frac{\partial \overline{u^*}}{\partial x^*} = -\frac{\partial \overline{p^*}}{\partial x^*} - \frac{\partial \overline{u'^* u'^*}}{\partial x^*} - \frac{\partial \overline{u'^* v'^*}}{\partial r^*}.$$

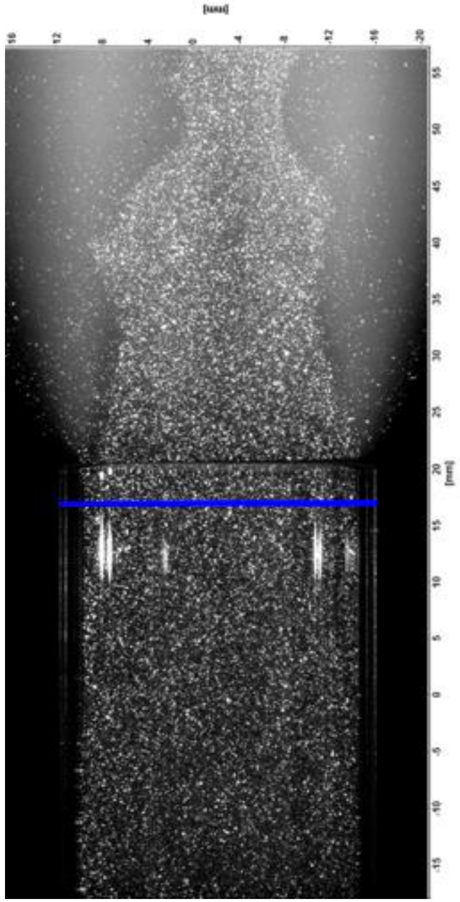


Adverse pressure gradient increases with flame closer to flashback

No influence of flame adverse pressure on incoming flow

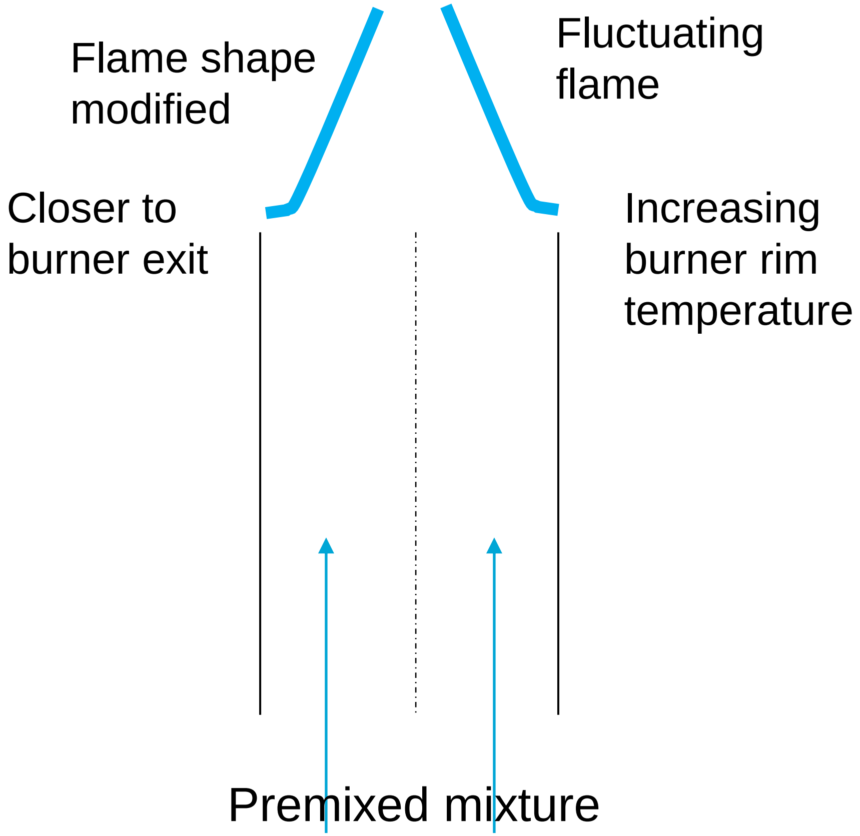


Closer
to flashback

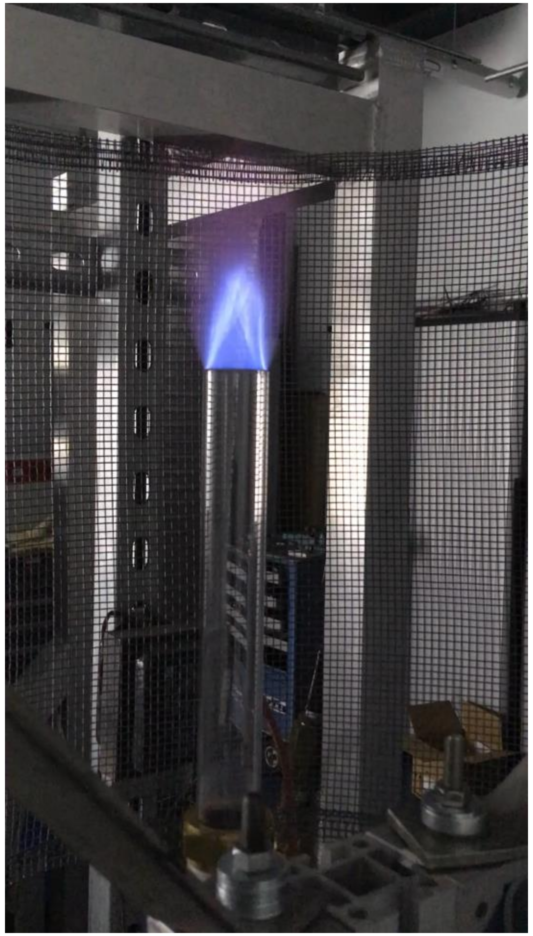


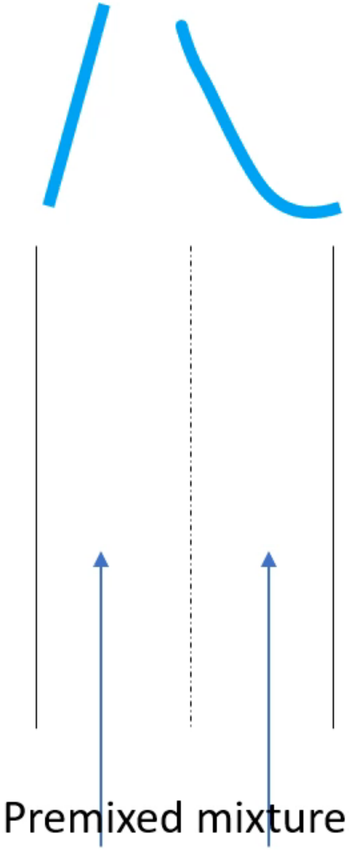
Boundary layer flashback: **at burner** (phase 2)

1. Fluctuating flame
2. Impact of burner rim temperature
3. Impact of turbulent fluctuations
   (~ “Turbulent flame speed effect”)
4. Impact of low velocities streaks



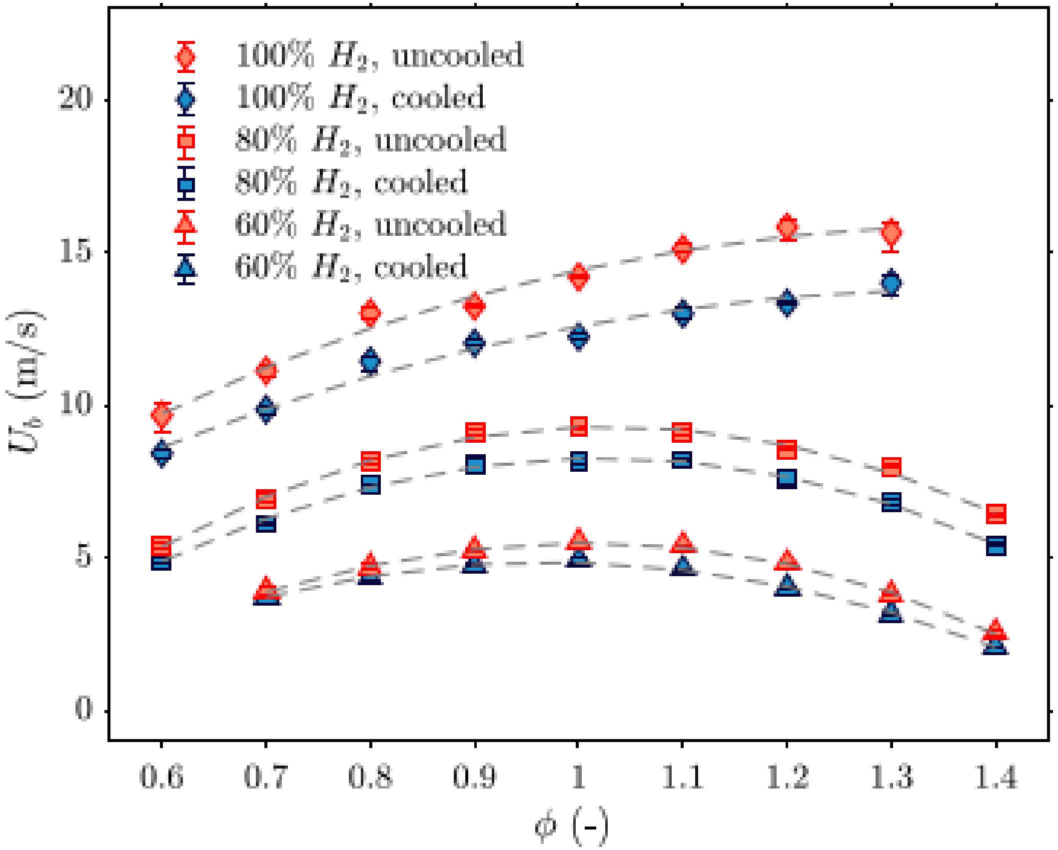
Boundary layer flashback: **at burner** : 1. Fluctuating flame





Boundary layer flashback: **at burner** : 2. Temperature

- Cooling of burner rim decreases minimum back velocity

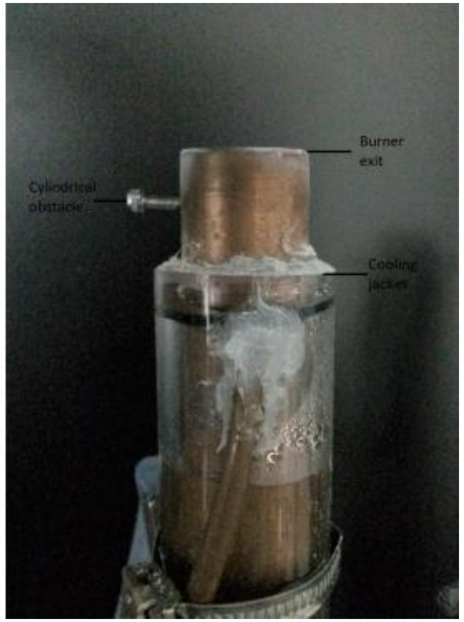


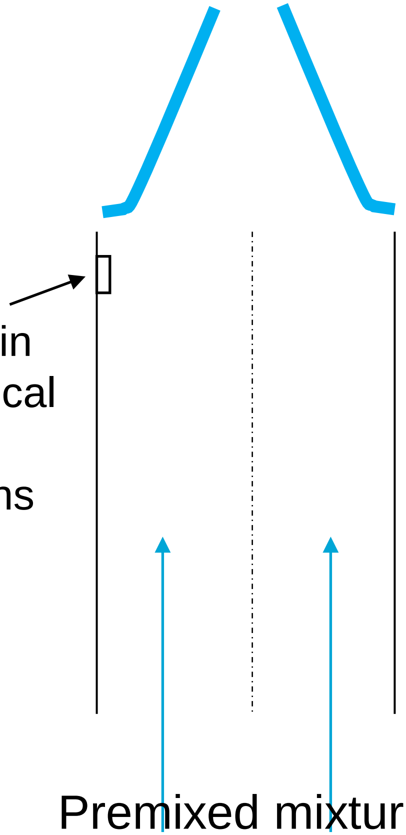
(a) Bulk velocity at flashback conditions for the cooled and uncooled burner configuration, as a function of equivalence ratio for different H_2 content in the fuel.

Faldella, 2020

Boundary layer flashback: **at burner** : 3. Turbulent flame speed

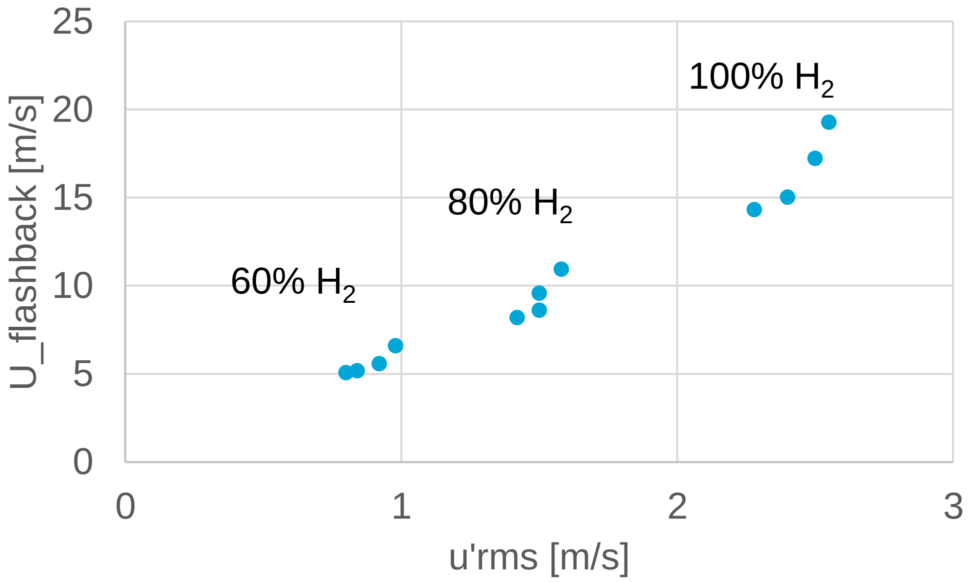
- Impact of turbulent flucutations
  (~ “Turbulent flame speed effect”)





Obstacle in flow => local velocity fluctuations

Premixed mixture



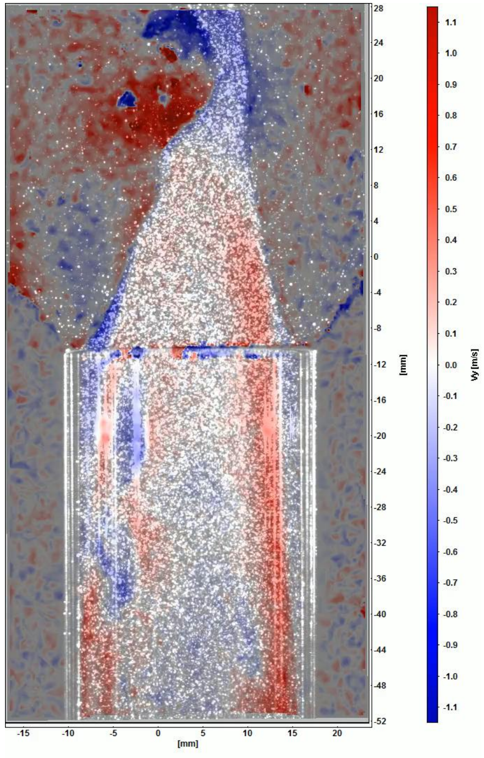
Increase velocity fluctuations
=> increased propensity on flashback

Correlates well with turbulent flame speed

Lambers, 2021

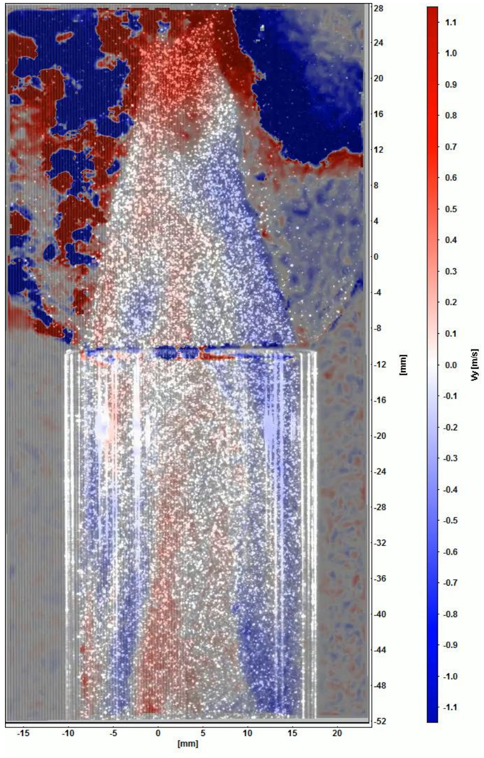
Boundary layer flashback: **at burner** : 4. Low velocity streaks

Flashback



Velocity

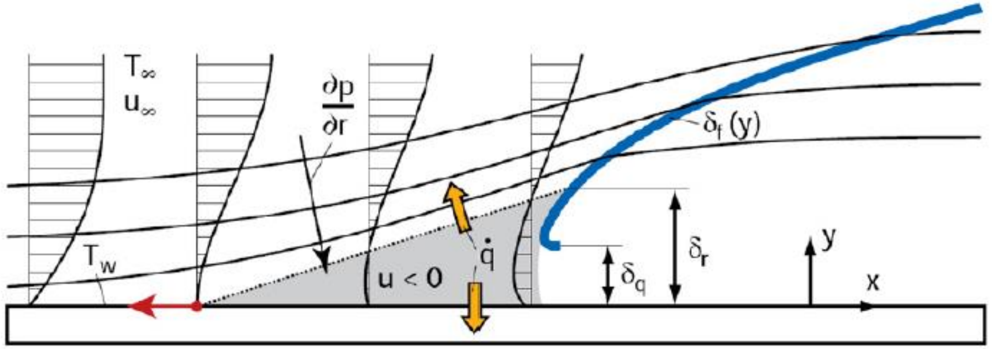
No Flashback

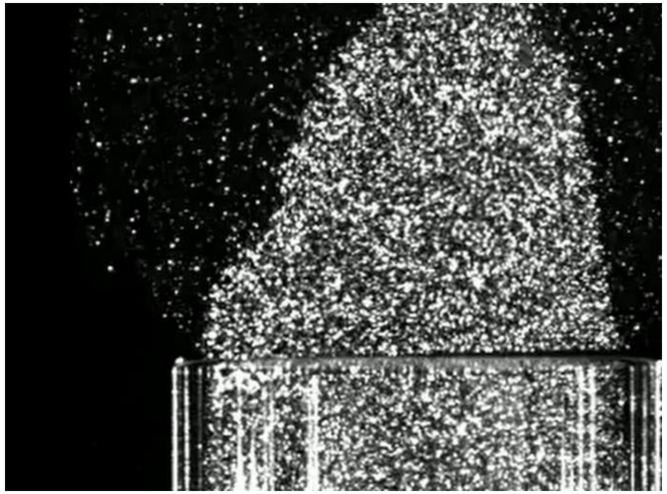


Occurrence of flashback: statistical phenomena

Boundary layer flashback: **in burner** (phase 3, “confined”)

- Flame adverse pressure gradient creates recirculation zone in front of flame
- Boundary layer instability due to adverse pressure gradient

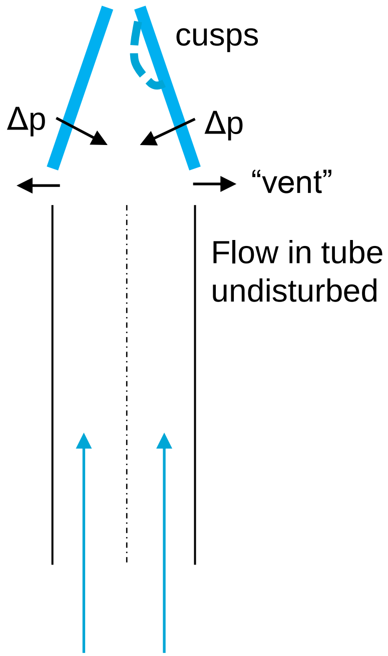




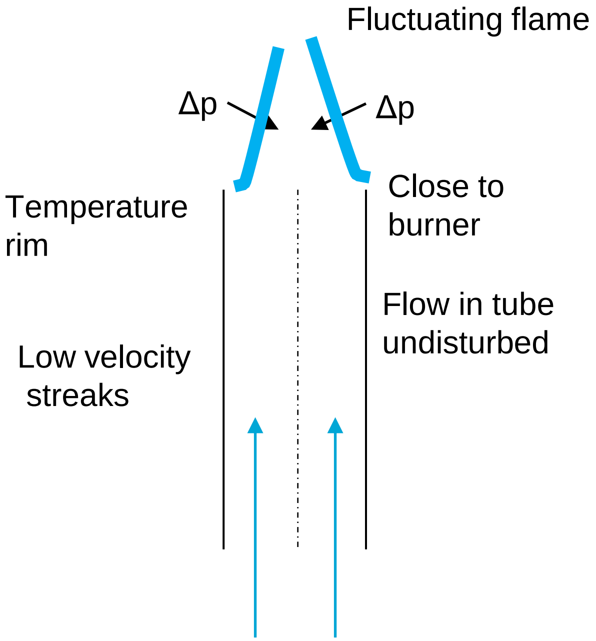
Will be discussed in more detail in modelling part of this presentation

Summary boundary layer flashback

Phase 1 :
above burner

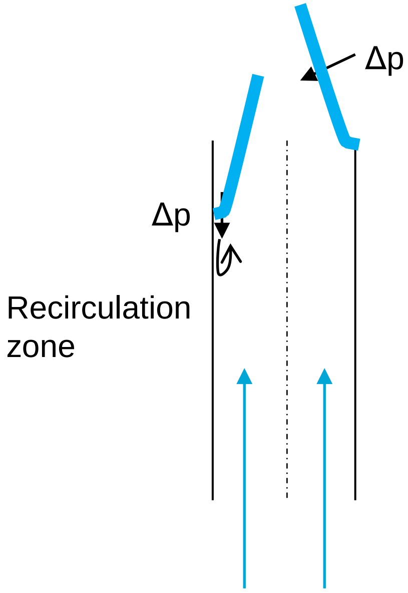


Phase 2 :
at burner



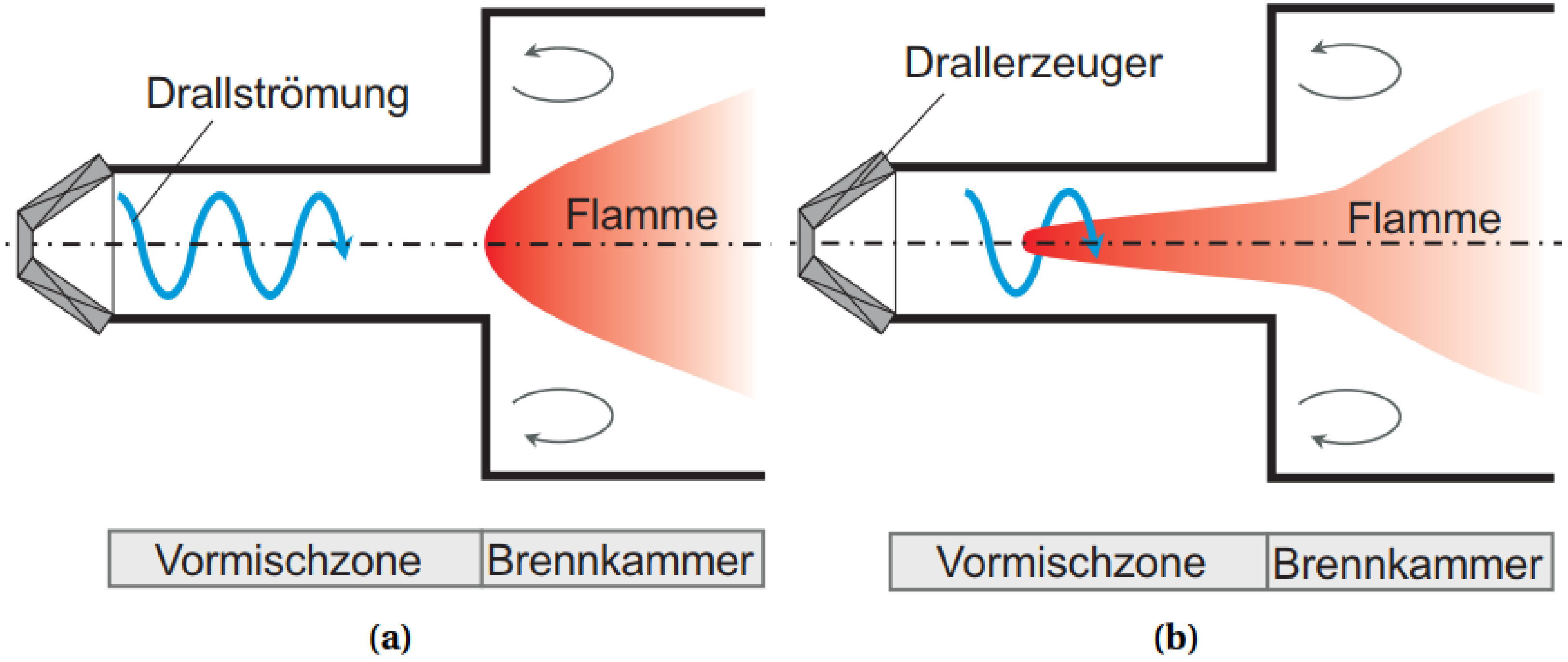
Flame flashes back into premixer at combination of momentary flame position, flame speed, low velocity streak

Phase 3 :
in burner



Confined flashback due to boundary layer instability caused by flame adverse pressure

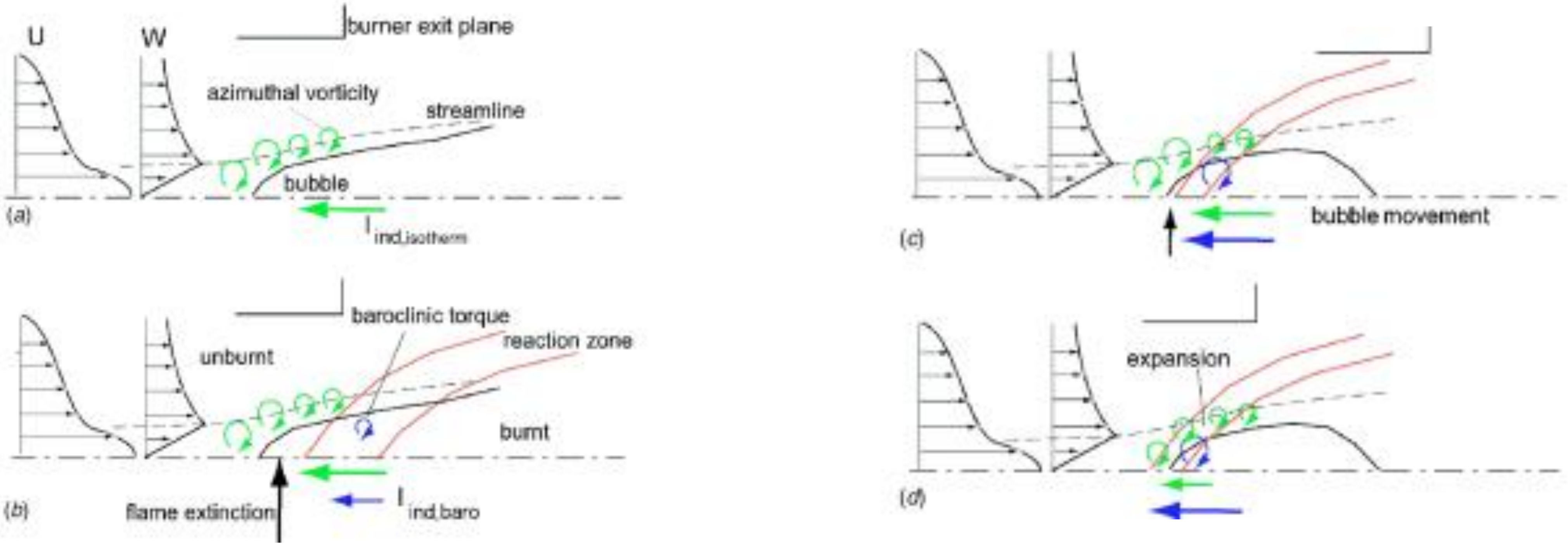
Swirling flames: Combustion Induced Vortex Breakdown



Burmberger (2009)

Swirling flames: Combustion Induced Vortex Breakdown

Adverse pressure gradient by flame and adverse pressure gradient from expanding swirling flow can move stagnation point further upstream



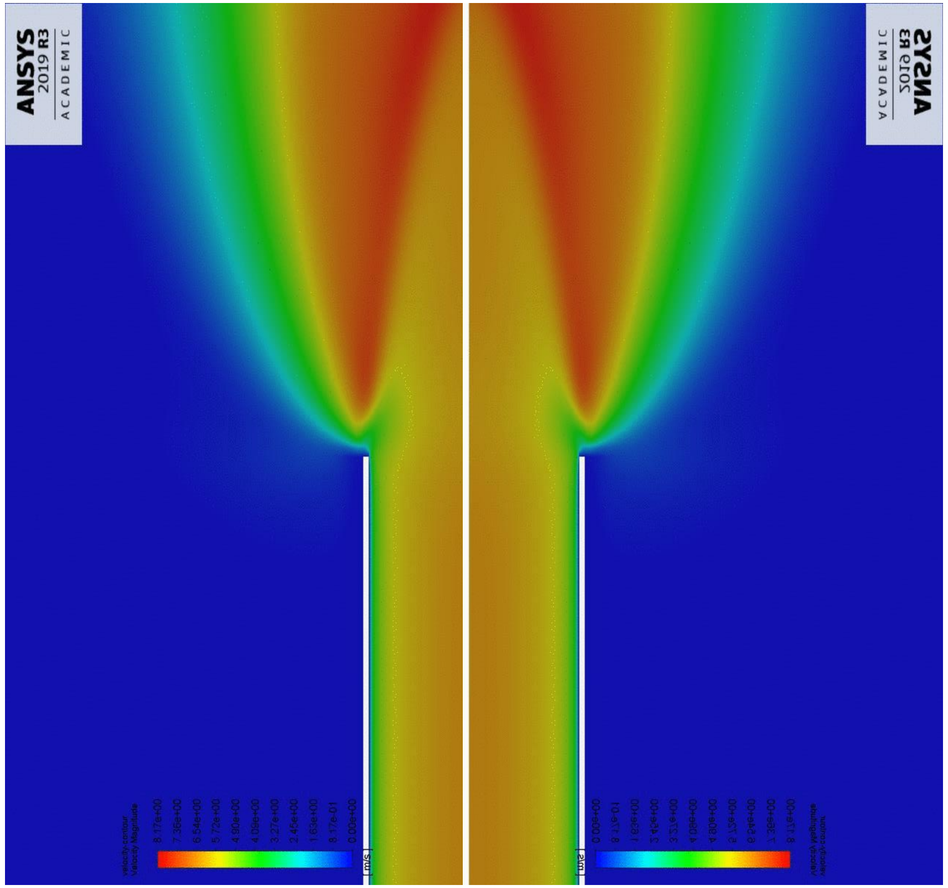
- (a) isotherm => stable recirculation bubble
  (b) expansion in reaction zone => flame moves upstream

(c) Flames closer to stagnation point

Kiesewetter (2007)

Flashback modeling

Flashback modeling for unconfined flames



Velocity

Figure 5.1: Pressure contours, bulk velocity = 5.5 m/s.

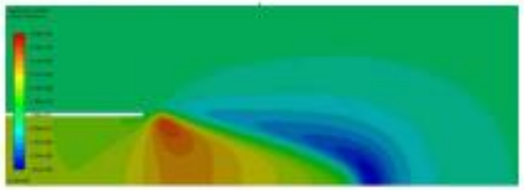


Figure 5.2: Pressure contours, bulk velocity = 4.5 m/s.

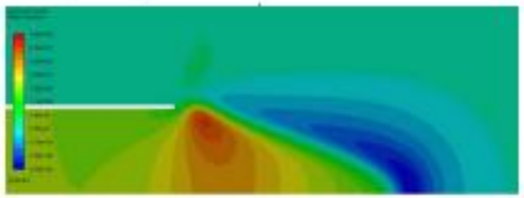


Figure 5.3: Pressure contours, bulk velocity = 3.5 m/s.

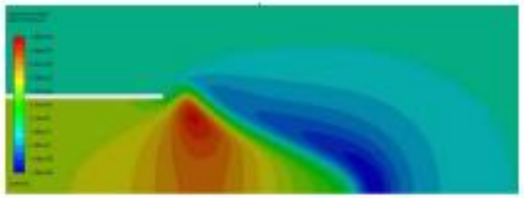


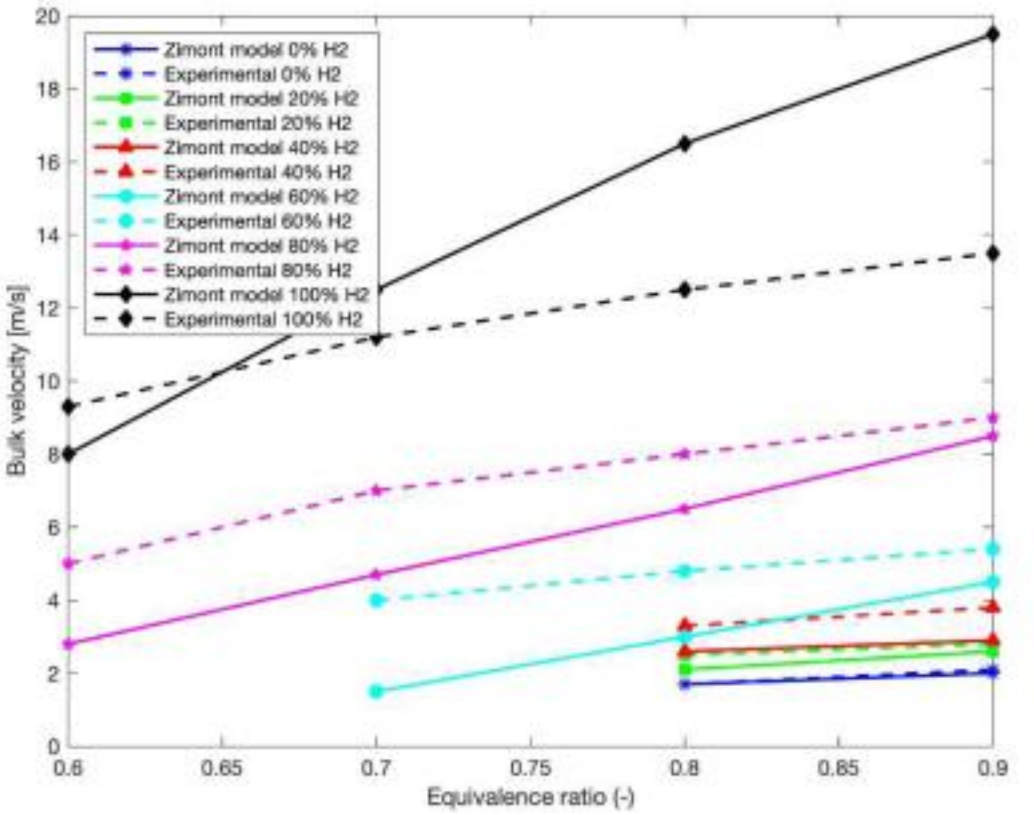
Figure 5.4: Pressure contours, bulk velocity = 2.64 m/s.

Pressure

Decreasing
bulk
velocity

Van Put (2021)

Flashback map for unconfined flames



- Standard Zimont turbulent flame speed closure captures flashback behaviour quite well
- Main deviations at higher H2 concentrations
- Flow retardation from flame adverse pressure

Van Put (2021)

Flame flashback confined flame: Eichler experiments (2011)

- μ-PIV + chemiluminescence
- CH4 and H2
- 0°,2°,4°channels
- Studied both turbulent and laminar flow
- Wide range of equivalence ratios, from 0.25 to 1.0
- **Recirculation area in front of an upstream propagating flame front**

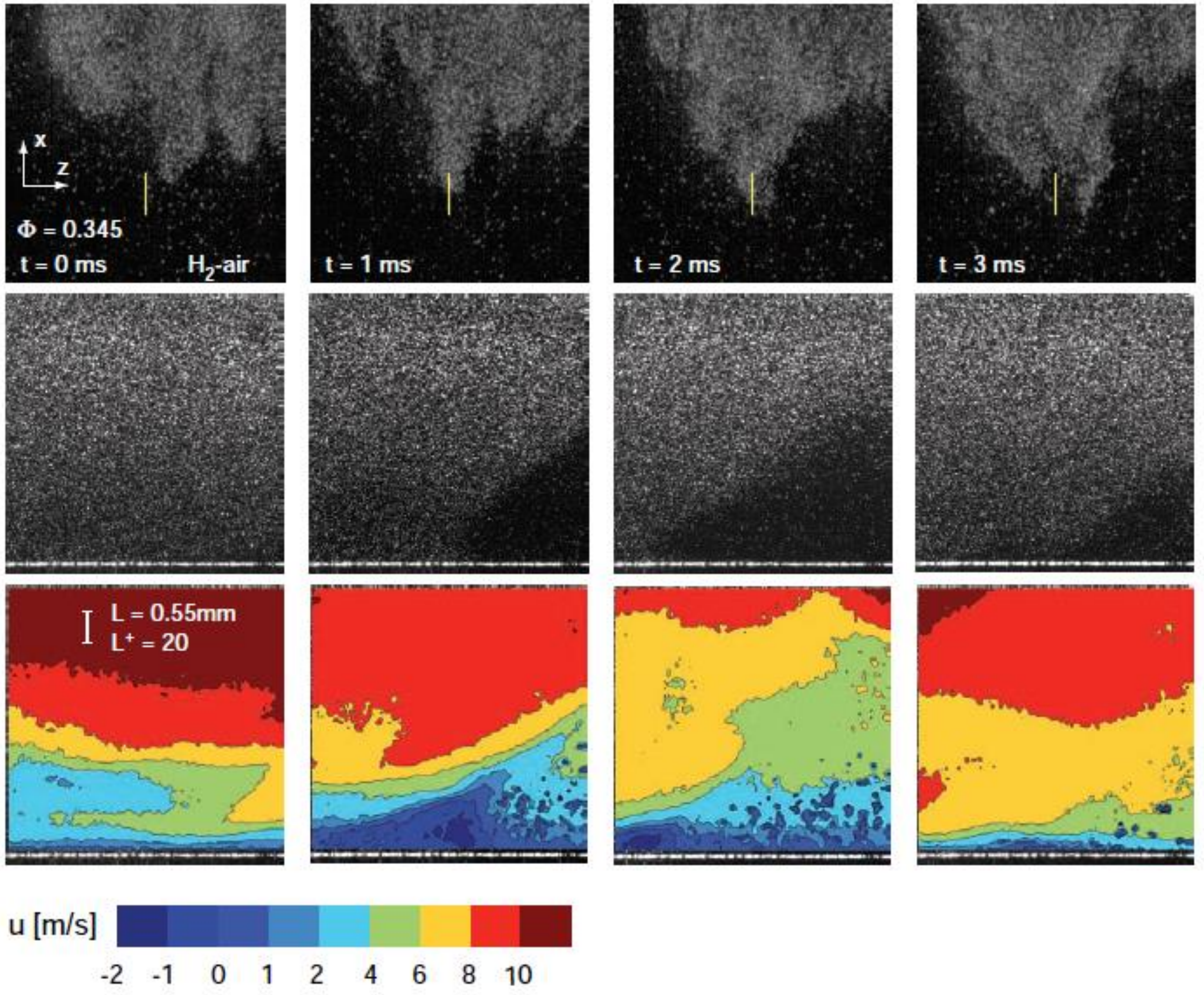
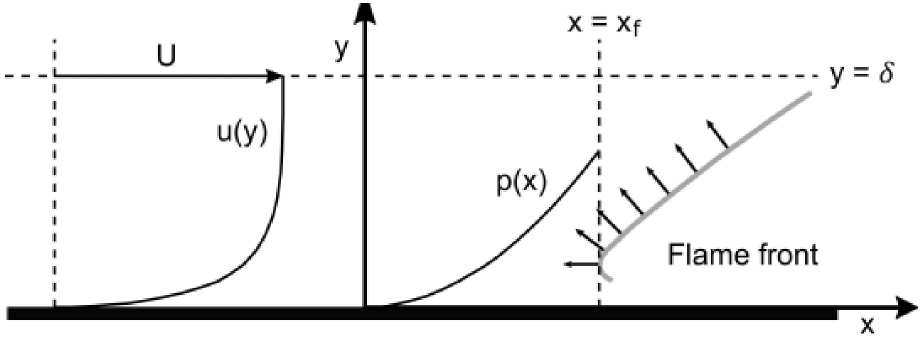


Figure 4.18: Axial velocity contours during turbulent H_2-air wall flashback in the 0° channel at $\Phi = 0.345$.

Flame adverse pressure gradient: impact on boundary layer flow



- Flow decelerates due to adverse pressure gradient => flow reversal at wall
- du/dy = 0 at wall => wall stress is zero

- Analysis worked out by Stratford in the 1950's to calculate boundary layer instability for a flow exposed to an adverse pressure gradient (e.g. flow over a wing)

  (First proposed by Hoferichter (2017) for boundary layer flashback)

Stratford criterion calculates zero velocity gradient at wall

- Assumed shape for boundary layer:

$$\frac{u}{U} = \left(\frac{y}{\delta}\right)^{\frac{1}{n}}$$

- General Stratford

$$C_p^{\frac{1}{4}(n-2)}\left(\delta\frac{dC_p}{dx}\right)^{\frac{1}{2}} = \left(\frac{3(0.41\beta)^4}{(n+1)n^2}\right)^{\frac{1}{4}}\left(1-\frac{3}{n+1}\right)^{\frac{1}{4}(n-2)}$$

Left hand side:
~Pressure gradient

Right hand side:
~Boundary layer profile

- LHS = RHS => τ = du/dy = 0 at wall
- LHS > RHS => negative velocity close to wa
  - Stratford boundary layer stability: unstable
  - Flash back analysis: onset of flashback

$$C_p(x) = \frac{p(x)-p_m}{\frac{1}{2}\rho U^2}$$

Björnsson (2019)

Stratford criterion for confined flame flashback

Left Hand Side ***Right Hand Side***

$$C_p^{\frac{1}{4}(n-2)}\left(\delta\frac{dC_p}{dx}\right)^{\frac{1}{2}} = \left(\frac{3(0.41\beta)^4}{(n+1)n^2}\right)^{\frac{1}{4}}\left(1-\frac{3}{n+1}\right)^{\frac{1}{4}(n-2)}$$

- Adverse pressure gradient:
  - Over flame (Rankine Hugionot)
  - Main flow (**from CFD**)

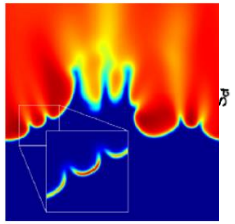
$$\frac{dC_p(x)}{dx} = \frac{4\Delta p x}{\rho_u U^2 x_f^2}$$

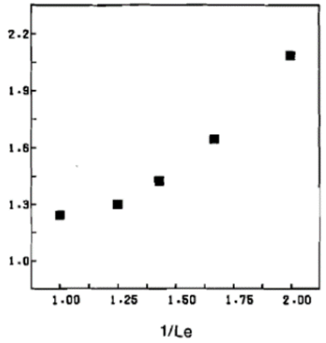
$$\Delta p = p_u - p_b = \rho_u {S_t}^2\left(\frac{\rho_u}{\rho_b}-1\right)$$

- Turbulent flame speed correlation (local value: **from CFD**)

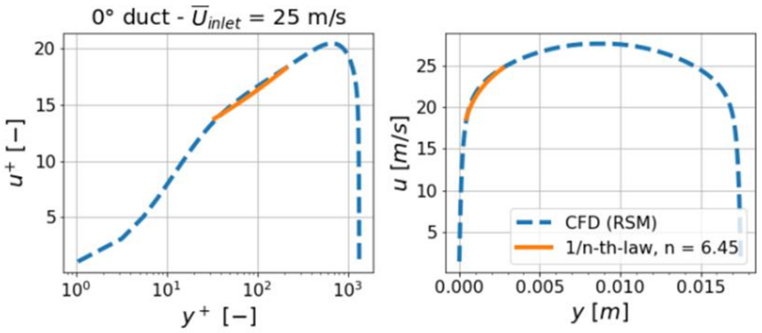
$$\frac{S_t}{S_l} = 1 + C\left(\frac{u'}{S_l}\right)^{0.5}$$

- Low Lewis number correction (local enrichment)





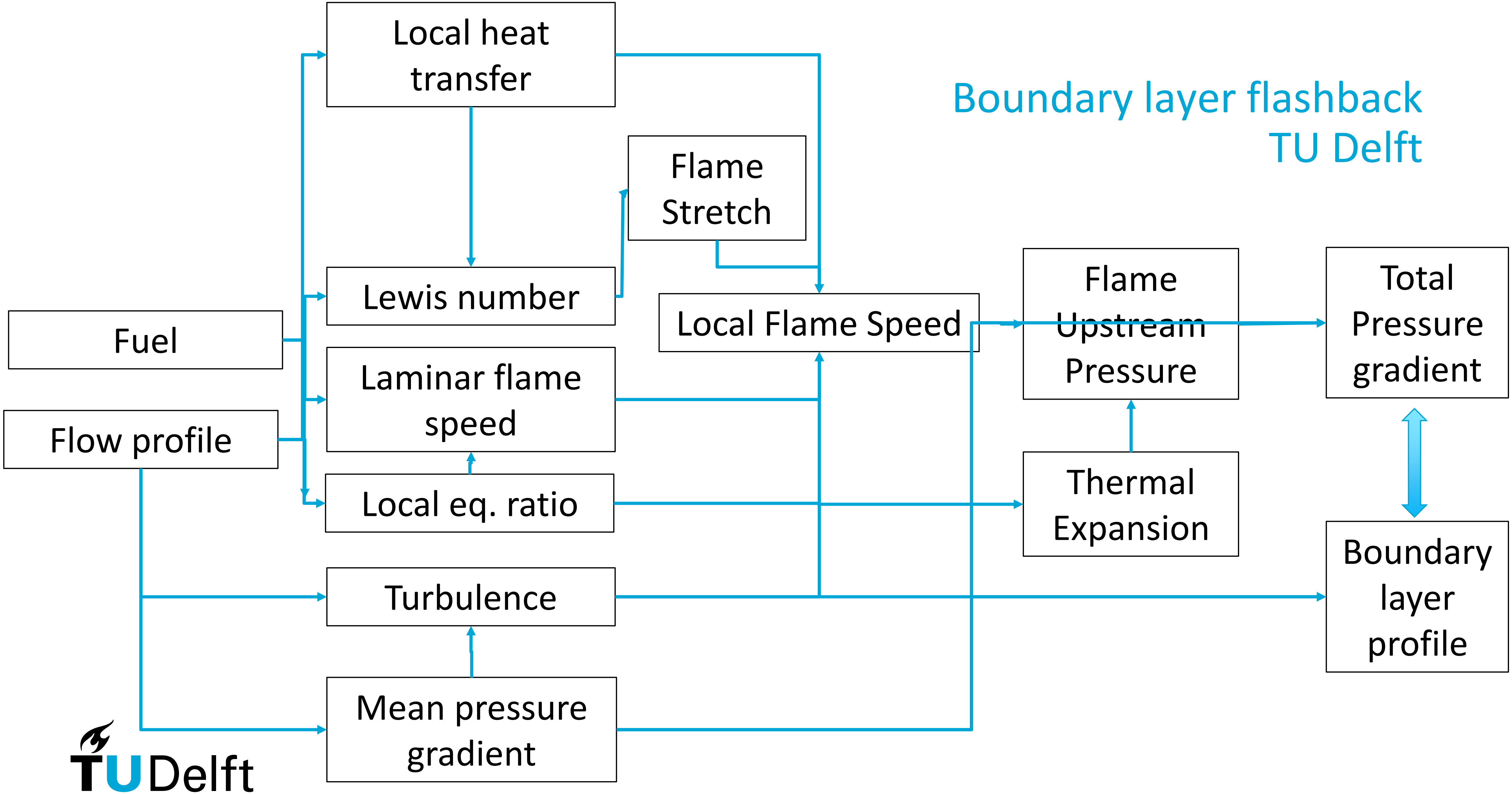
Tober(2018)/Björnsson (2019)



β: empirical constant derived by Stratford

From CFD:
δ: ‘boundary layer thickness’
n: profile constant
U: far field (‘mean’) velocity

Boundary layer flashback
TU Delft



Local heat transfer

Flame Stretch

Lewis number

Local Flame Speed

Fuel

Laminar flame speed

Flow profile

Local eq. ratio

Turbulence

Mean pressure gradient

Flame Upstream Pressure

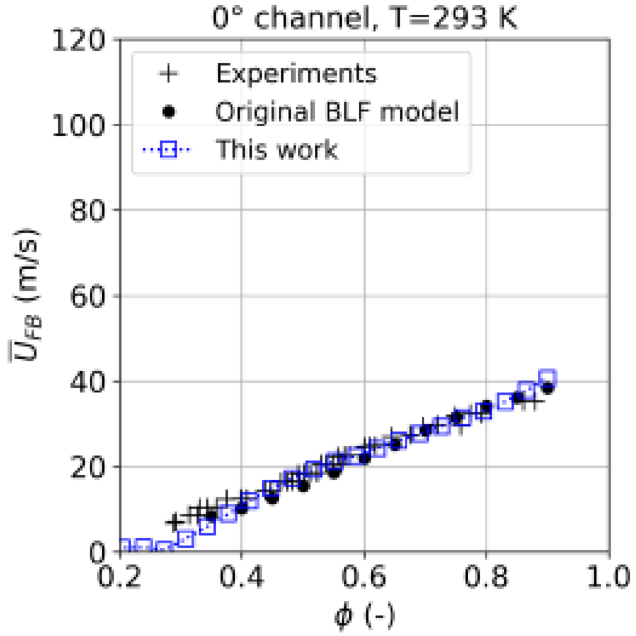
Thermal Expansion

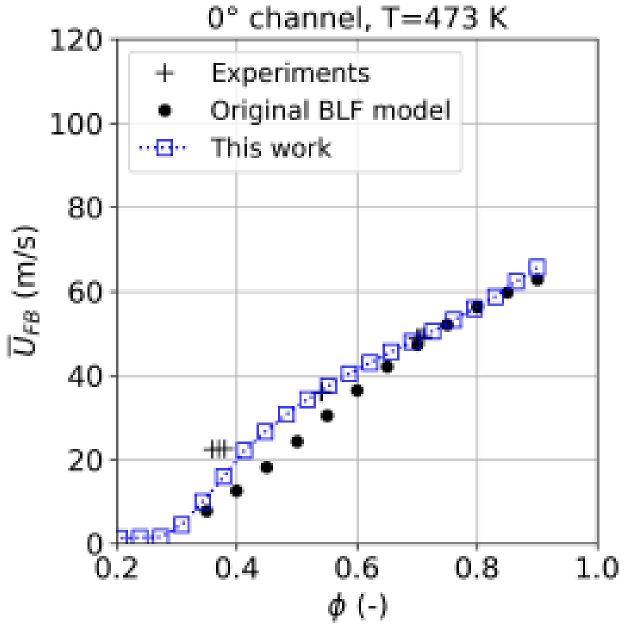
Total Pressure gradient

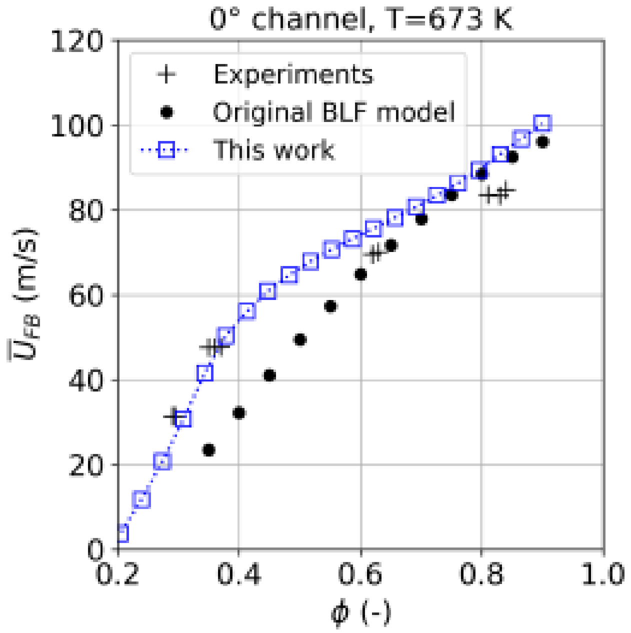
Boundary layer profile

TU Delft

BLF Model compares very well for academic cases



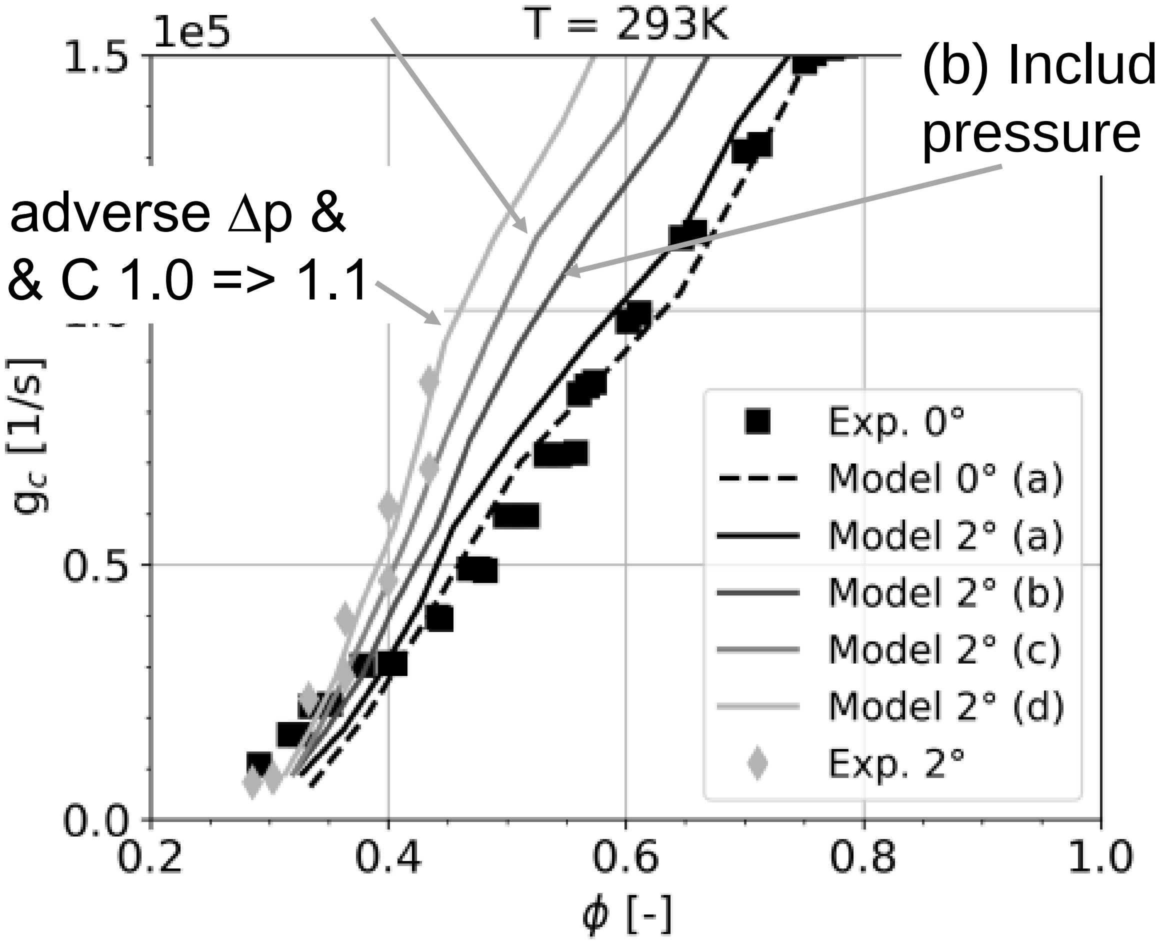




Increasing inlet temperature

- Original BLF model : TU Munich/Hoferichter model
- Improvement at higher temperatures: Consequence of other low Lewis number correction

Flash back in 2° diffuser well predicted



(c) Including mean adverse pressure gradient & correction u’

(b) Including mean adverse pressure gradient

(d) Including adverse Δp & correction u’ & C 1.0 => 1.1

TUDelft

Application for hydrogen in gas turbines

What did we learn till now?

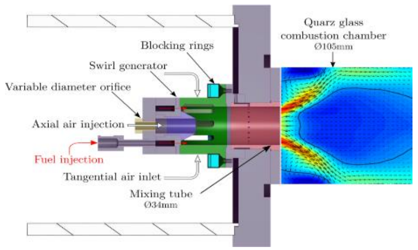
- Important for flashback in premixed hydrogen flames
  - Local turbulent/laminar flame speed (composition, temperature, equivalence ratio, Lewis number,..)
  - Local flow structure
  - Swirl/Recirculation zone
  - Local mean flow pressure gradient

- Lot of insights is still missing
  - Statistical phenomena ⇔ modeling with averaged quantities
  - Detailed interaction flame front ⇔ incoming flow in boundary layer
  - Near wall effects
  - …….

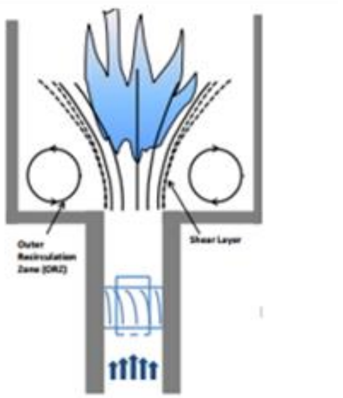
Combustor designs under development for high hydrogen gas turbines

Premixed combustion => low NOx

Control of swirl

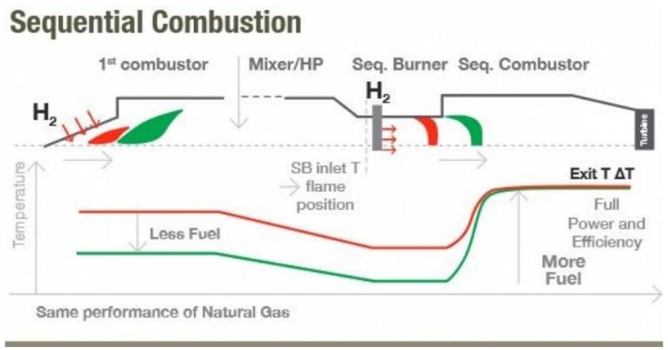


High swirl + axial injection

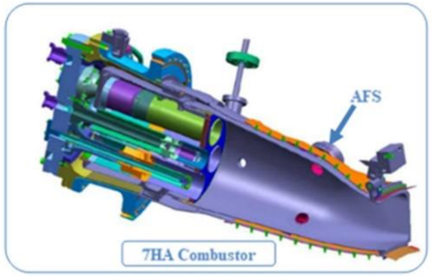


Low Swirl

Control of flame speed

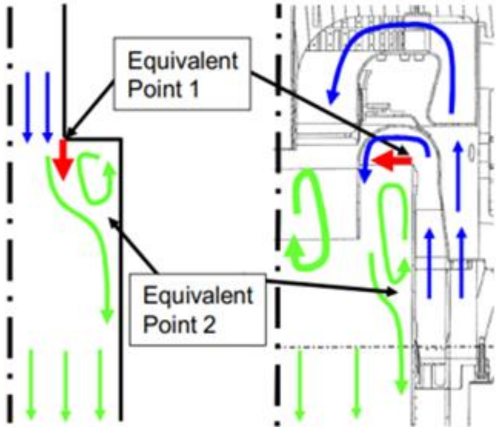


Sequential combustion



Axial staged combustion

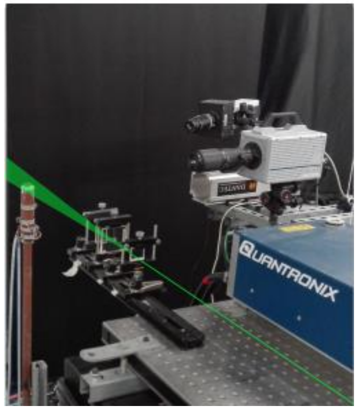
“Fixed” vortex stabilisation



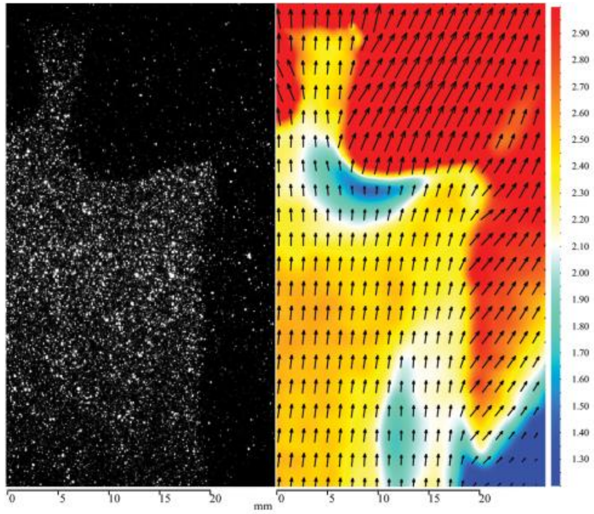
Trapped vortex

TU Delft H_2 Combustion & Flashback research

Experimental

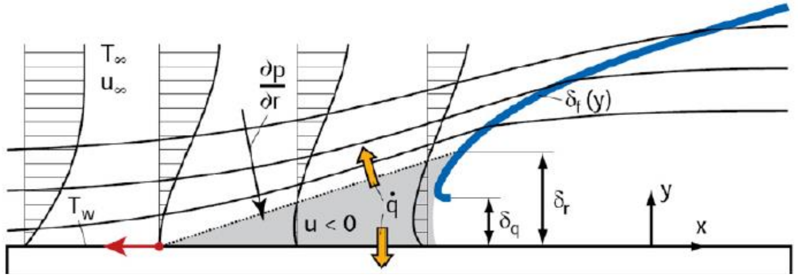



GT combustor set up



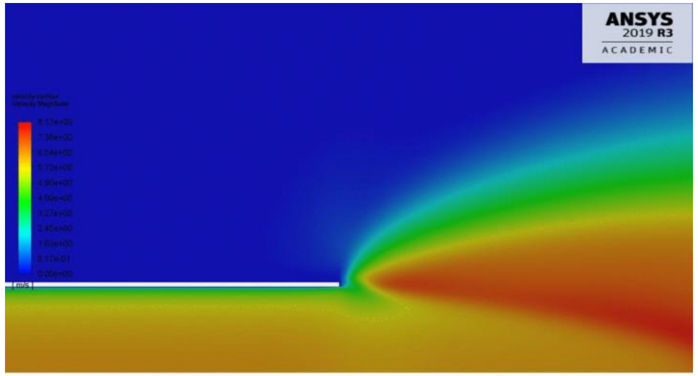
Advanced laser diagnostics

Theoretical/Modelling



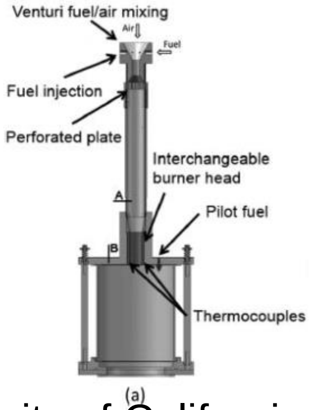
$$C_p^{\frac{1}{4}(n-2)}\left(\delta\frac{dC_p}{dx}\right)^{\frac{1}{2}} = \left(\frac{3(0.41\beta)^4}{(n+1)n^2}\right)^{\frac{1}{4}}\left(1-\frac{3}{n+1}\right)^{\frac{1}{4}(n-2)}$$

Boundary layer flashback model

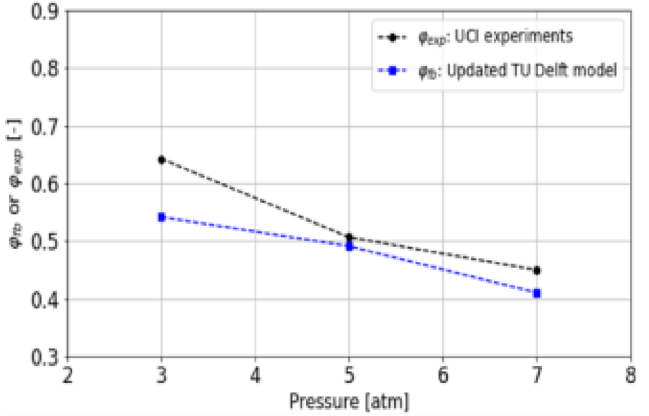


Transient CFD

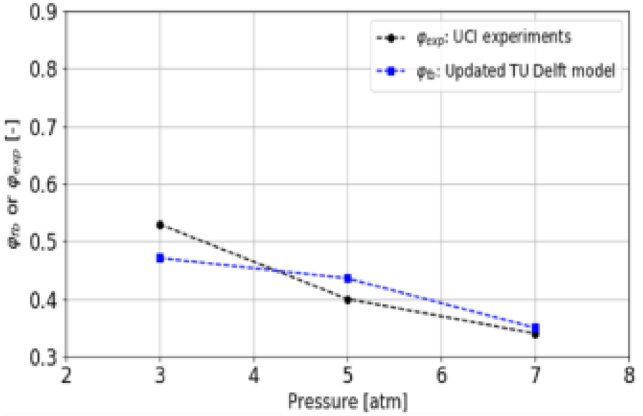
TU Delft BLF model performs well on gas turbine relevant geometries



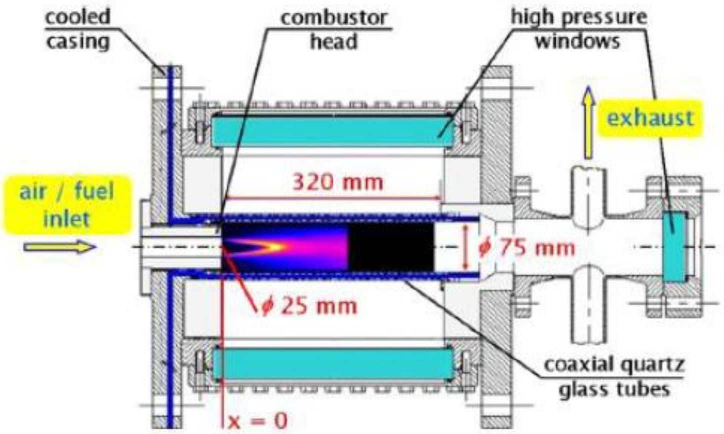
University of California, Irvine
Kalantari et al. (2016)

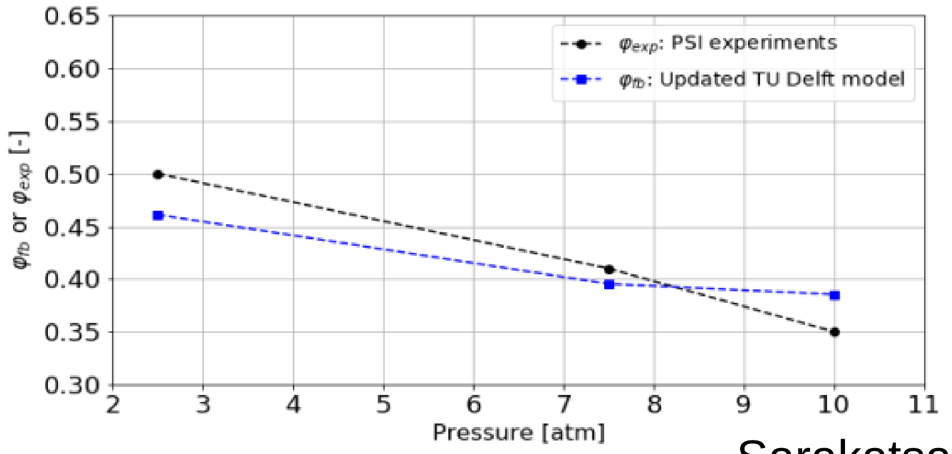


a)T=300 K, u_{bulk}=30 m/s



b)T=500 K, u_{bulk}=30 m/s

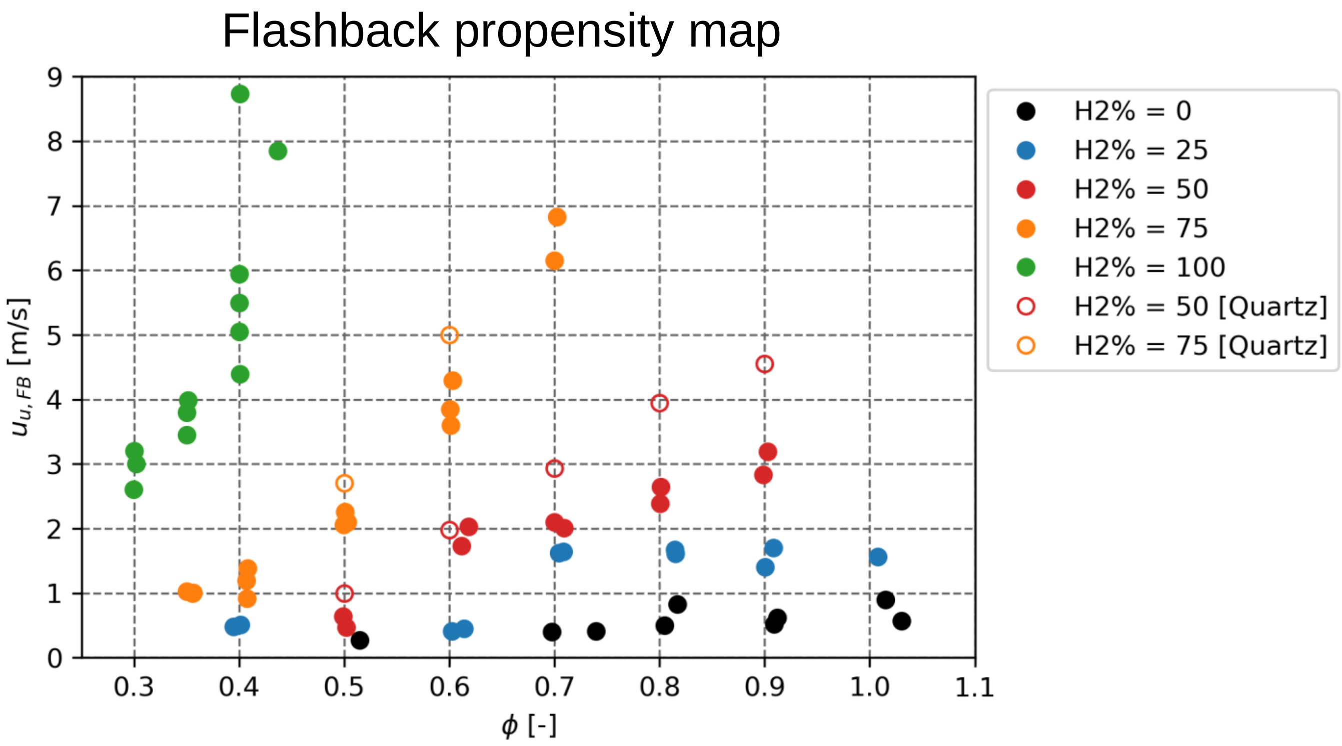




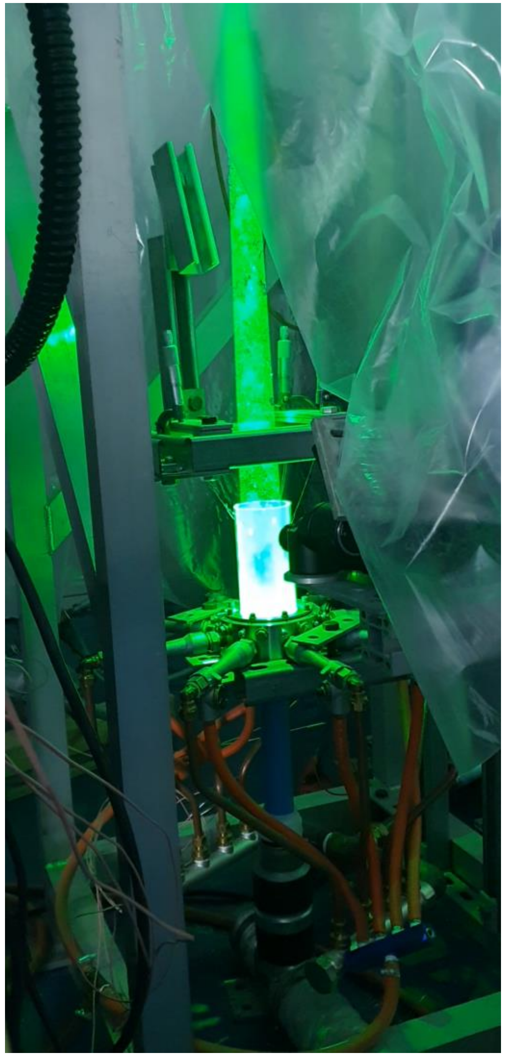
Paul Scheerer Institute
Lin, Daniele, Jahnson et al (2012)

Sarakatsanis (2020)

Experiments with the TU Delft trapped vortex burner

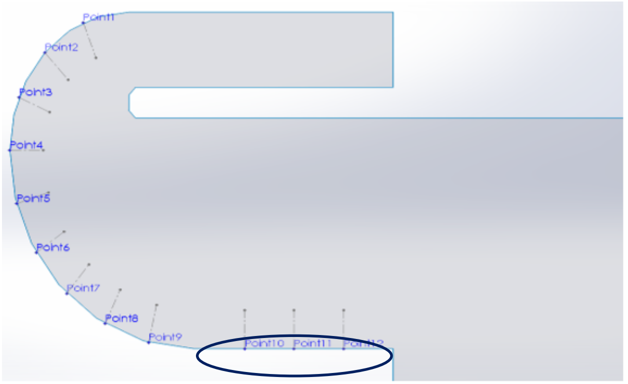


Top view



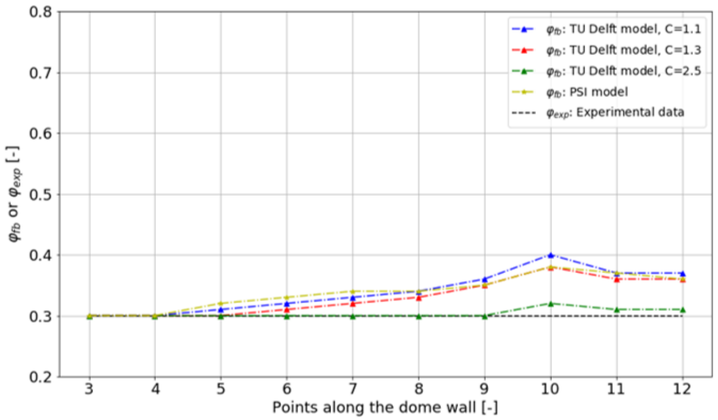
Altenburg (2020)

Application of the TU Delft BLF model to TU Delft trapped vortex burner

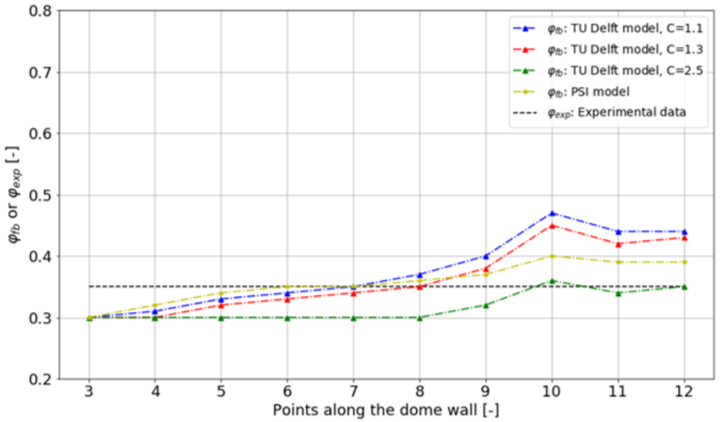


a) Dome wall.

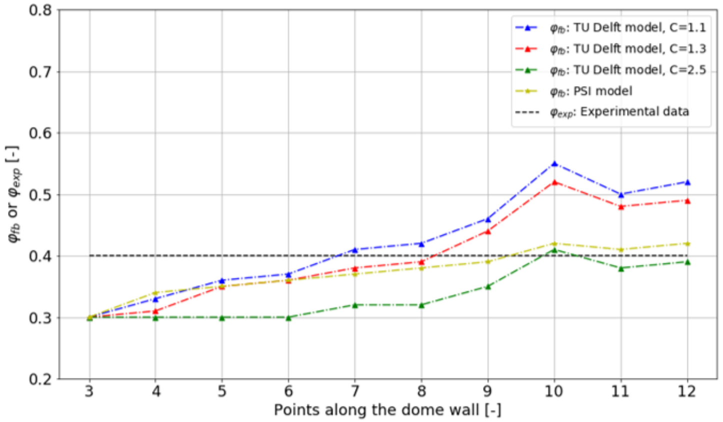
Location most prone to flashback



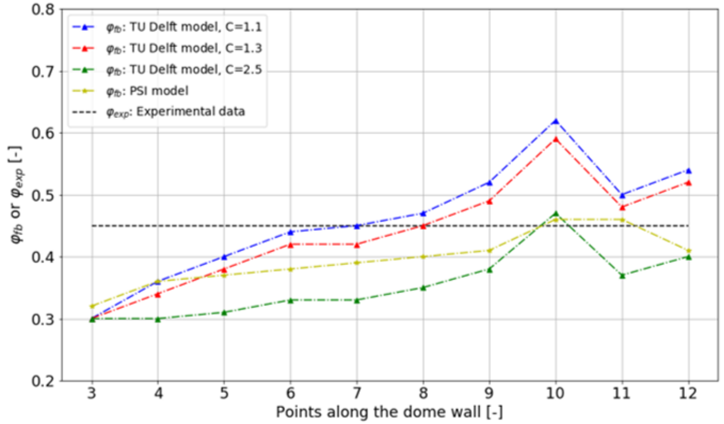
a) Points along the dome wall, inlet u_{bulk}=2.6 m/s.



b) Points along the dome wall, inlet u_{bulk}=3.8 m/s.



c) Points along the dome wall, inlet u_{bulk}=5.5 m/s.



d) Points along the dome wall, inlet u_{bulk}=7.9 m/s.

Sarakatsanis (2020)

Conclusions
&
Future developments

Conclusions

- Hydrogen electricity from (retrofit) combined cycle power plants good candidate for zero carbon balancing of grid
- 100% H_2 burners for gas turbines in development, close to demonstration phase

- Flashback much more complex phenomena than simple : flame speed > flow velocity
  - Transient phenomenon => occurrence in turbulent flows to be based on statistics
- For unconfined flashback : good predictor: flame speed > local flow velocity
- For confined flashback: flame adverse pressure => boundary layer instability

- TU Delft boundary layer flashback model performs well both for academic burners and gas turbine configuration
- TU Delft BLF model very valuable tool for design of flashback resistant gas turbine combustors

Projects/Research in progress/under development

- HighHydrogen project (RVO support)
  - Increase insights in Flamesheet behavior: semi 2D burner with full optical access
  - Validate model with pressurized Flamesheet results
  - Develop detector/active control of flashback by using a precursor

- Strengthen knowledge and application for swirl burners: H2Flex project with OPRA (RVO support)

- Detailed insights in confined flashback using set up with controllable pressure gradient for better insight into interaction boundary layer-flame **(looking for funding)**

- Continue academic research on elementary burners

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- Companies: Thomassen Energy, OPRA, Vattenfall, Nobian, Emmtec, Dow, ..
- Funding: RVO : HighHydrogen (phase I and II)

  RVO : H2 Flex

  SGO: Stichting Gas turbine Onderwijs

QUESTIONS ?

TU Delft

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MSc theses TU Delft

Boundary layer flashback prediction of a low emissions full hydrogen burner for gas turbine applications.	Joeri Tober	http://resolver.tudelft.nl/uuid:be4a3f30-b39d-4be5-9d88-f165ef68d851
Boundary layer flashback prediction for low emissions full hydrogen gas turbine burners using flow simulation	Olafur Bjornsson	http://resolver.tudelft.nl/uuid:8272a27d-692d-4721-a24c-98ffd4c52511
Hydrogen flash back experiments	Filippo Faldella	http://resolver.tudelft.nl/uuid:ab0c472e-0dd1-4086-8eeb-18ef14ee226e
Modeling of hydrogen-elektrolysis-storage-utilization chain	Nick Kimman	http://resolver.tudelft.nl/uuid:46183251-f22a-42b5-a994-ed353d4338c0
Modeling of hydrogen flash back, application of TU Delft model to different geometries	Christos Saraktsanis	http://resolver.tudelft.nl/uuid:a4ef3e3d-29cb-4855-a14a-5f0fafc50966
Modeling of hydrogen flash back in diffuser using Large Eddy Simulations	Akhil Penmatsha	http://resolver.tudelft.nl/uuid:968bb3f5-0378-4872-9d05-cb0ec4fc629a
Numerical modelling of flame flashback in premixed tube burners with turbulent flow and high hydrogen content	Max van Put	http://resolver.tudelft.nl/uuid:84b5e88d-72b8-4663-a597-84993aa347f7
Boundary Layer Flashback of Turbulent Premixed Hydrogen/DNG/Air Flames produced by a Bunsen Burne	Tim Lamberts	http://resolver.tudelft.nl/uuid:ad99dd53-063a-48c8-9cf2-cafd31ca3deb