INTERACTION OF HYDROGEN JETS WITH HOT SURFACES

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ICT

Problem

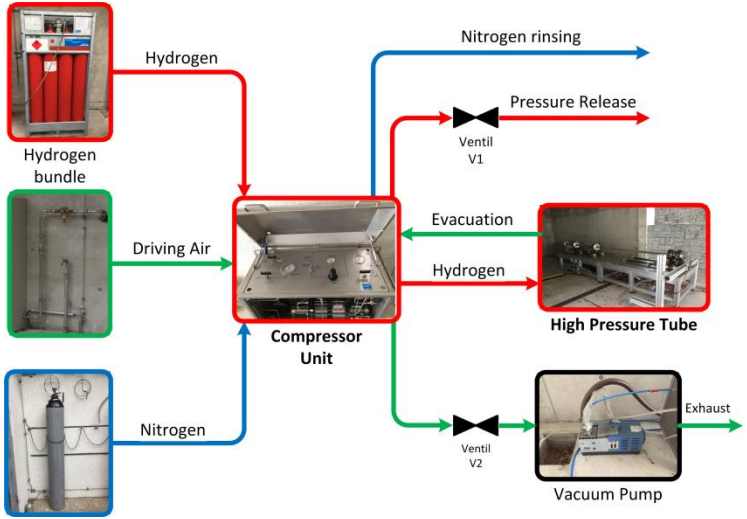
- High pressure hydrogen storage and refueling
  - Safety valve / rupture disk activation, accidents,…
- Resulting hydrogen jets may ignite sponaneously – or not!
- Moving scheme (explosion / cold jet) depends of various parameters
  - Most important: pressure & nozzle configuration
  - „Late ignition“ at hot sufaces: **important issue**
    - Strongly enhanced flame velocities by turbulence
- Mechanisms not fully understood

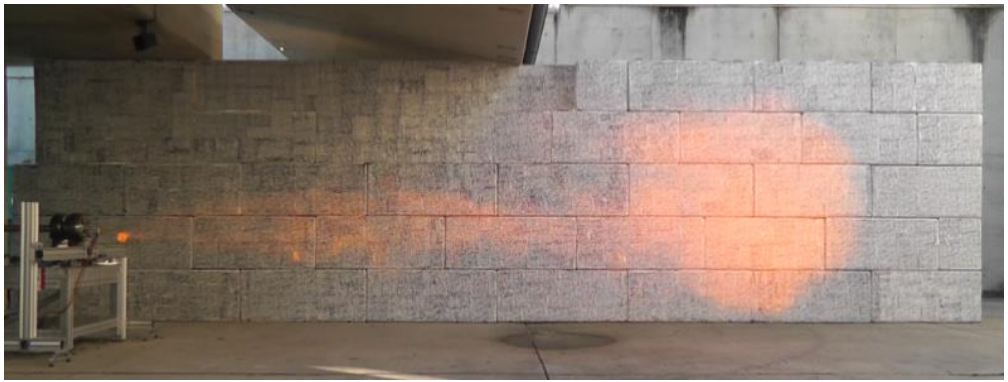
Approach

- Highly dynamic hydrogen jets
- Spontaneous release by rupture disk out of pipe Ø 10mm
- 2.5 / 10 / 20 / 40Mpa nominal release pressure
- Ignition source: glow plug
  - 3m / 5m / 7m distance to nozzle
  - 450°C – 950°C temperature range in steps of 100°C
- Fast scanning NIR spectroscopy 1.2-2.2µm (H_2O Bands)
- In total 57 experiments

Interaction of Hydrogen Jets with Hot Surfaces
Experimental Setup

- Fraunhofer ICT high pressure release facility
  - ~5l Volume
  - Fully remote controlled





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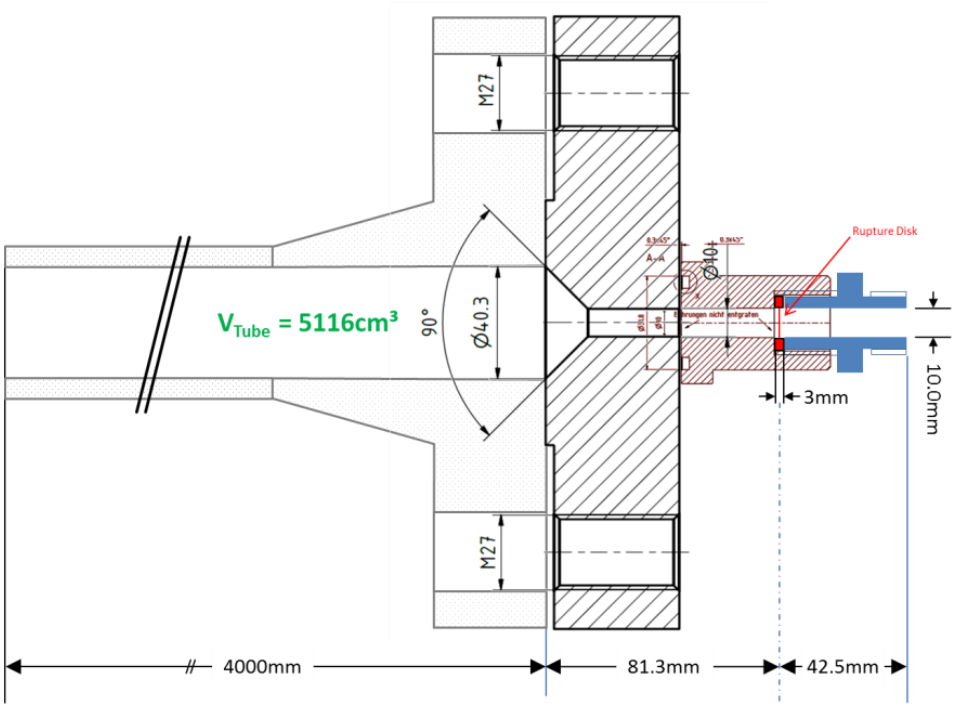
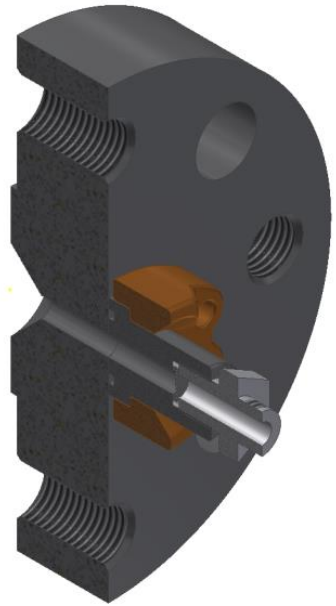
Release configuration





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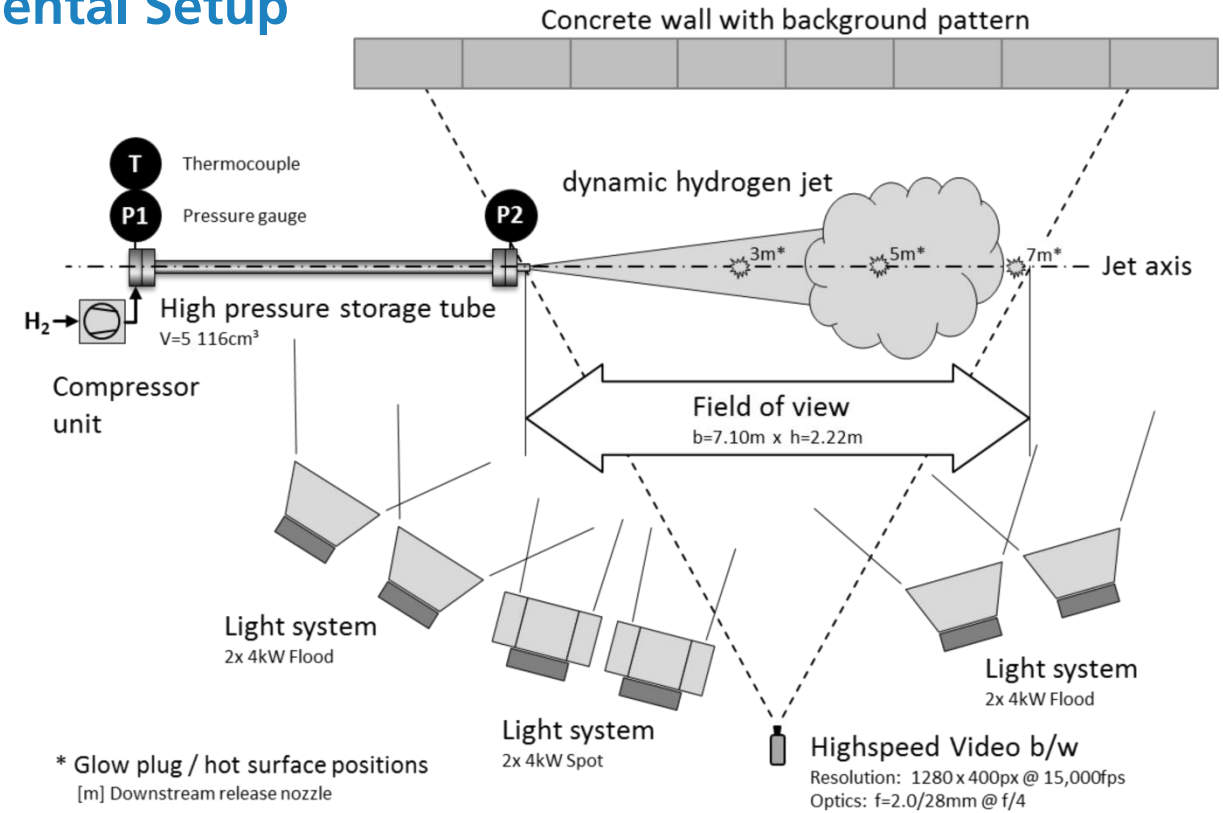
Interaction of Hydrogen Jets with Hot Surfaces

Experimental Setup



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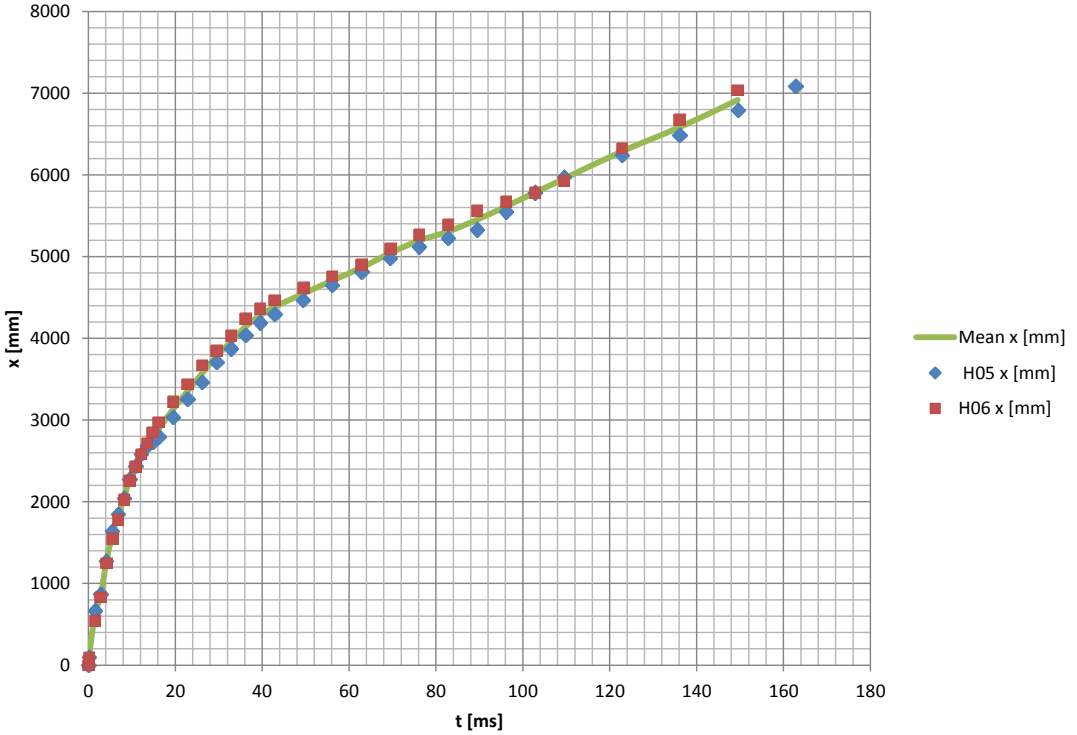
Measured release conditions

Nominal pressure [bar]	Activation pressure [MPa]	$t_{90\text{-}10}$ [s]	Initial pressure decay [bar/s]	Averaged pressure decay [MPa/s]	Initial gas temperature [°C]
25	2.82 ±0.09	0.225 ±0.000	310.9 ±10	9.52 ±0.3	12.8 ±0.1
100	10.56 ±0.29	0.218 ±0.000	1350 ±37	37.6 ±1	12.3 ±0.3
200	22.26 ±0.58	0.200 ±0.004	3206 ±97	83.7 ±2.5	11.4 ±0.4
400	40.92 ±1.21	0.180 ±0.003	6739 ±233	170.3 ±6.2	9.1 ±1.2

Reproducibility

- Data evaluation
  - Video analysis methods
- Exemplaric results:
  - Jet head propagation on jet axis



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Results & discussion

- Classification of results based on criterium **„flame speed“**
  - **> 30m/s**: „strong“
  - **< 30m/s**: „weak“, further divided in
    - **„Weak“** reaction
    - **„Normal“** reaction
      - Effects close to premixed spherical H_2-Air explosion

Interaction of Hydrogen Jets with Hot Surfaces

Reaction type

d = 3m		T [°C]					
		450	550	650	750	850	950
P [MPa]	2.5	-	-	H44	H43	H42	H41,H45,H46
	10	-	-	H56, H57*	H55	H54	H53
	20	-	-	-	H77, H78	H76	H74
	40	-	-	H48	H49, H50	H51	H52
d = 5m							
P [MPa]	2.5	-	-	-	-	-	H40
	10	-	-	H61, H62*	H60	H59	H58
	20	-	-	H66, H67*	H65	H64	H63
	40	H24	H33	H34	H35	H37	H23
d = 7m							
P [MPa]	2.5	-	-	-	-	-	-
	10	-	-	-	-	H69	H68
	20	-	-	H73*	H72	H71	H70
	40	H25	H26	H27	H29	H30	H32

* @700°C

Reaction Type	No Reaction	Weak Reaction	Strong Reaction

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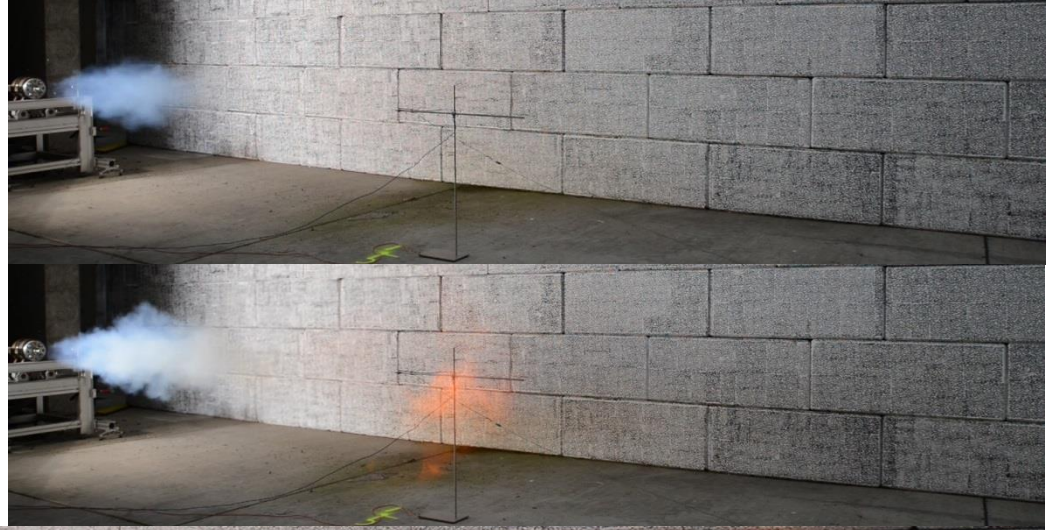
Interaction of Hydrogen Jets with Hot Surfaces

Reaction Type „Normal“



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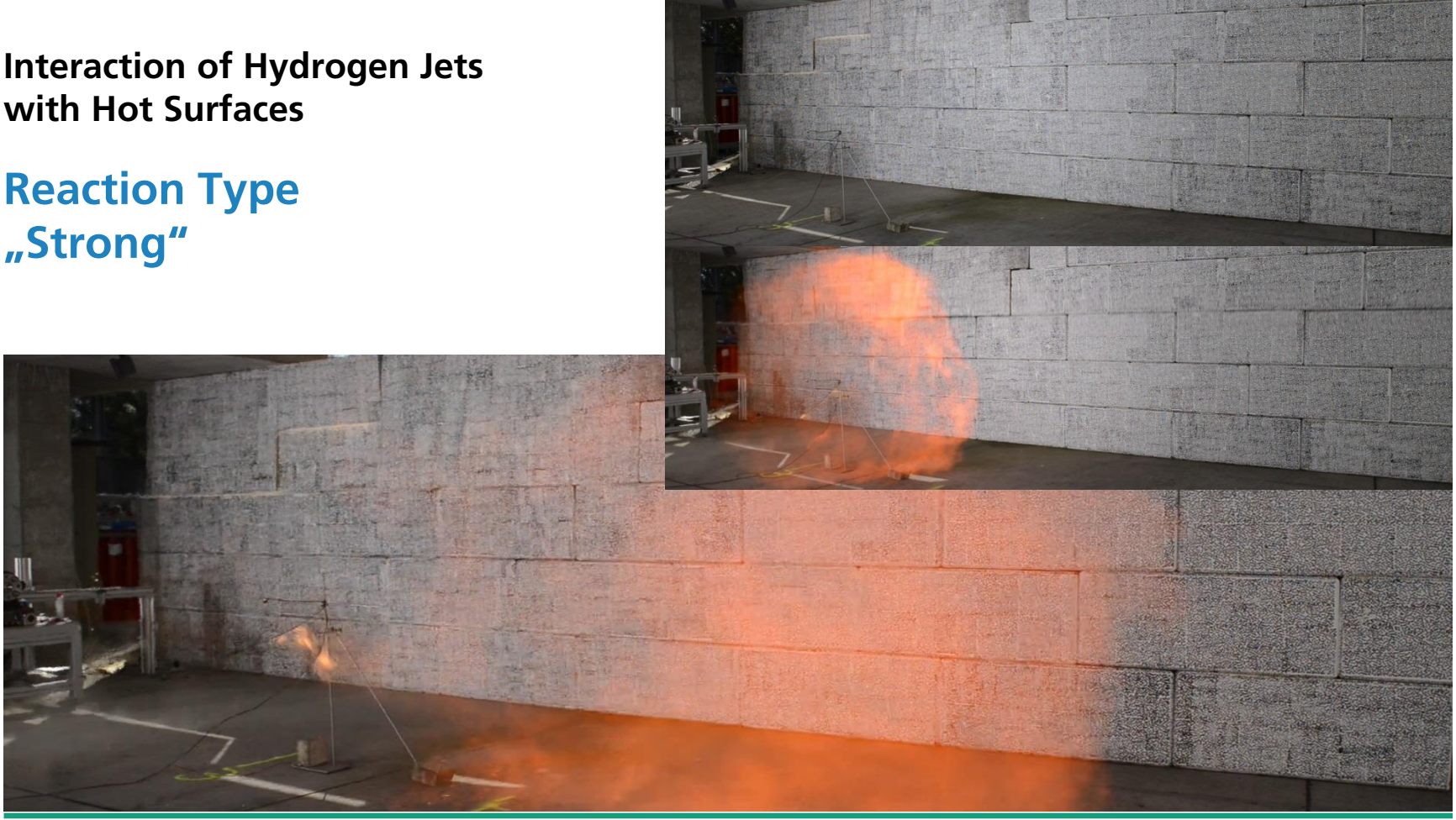
Interaction of Hydrogen Jets with Hot Surfaces

Reaction Type „Strong“



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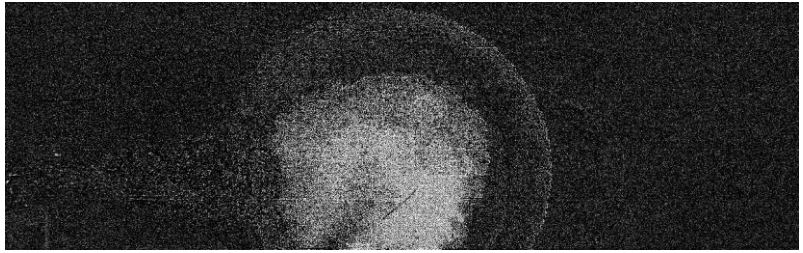
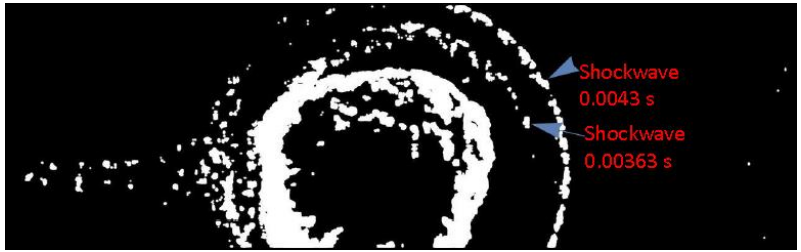
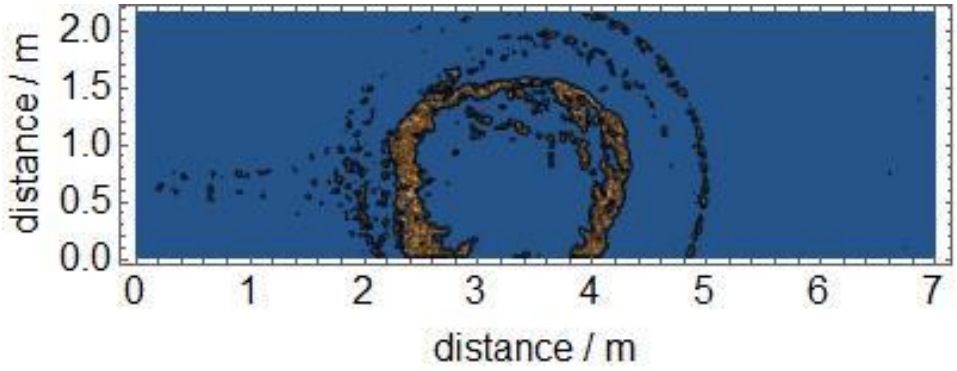
Interaction of Hydrogen Jets w. Hot Surfaces

Reaction Type „Strong“

- Steps of video data analysis
- Experiment H51
  - 40MPa
  - Glow plug
    - 3m
    - 850°C
- Resulting jet
  - expected12° opening angle
- Strong explosion with shock wave







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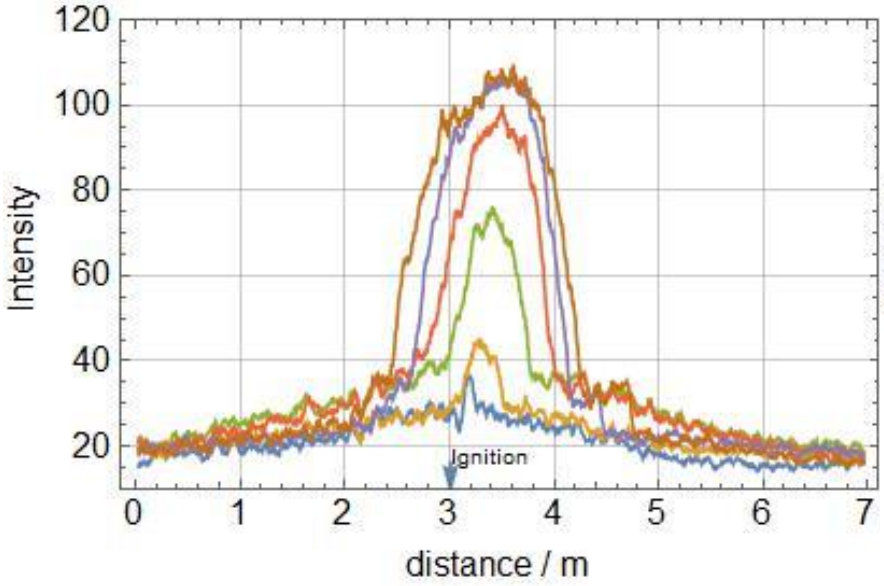
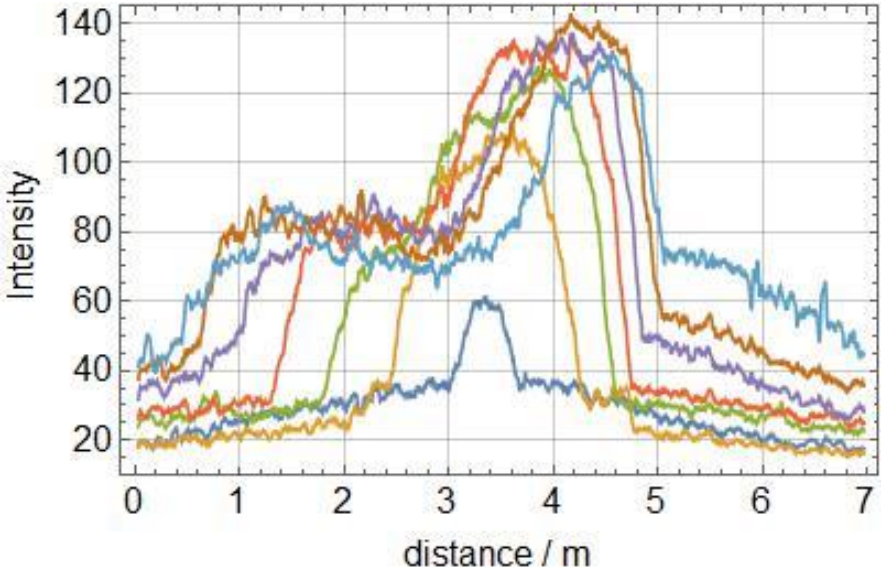
Interaction of Hydrogen Jets with Hot Surfaces

Explosion on ignition & upstream propagation



0.67ms time step



3.3ms time step

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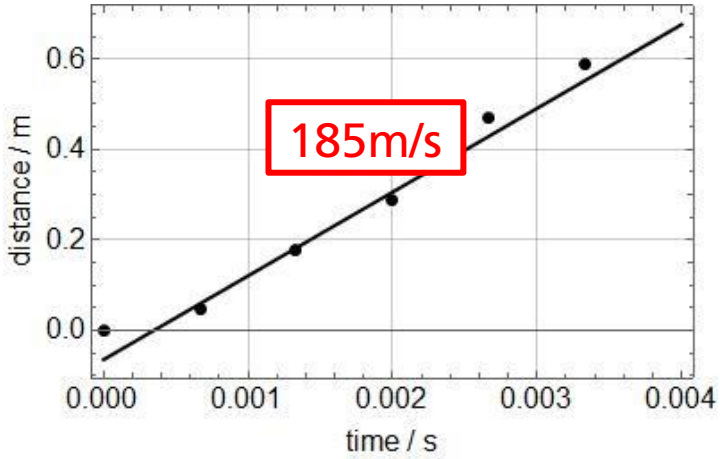
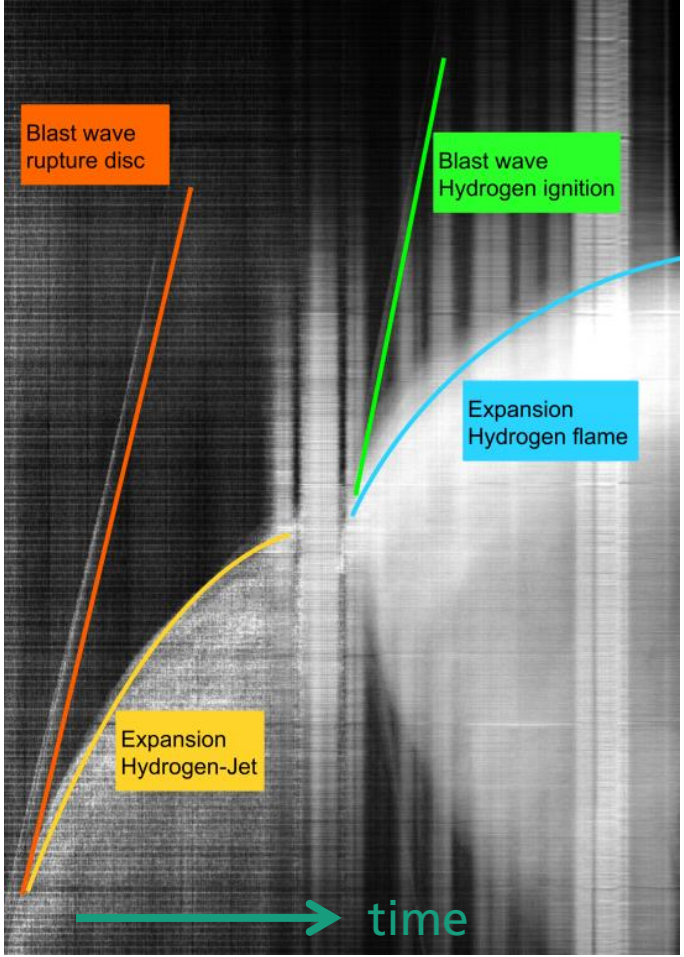
Interaction of Hydrogen Jets with Hot Surfaces
Overview on the movement

- All image sections around ignition point in the sequence compacted →
- Flame velocity of explosion ↓





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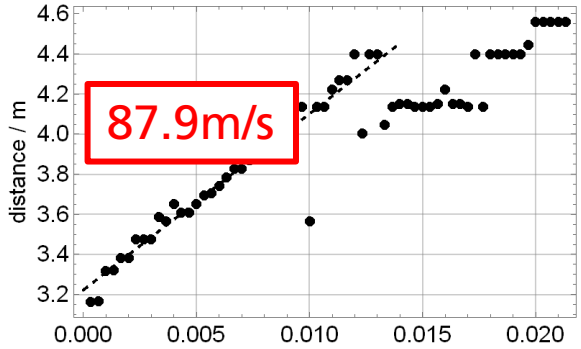
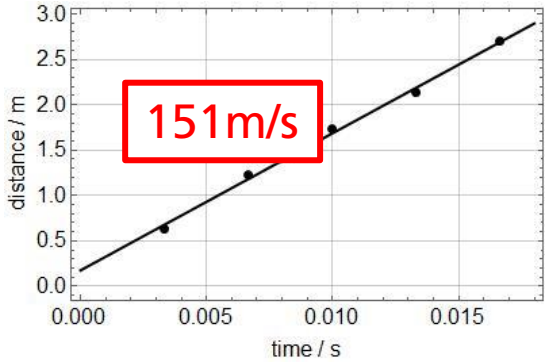
Movement





Downstream movement

maximum intensity

Fireball

Flame velocity

Upstream front

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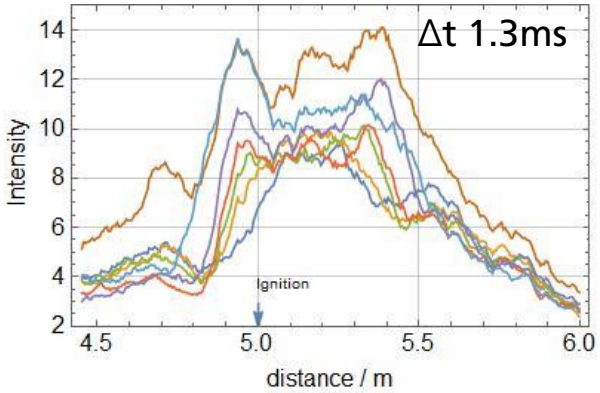
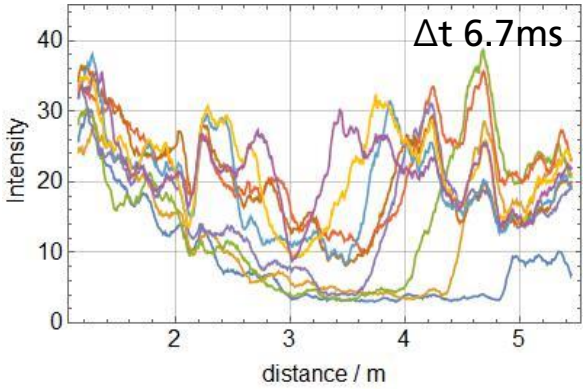
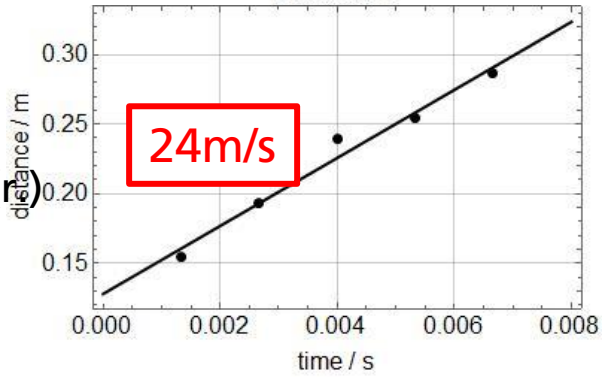
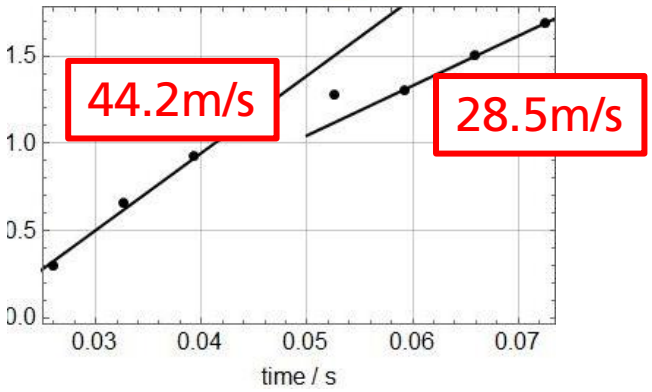
Interaction of Hydrogen Jets with Hot Surfaces
„Normal“ reaction

- Experiment H63
  20MPa / 5m / 950°C
- Explosion flame velocity (l.)
  24m/s close to spherical premixed
  → „Normal“
- Flame velocity running upstream (r.)
- Delayed when explosion @2m occurs









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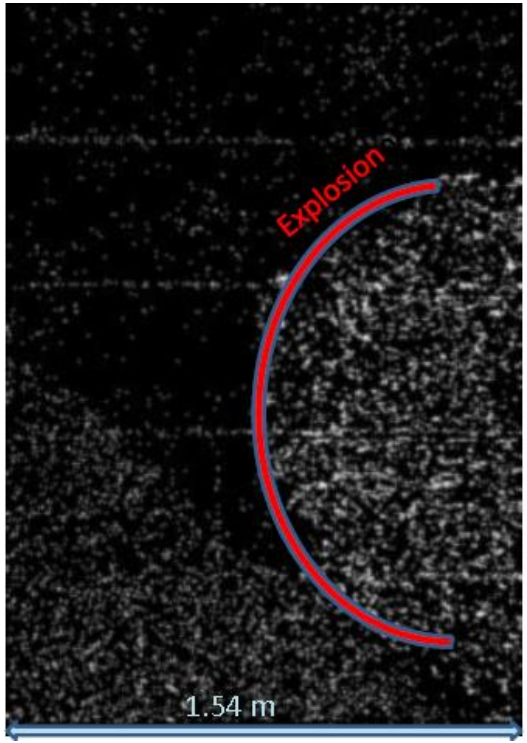
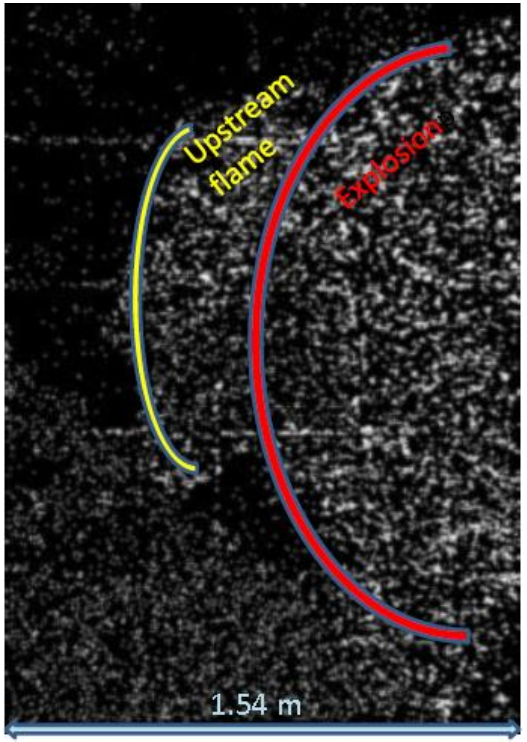
Interaction of Hydrogen Jets with Hot Surfaces
„Weak“ reaction

- Experiment H71
  20MPa / 7m / 850°C
- Reaction nearly invisible
- Explosion after 47ms
- No shockwaves
- Explosion and upstream propagation of the flame **ends after 166.7ms**





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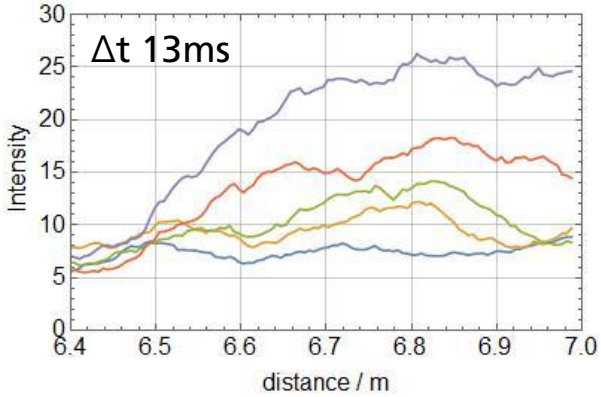
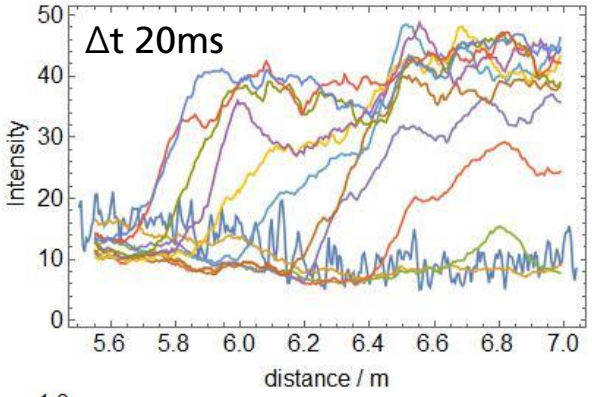
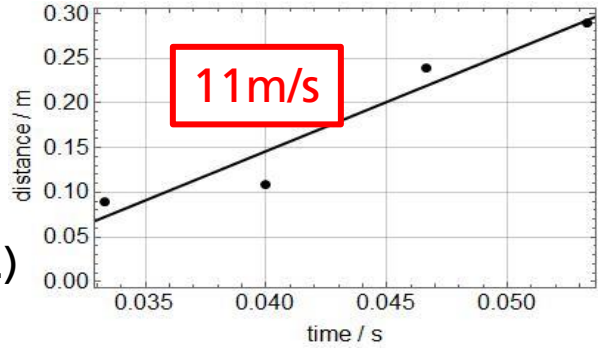
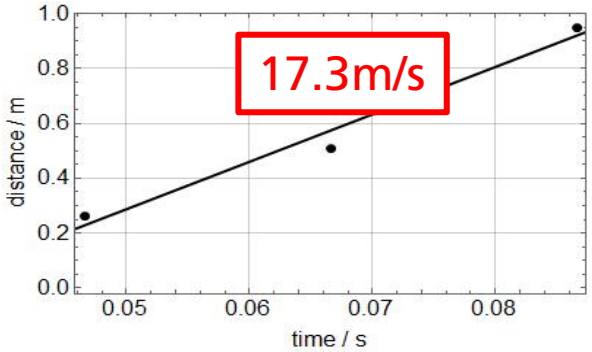
Interaction of Hydrogen Jets with Hot Surfaces
„weak“ reaction

- Experiment H71
  20MPa / 7m / 850°C
- Contour of explosion
- Contour of flame propagation
- Downstream shift after red & blue profile
- Corresponding explosion velocities (l.) & flame speed (r.)









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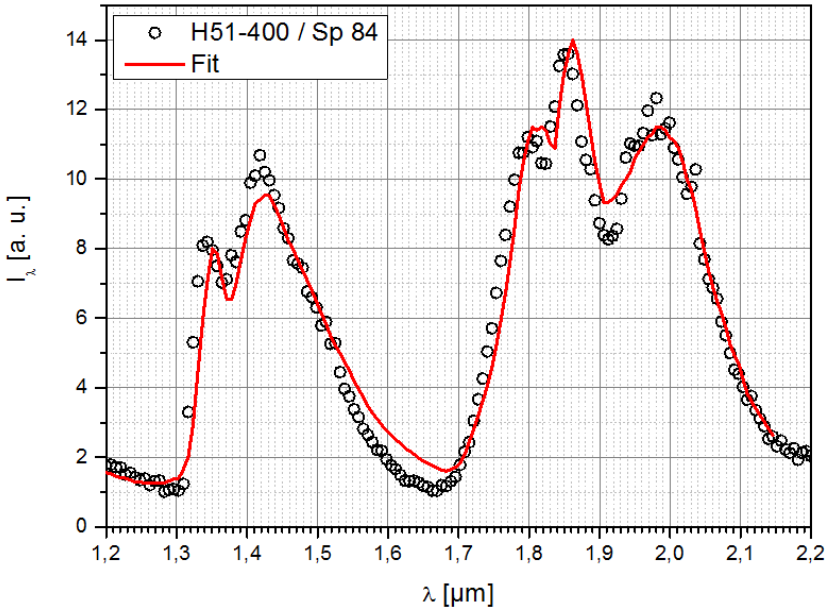
Spectroscopy

- Spectrometer
  - Avantes Avaspec NIR256-2.5TEC
  - 2000Spectra/s
- Field of View
  - Ø ≈ 10cm
  - Close to ignition point
- Least squares fit of waterbands
  - → Gas temperature
  - → 0.5 ms resolution in time



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Spectroscopy

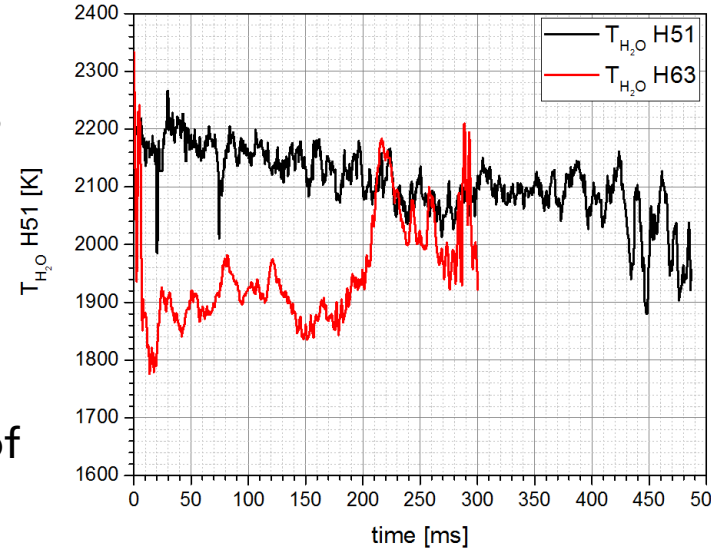
„Normal“ reaction:

- Colder for 200ms until stagnation

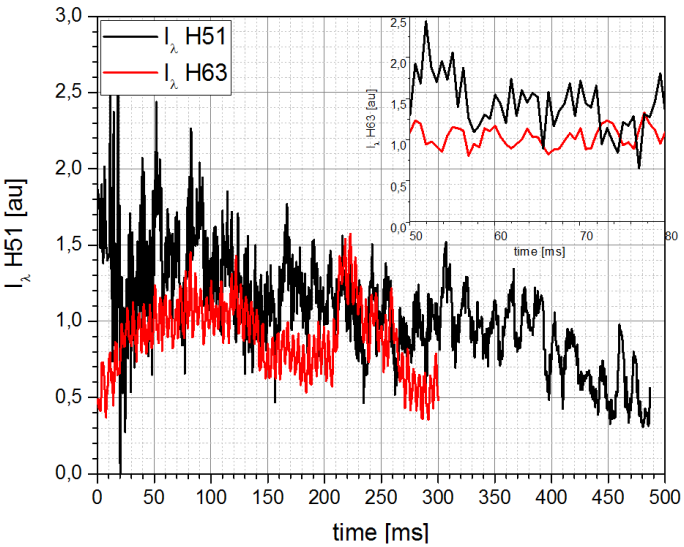
Oszillations

- lower & higher frequencies
- Probably effect of turbulent combustion
- To be investigated in more detail

Gas temperature



Over all intensities



Reaction type: „normal“ / „strong“

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Conclusion

- Interaction of H_2 jets investigated using high speed video analysis & BOS method
- Highspeed NIR spectroscopy used to obtain temperature profiles of deflagrations

- Jets ignite above 700°C under certain conditions
- Flame front propagation depends on all three varied parameters
  - Initial H_2 reservoir pressure
  - Temperature of the hot surface
  - Distance between nozzle and hot surface

Conclusion

- Resultion reactions can be classified into
  - **Strong** Generate shockwaves, deflagrate with velocities >100m/s
  - **Normal** Similar to premixed stochiometric spherical hydrogen-air explosions
  - **Weak** well below
- >20MPa strong deflagrations due to high turbulence possible
- Upstream flame propagation occurs in most cases
- Acquired temperature profiles allow estimations of
  - radiation emission
  - heat transfer on structures

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INTERNATIONAL CONFERENCE ON HYDROGEN SAFETY

September, 11-13 2017 - Hamburg (Germany)

ICHS International Conference on Hydrogen Safety

Thank you for your attention !