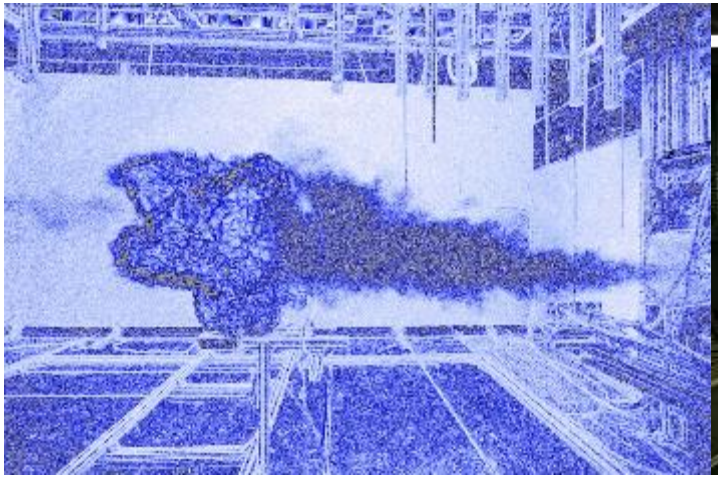
PRESLHY

PRESLHY Pre-normative REsearch for the Safe use of cryogenic Liquid HYdrogen



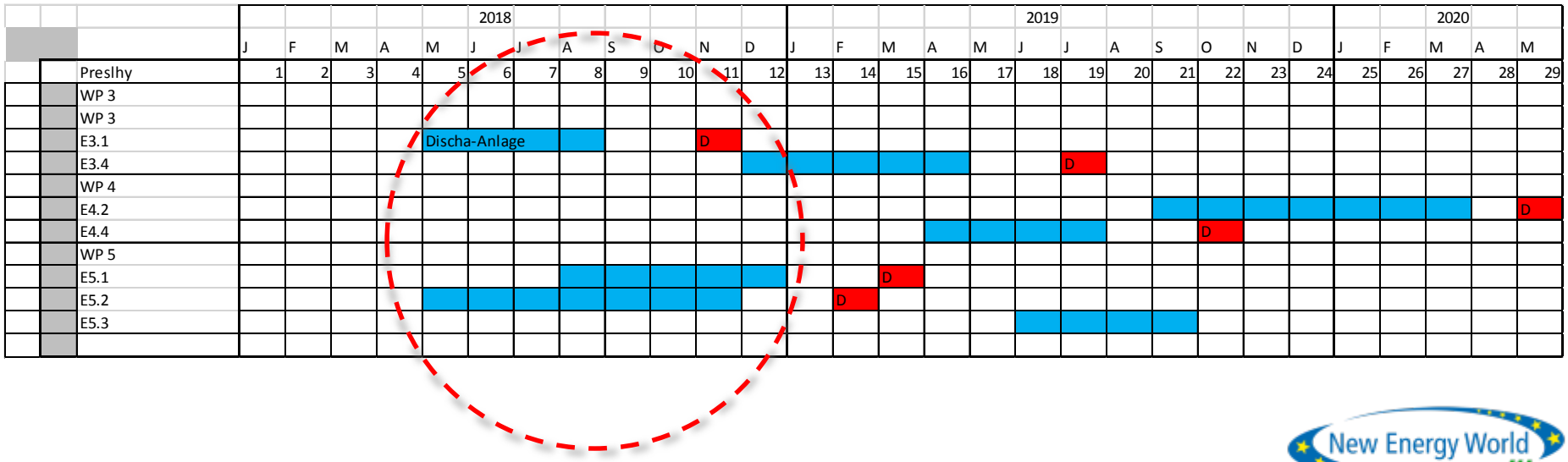
Kick-off meeting, KIT, Karlsruhe, 16-20 April 2018

Mike Kuznetsov, KIT

WP5 experimental program “Combustion”

Work package 3: **Release and Mixing**

Work package number	3	Start Date or Starting Event				Month 1				
Work package title	**Release and Mixing**									
Participant number	1	2	3	4	5	6	7	8	9
Short name of participant	KIT	AL	HSL	HySafe	INERIS	**NCSRD**	PS	UU	UW
Person/months per participant:	2	2	9	-	2	12	8	4	3



Small scale multiphase hydrogen release

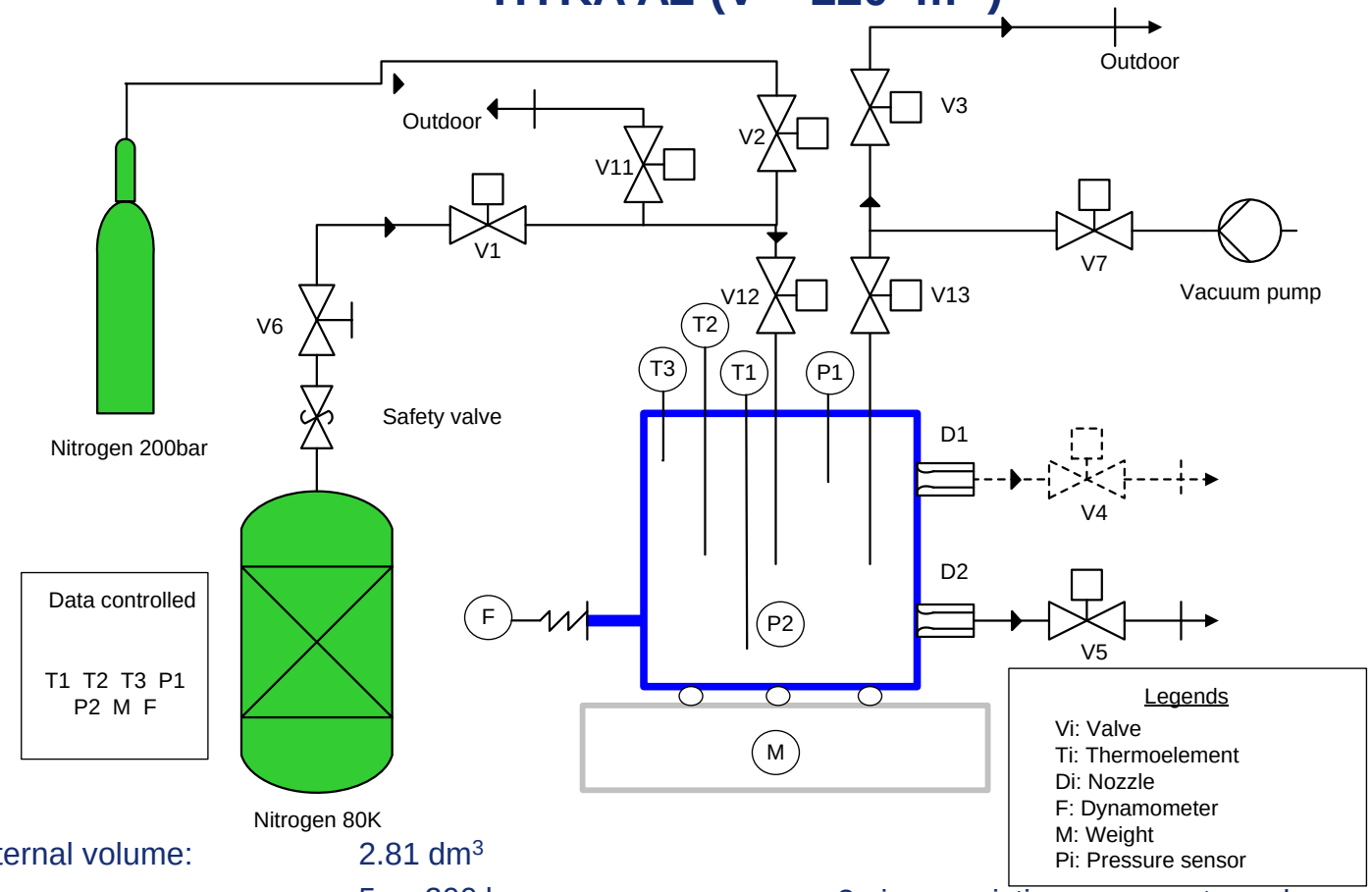
- Objectives
  - To investigate a transient two-phase discharge of cryogenic hydrogen jets in order to develop engineering correlations and provide experimental data for model validation. Dispersion measurements will also be performed to study the cryogenic jet structure and hazard distances.

- Measurements
  - Pressure inside the tank (1 sensor)
  - Temperature inside the tank (3 thermocouples)
  - Temperature at the exit nozzle (1 thermocouple)
  - Axial temperature along jet (5-10 sensors)
  - Tank weight (?)
  - Jet inertia (1 sensor)
  - Mass flow rate, exit velocity and exit vapour quality will be derived from the raw data. A high speed video combined with BOS technique monitor hydrogen dispersion (2-3 cameras)

- Variables
  - 4 bulk pressures within the range 1-200 bar
  - 4 storage temperatures in the range 25-200K
  - 4 release diameter sizes (0.5-4 mm)
  - 2 release positions (top/gaseous, bottom/liquid)

Experimental facility

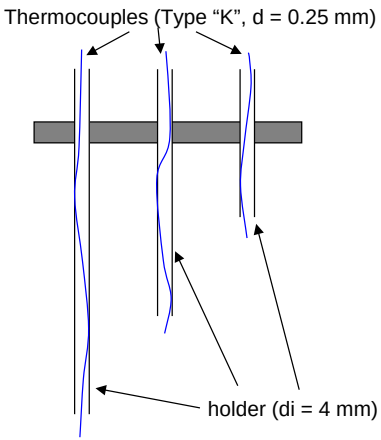
HYKA A2 (V = 220 m³)

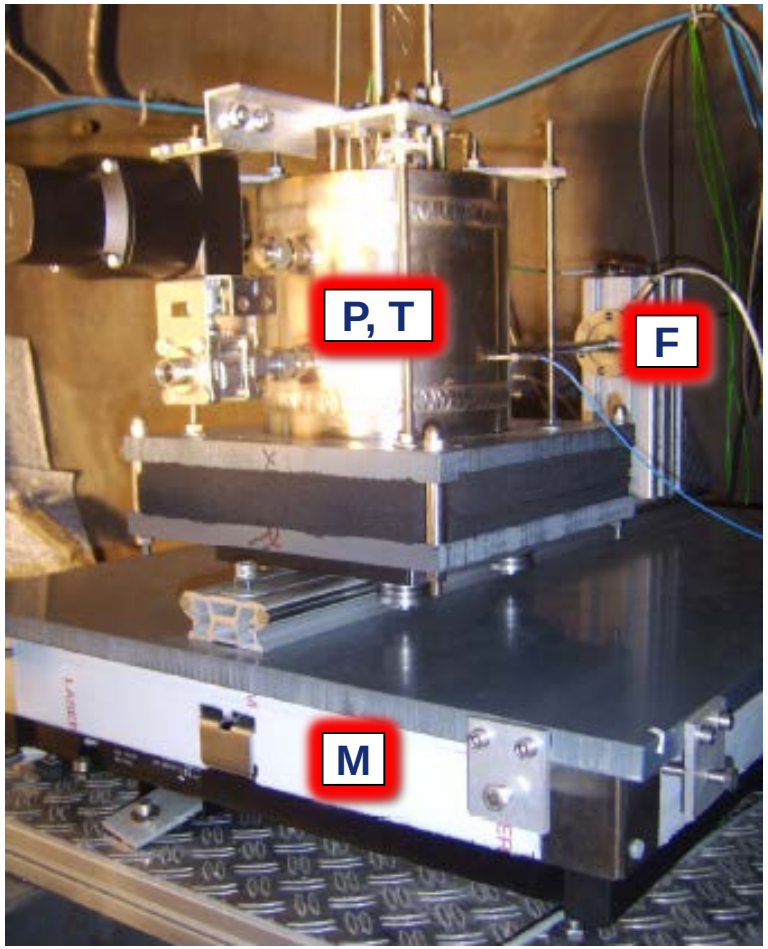


- Size of internal volume: 2.81 dm³
- Initial pressure: 5 … 200 bar
- Initial temperature 300K
- Two nozzle positions D1, D2
- Nozzle diameters 0.5, 1, 2, 3, 4 mm

- 2 piezo-resistive pressure transducers (P1, P2)
- 3 thermocouples (T1-T3)
- 1 force transducer (F)
- 1 scales (M)

Experimental facility (side view)





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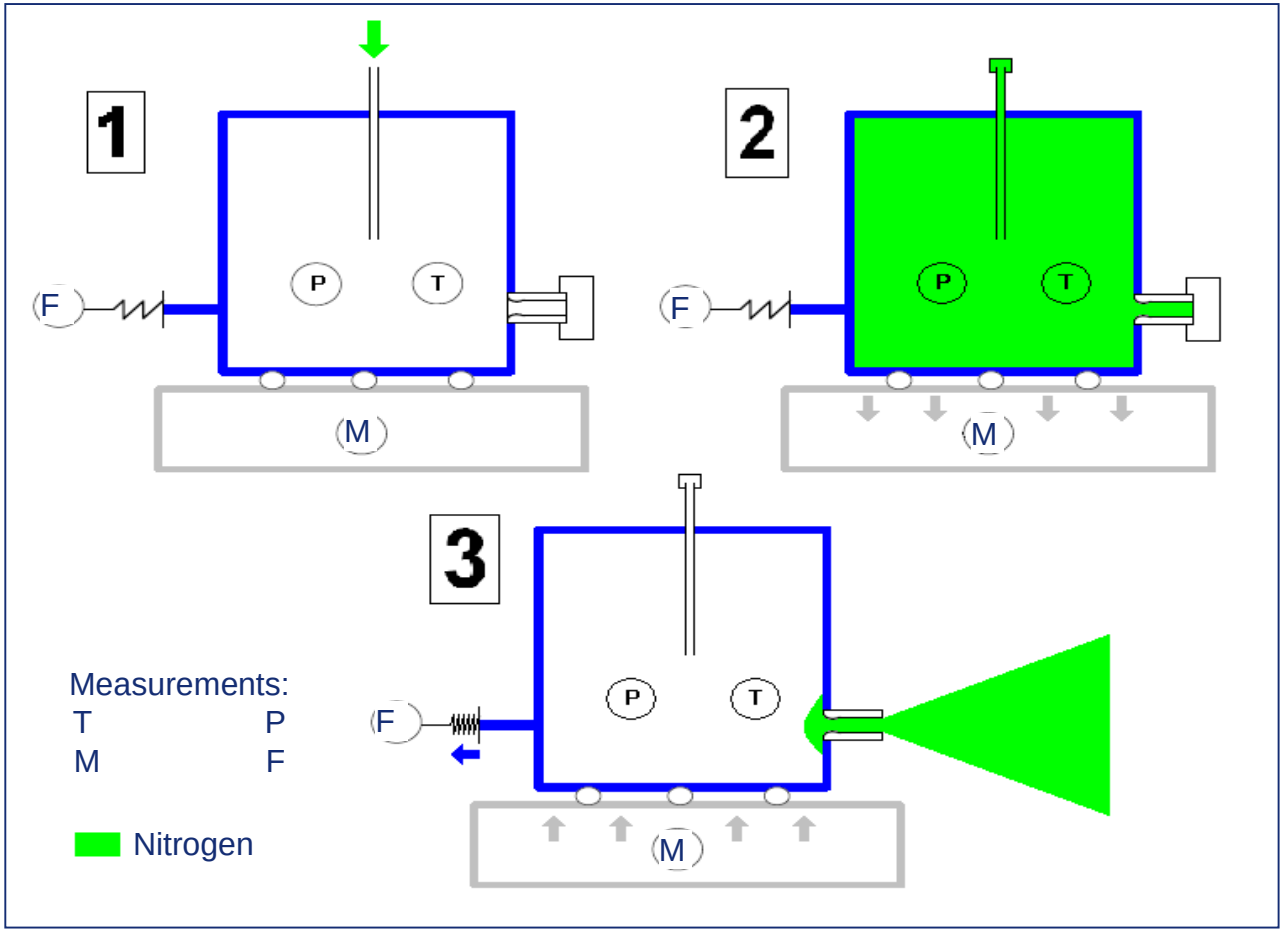
Test procedure



1 Pre-evacuation and gas filling
2 Equilibrium of state (P, T)
3 Blow down process(T, P, F, M)

- Simultaneous temperature, pressure, force and weight measurements provide independent measurements of mass flow rate

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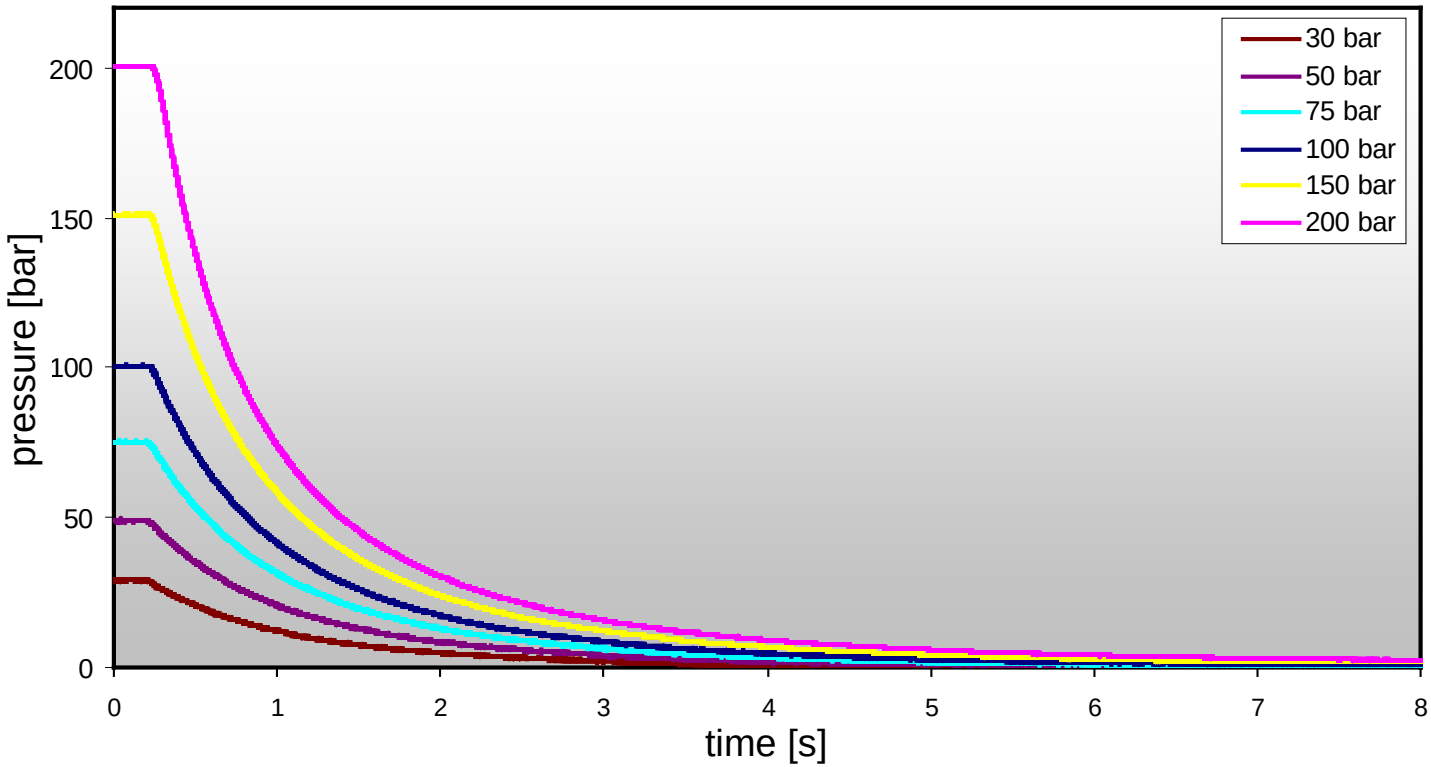
Expected results: pressure dynamics



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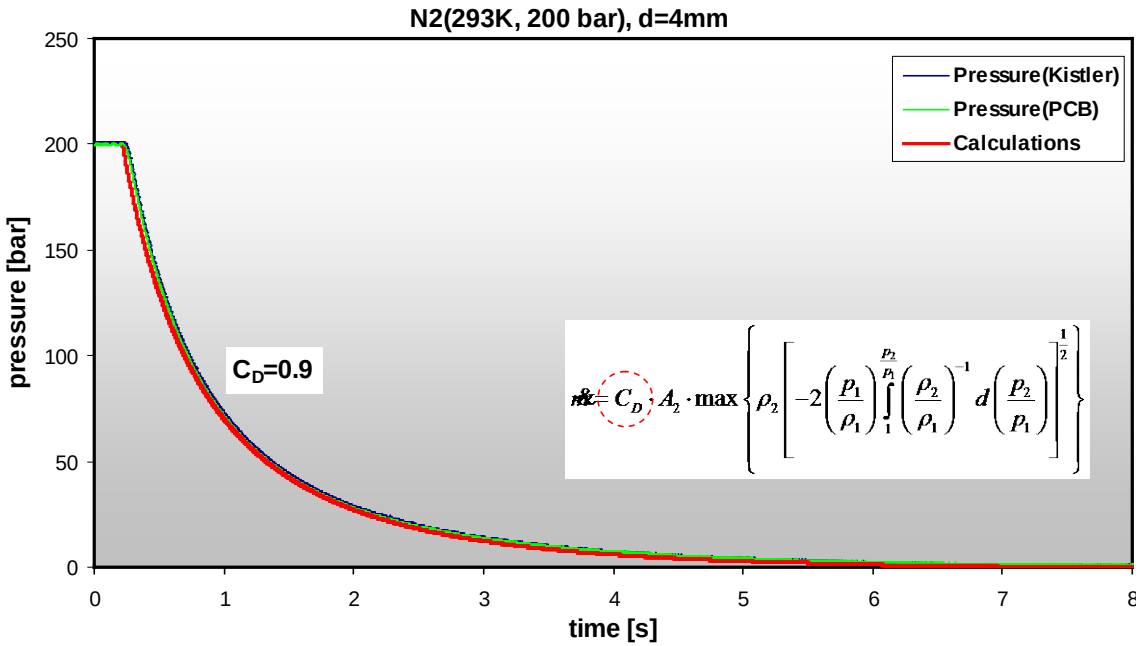
Calculations: a comparison with pressure measurements



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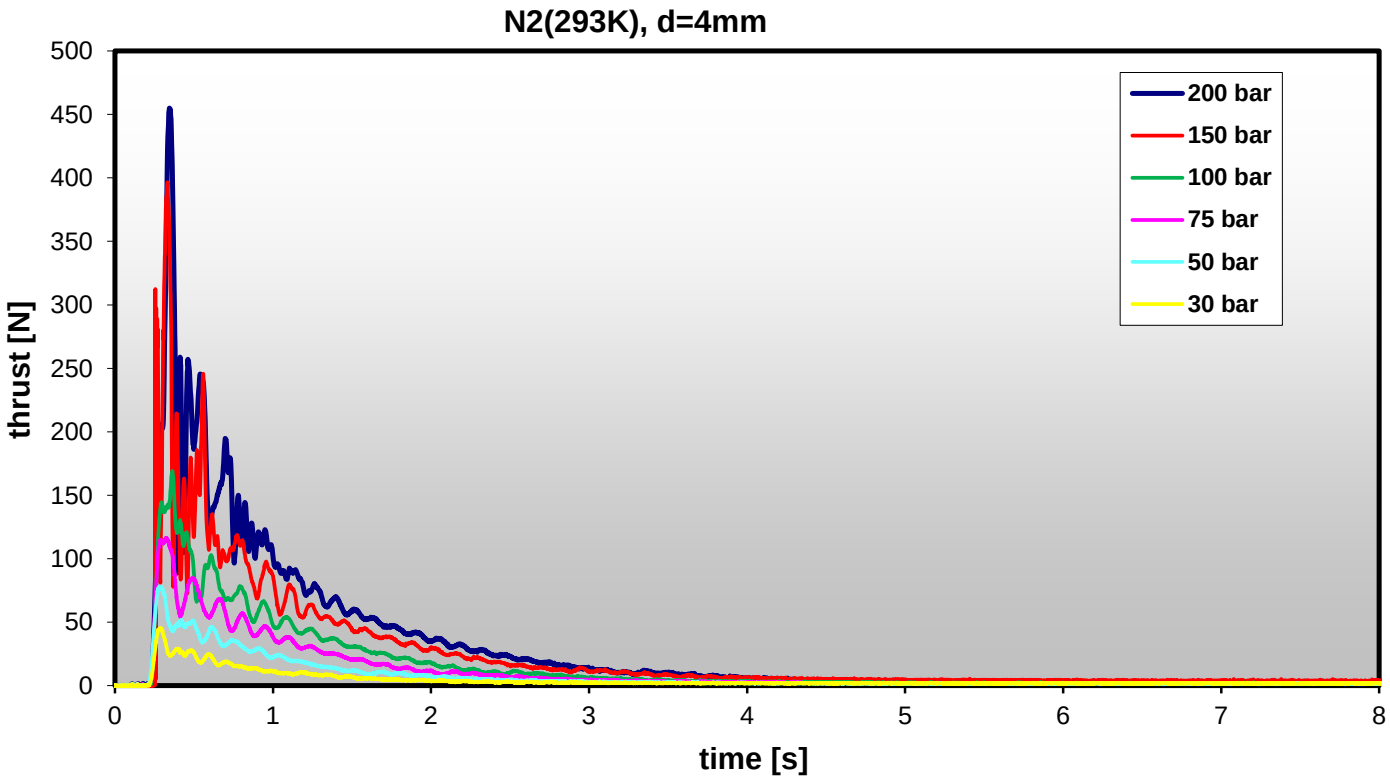
Expected results: thrust measurements



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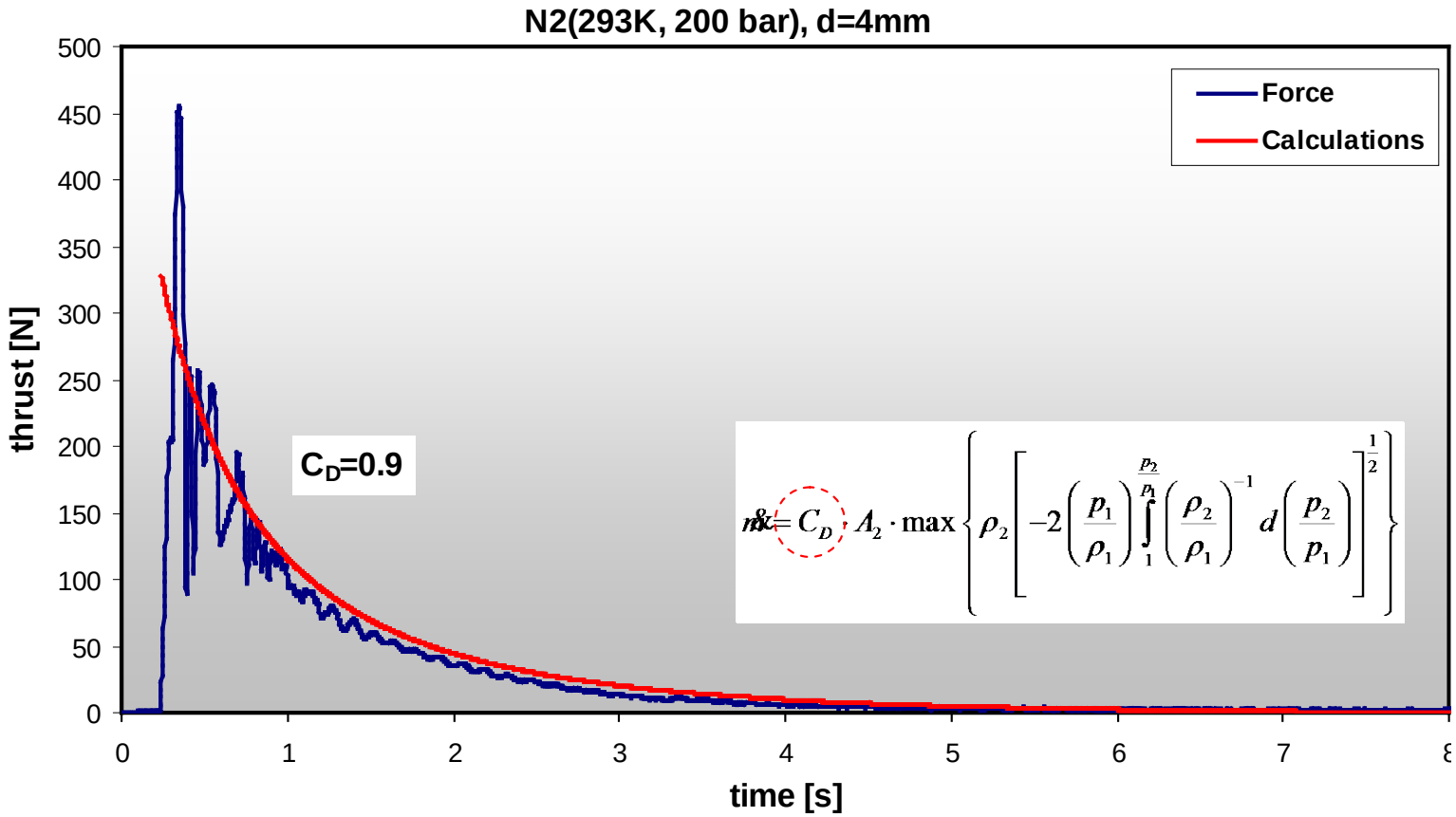
Calculations: a comparison with thrust measurements

$$F = \dot{m} V_e + (p_e + p_0) A_e$$



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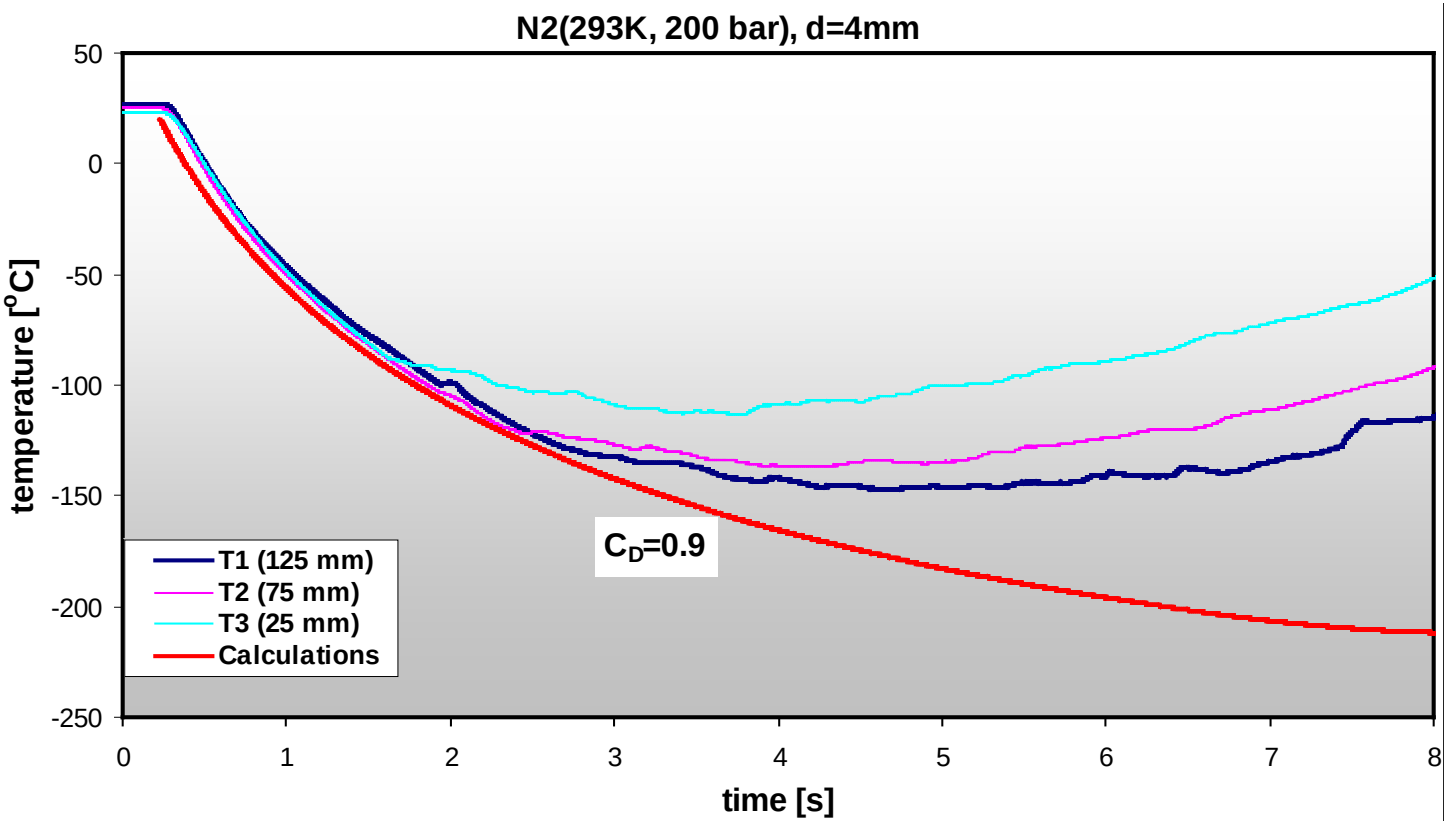
A comparison of experimental temperature measurements and calculations



- The biggest deviation of theoretical and experimental values was found for temperature measurements
- Main reason was the nonadiabatic process due to heat exchange gas – solid walls
- The longer was the blow-down process, the higher deviation occurred

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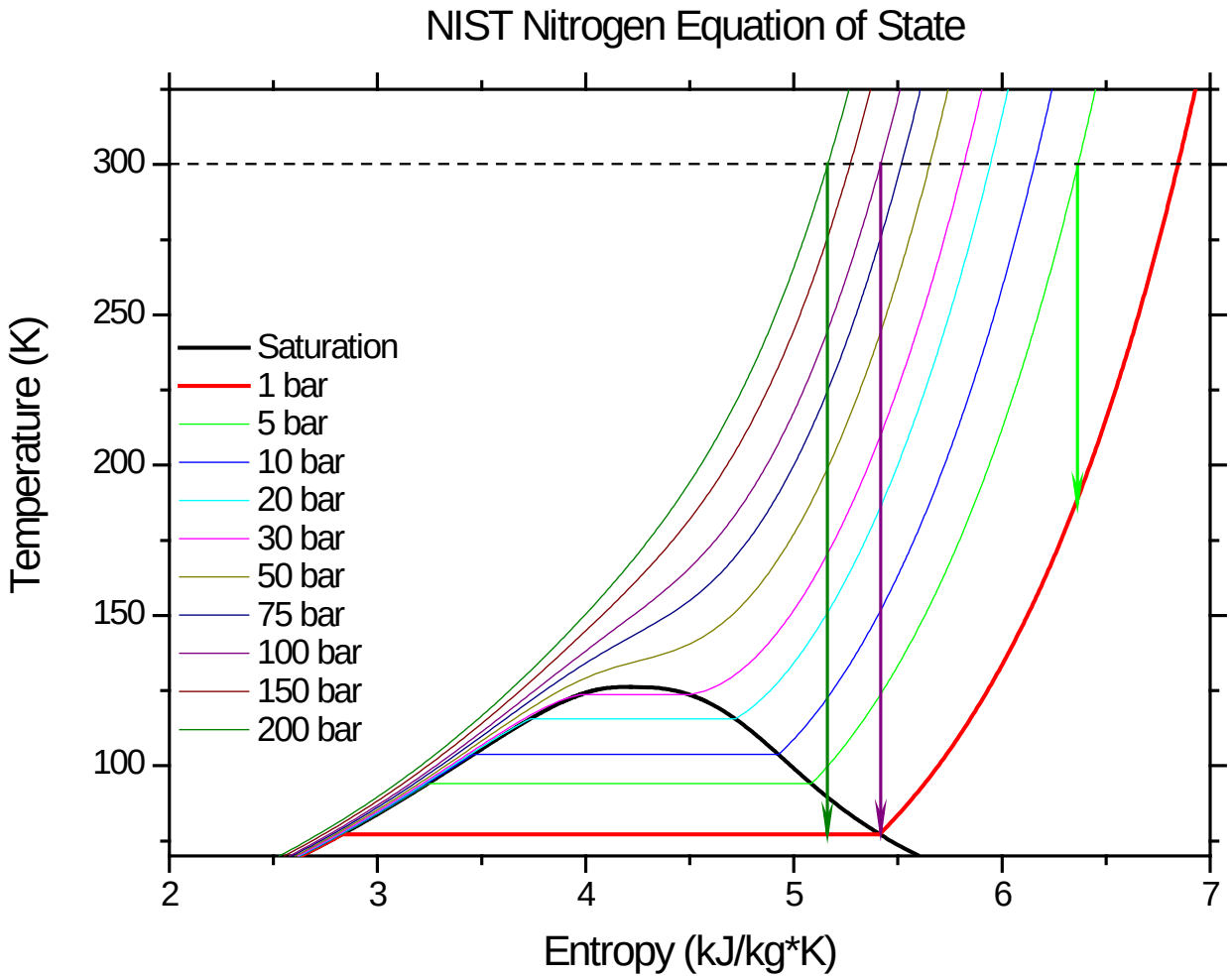
Experimental data analysis

Temperature – entropy (T-S) – diagram of state of real nitrogen (NIST)



- At initial pressure above 100 bar two-phase flow may occur

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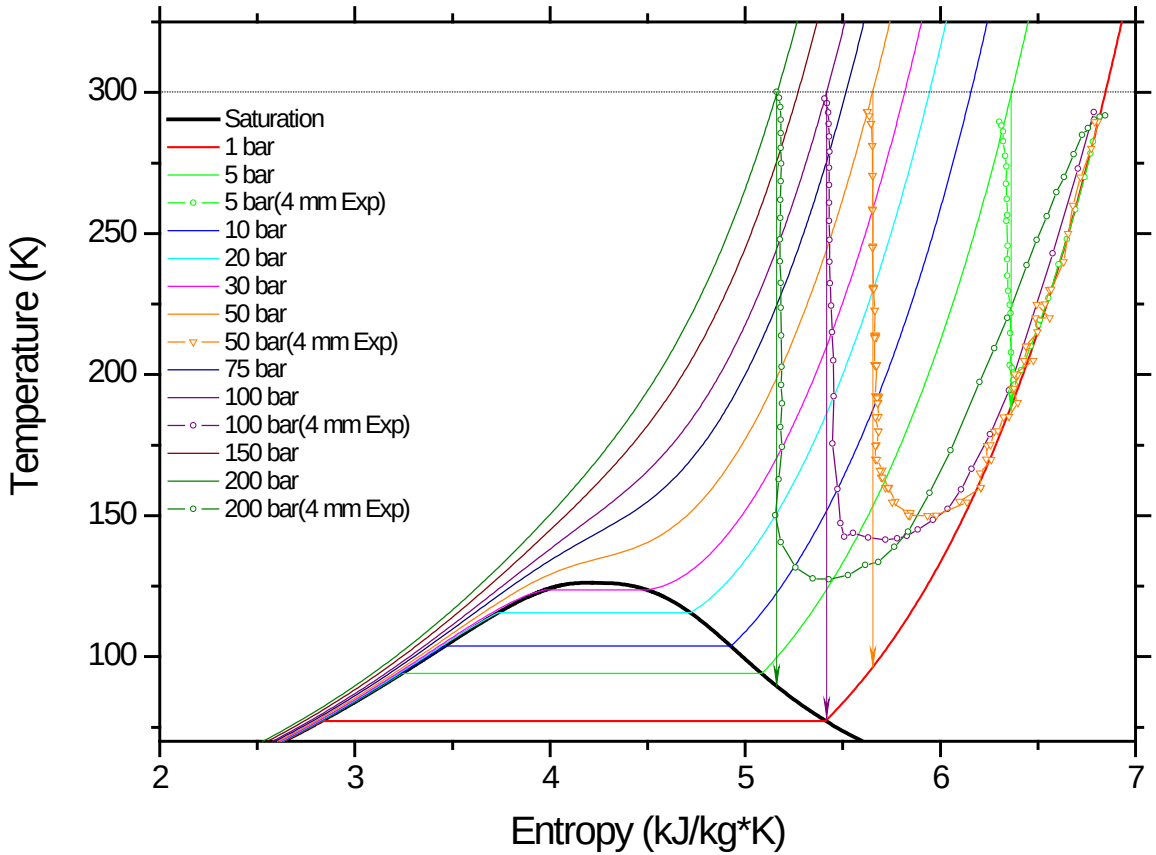
Experimental data analysis

Real nitrogen release at different initial pressures (4-mm nozzle)



- For 4-mm nozzle the entropy deviation appears when temperature difference reaches 120 – 150K due to heat transfer gas – solid wall
- Non- adiabatic blow down process occurs approaching subcritical blow down regime
- This was the reason why we did not reach the two-phase blow down process

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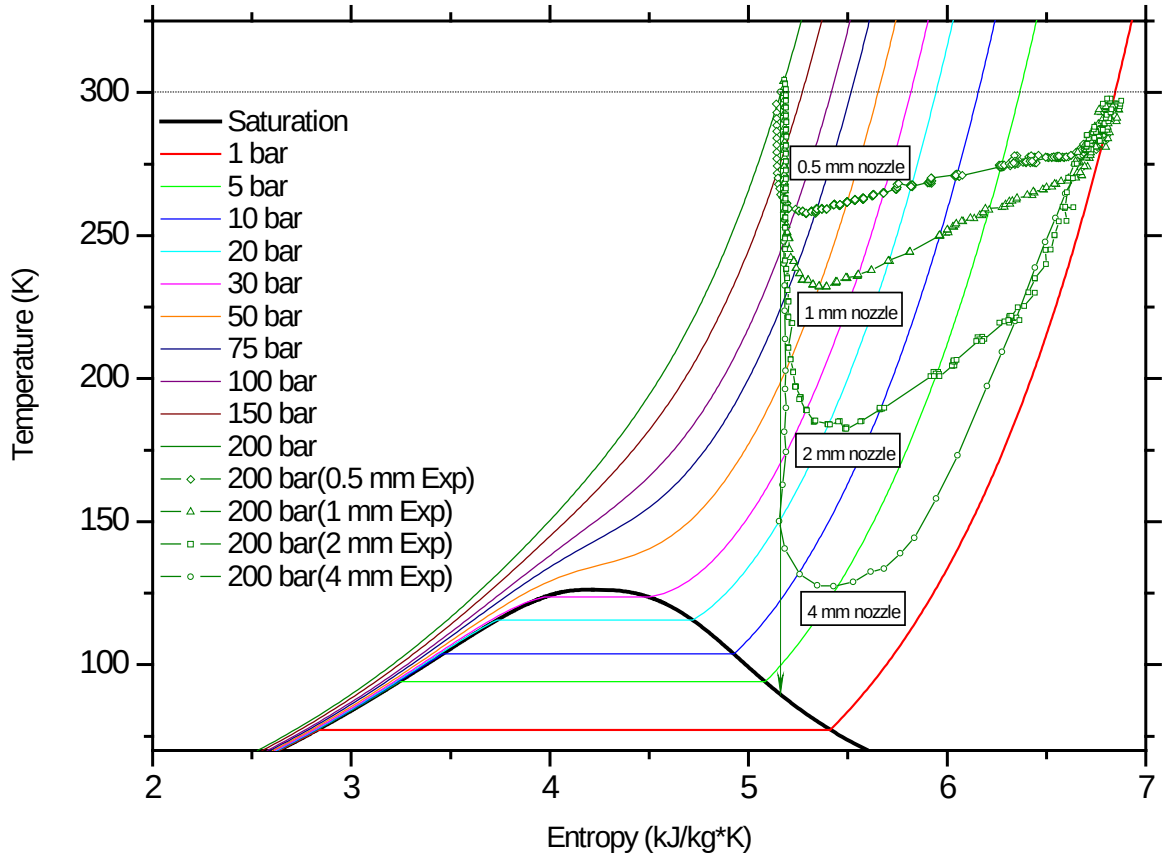
Experimental data analysis

Real nitrogen release at 200 bar and different nozzle diameter



- The less nozzle diameter and the longer the blow down process, the lower the temperature when non adiabatic effect or entropy deviation appears (at 200 bar):
  0.5-mm nozzle ΔT = 40K ; 1-mm nozzle ΔT = 60K ;
  2-mm nozzle ΔT = 120K ; 4-mm nozzle ΔT = 170K ;

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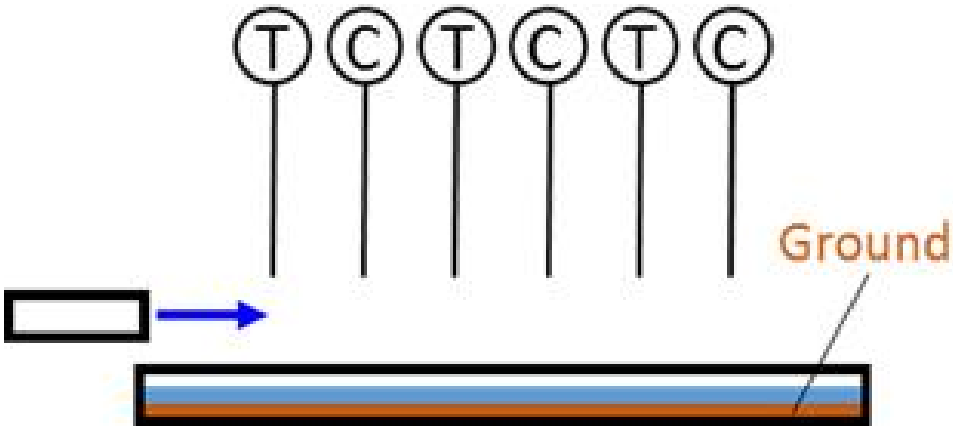
LH2 pool experiments

- Objectives
  - → To investigate the evaporation rate from an LH2 pool and the cold gas mixing phenomena in the near field above the pool. The experimental data will be used for validation of pool models and CFD dispersion models.
- Measurements
  - → Evaporation rate (weight)
  - → Vertical hydrogen concentration profile (an array 5x6 units)
  - → Vertical temperature profile (3-5 thermocouples)
  - → A high speed video combined with BOS technique (2-3 cameras)
  - → Ambient atmospheric conditions (temperature, pressure, humidity)
- Variables
  - → 3 ground materials (solid, liquid, porous)
  - → 3 initial ground temperatures in the range (77-300 K)%)

Experimental facility

HYKA A1, A2 (V = 100, 220 m^3)



- Experimental procedure
  - → Inside A2 vessel the tests should be done in inert atmosphere (N2)
  - → If the consequence will be a combustion process then experiments will take part inside vessel A1

Work package 5: Combustion

Work package number	5	Start Date or Starting Event				Month 1	
Work package title	**Combustion**						
Participant number	1	2	3	4	5	6	7
Short name of participant	**KIT**	AL	HSL	HySafe	NCSRD	Pro-Science	UU
Person/months per participant:	6	4	4		4	12	4

Objectives

- To complete the experimental database on cryogenic LH2 combustion, including laminar steady state and turbulent combustion and detonation of LH2 and gaseous hydrogen in air at cryogenic temperatures.
- To analyze experimental data in order to develop and validate existing or to generate new models for LH2 combustion.
- To develop empirical and semi-empirical engineering correlations for practical applications.
- The phenomena to be considered
  - → LH2 jet fire behaviour, including scaling and radiation properties
  - → Burning LH2 pool behaviour, radiation characteristics
  - → Cryogenic hydrogen combustion in a layer geometry relevant to flame spread over the spill of LH2
  - → Flame acceleration and DDT for cryogenic hydrogen-air clouds in an enclosure.
  - → BLEVE
  - → LH2 combustion in an enclosure. Effects of pressure, temperature, heat radiation, convection, geometry, pressure peaking
- The major characteristics to be investigated should be the pressure, temperature, heat flux, and dynamics of the processes. Effects of scale and turbulence should also be considered as parameters of the processes. Similar to LH2 distribution the combustion analysis shall include confinement geometry and obstructions

Theory and Analysis

- Based on theory and analysis a special attention will be paid to
  - Hydrogen combustion under cryogenic temperatures, at the conditions of very dense real gas state, close to condensed phase density.
  - Heterogeneous combustion in presence of condensed (liquid or solid) oxygen, nitrogen, CO_2 and H_2O (above hydrogen spill).
  - Effect of cryogenic temperatures on thermodynamics and kinetics of combustion process leading to several times lower speed of sound and viscosity of the gas
  - Simultaneous combustion and flush evaporation of hydrogen above the spill of LH_2
  - Effect of inverse hydrogen concentration gradient (higher hydrogen concentration at the ground level) on combustion dynamics in a layer geometry (above hydrogen spill).
  - Radiation characteristics of LH_2 combustion

Simulations

- Simulations to be done
  - The development of numerical models based on the theory and recent experimental results
  - Pre-test (blind) simulations of all phenomena for cryogenic LH2 combustion
  - Validation against new combustion experiments and code improvement
  - Competitive comparison or numerical results between partners' simulations
  - Simulations of real accident scenarios relevant to LH2 combustion
  - Generation of simplified engineering correlations for safety analysis

- The phenomena to be considered
  - LH2 jet fire behaviour, including scaling and radiation properties
  - Burning LH2 pool behaviour, radiation characteristics
  - Cryogenic hydrogen combustion in a layer geometry relevant to flame spread over the spill of LH2
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  - BLEVE
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Experiments

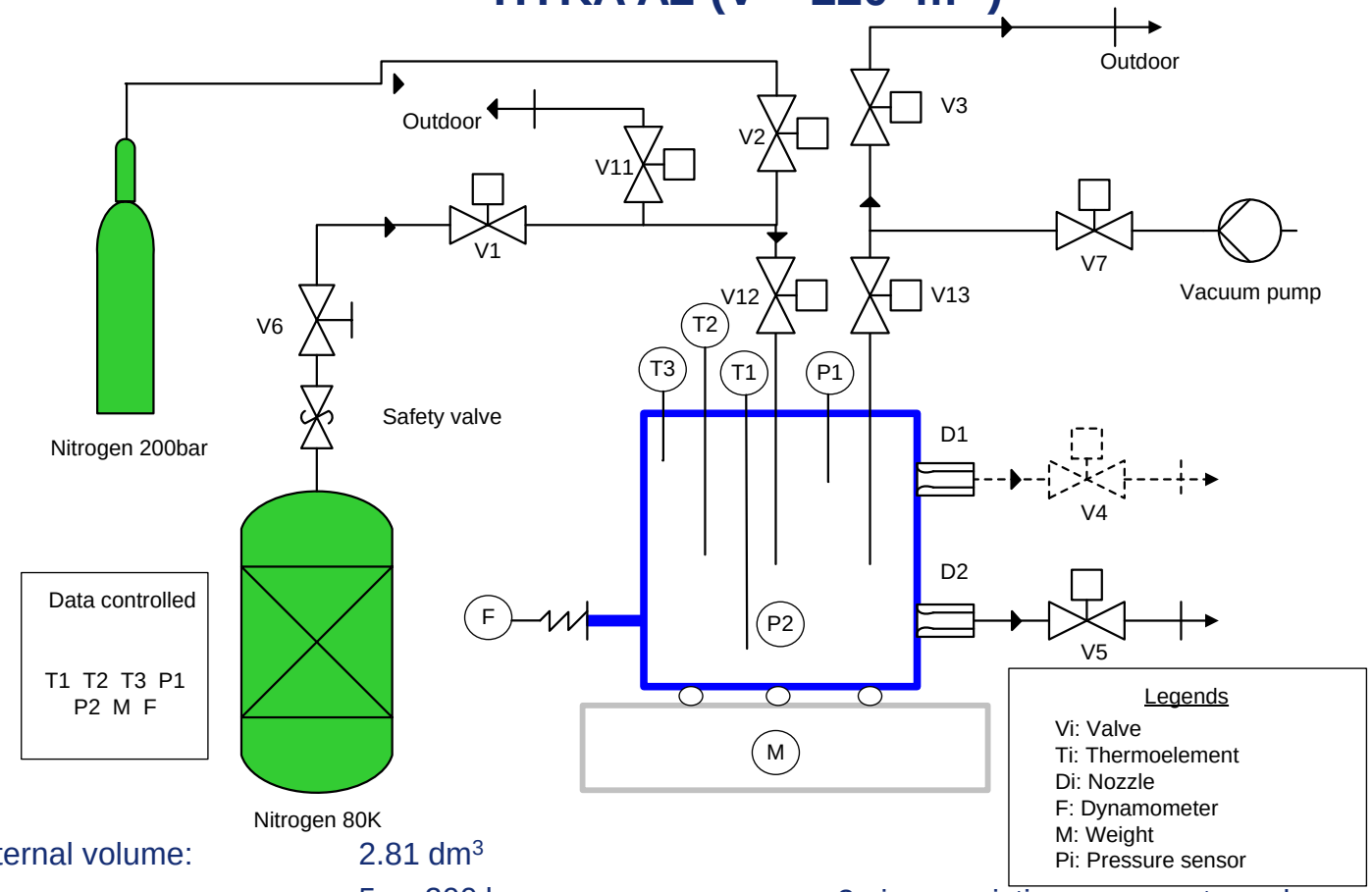
- Cryogenic hydrogen jet fire experiments with detailed temperature and heat flux measurements
- Flame propagation regimes at cryogenic temperatures
- Flame propagation over a spill of LH2
- BLEVE

Cryogenic hydrogen jet fire experiments

- Objectives
  - To close knowledge gaps and to generate the data for model validation on hazard distances due to pressure and heat radiation effects under delayed ignition of cryogenic hydrogen jet.
- Measurements
  - Pressure inside the tank (1 sensor)
  - Temperature inside the tank (3 thermocouples)
  - Distant pressure (3-5 sensors)
  - Heat flux (2-3 sensors)
  - Axial temperature along ignited jet (5-10 sensors)
  - A high speed video combined with BOS technique (2-3 cameras)
- Variables
  - 3 bulk pressures within the range 1-200 bar
  - 3 nozzle diameters (1, 2, 4 mm)
  - 5 ignition locations (0-2 m)
  - 4 time delays (0-1 s)

Experimental facility

HYKA A2 (V = 220 m³)



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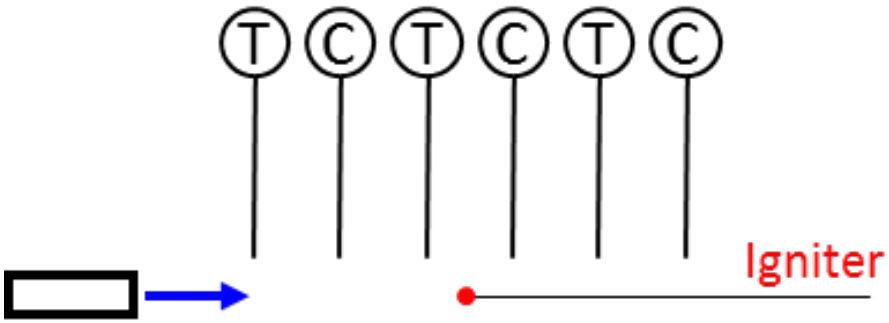
Experimental facility

HYKA A2 (V = 220 m^3)



Flame propagation regimes

- Objectives
  - To evaluate critical conditions for flame acceleration and detonation transition for hydrogen-air mixtures at cryogenic temperatures, possibly in presence of condensed oxygen and nitrogen. To evaluate the strongest possible combustion pressure for safety distances under LH2 explosions.
- Measurements
  - Dynamic pressure along the tube (5 sensors)
  - Photodiodes along the tube (10 units)
  - Static initial pressure (1 sensor)
  - Initial temperature along the tube (3-5 thermocouples)
  - A sooted plates technique for detonation cell size measurements
- Variables
  - 2 cryogenic initial temperatures in the range 77-100K
  - 2 blockage ratios (30%, 60%)
  - 2 spacing distances (1D, 2D)
  - 10 hydrogen concentrations in the range 6-12%H2, 15-20%H2, 30%H2, 60-75%H2

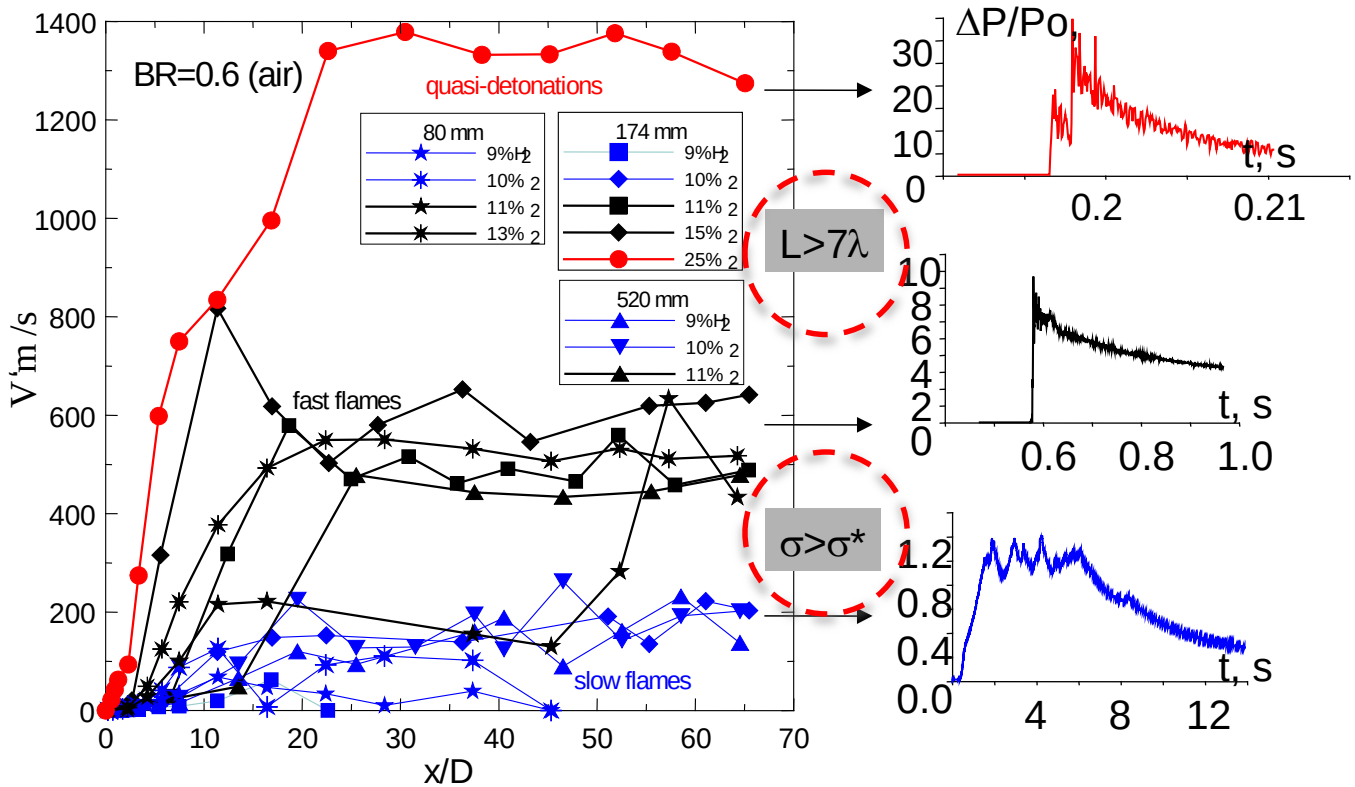
Experimental facility

HYKA A1 (V = 100 m^3)

- Experimental procedure
  - → The tests will be performed in an enclosed shock tube of 50 mm id and 5-m long (inside the safety vessel HYKA-A1). Different flame propagation regimes for hydrogen-air mixtures at cryogenic temperatures within the flammability limits will be investigated.

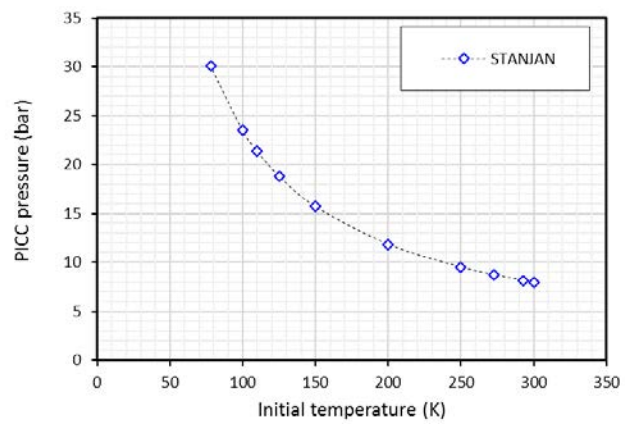
Expected results (reference data)

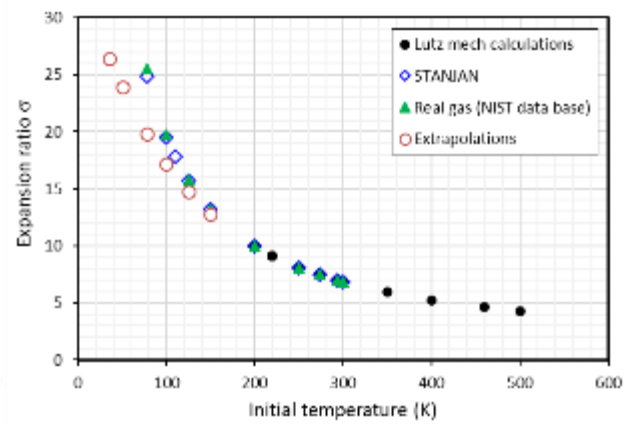
Flame propagation regimes

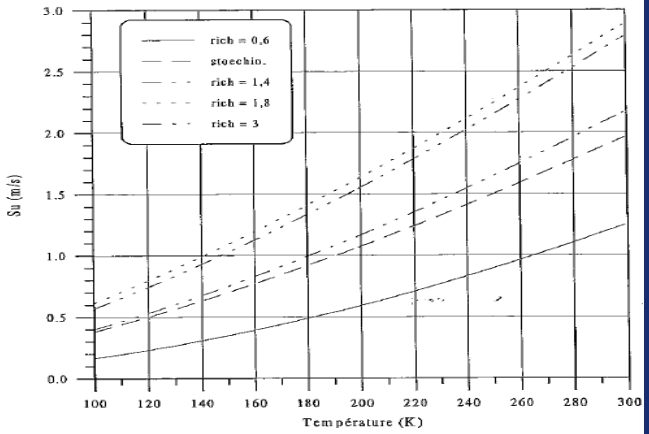


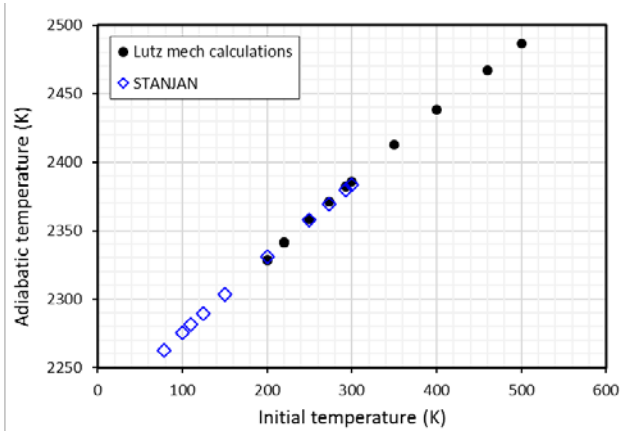
Expected results

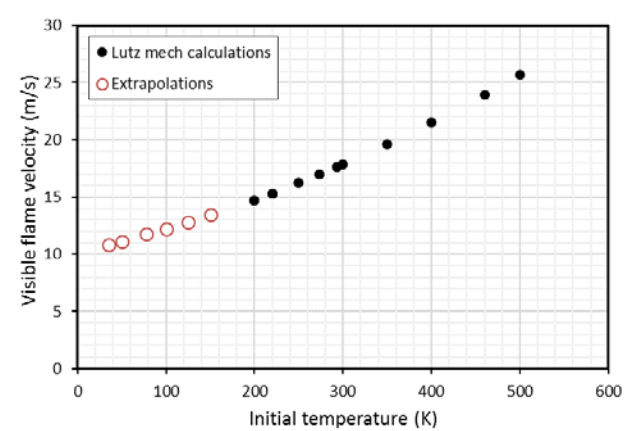
Combustion properties at cryogenic temperatures

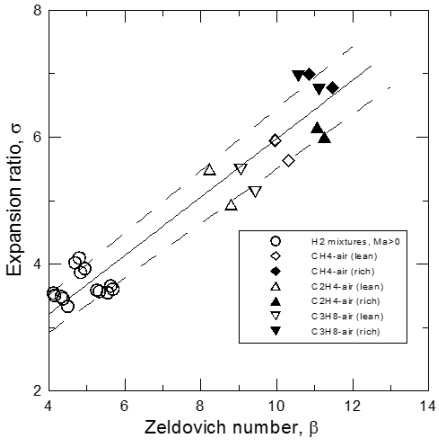








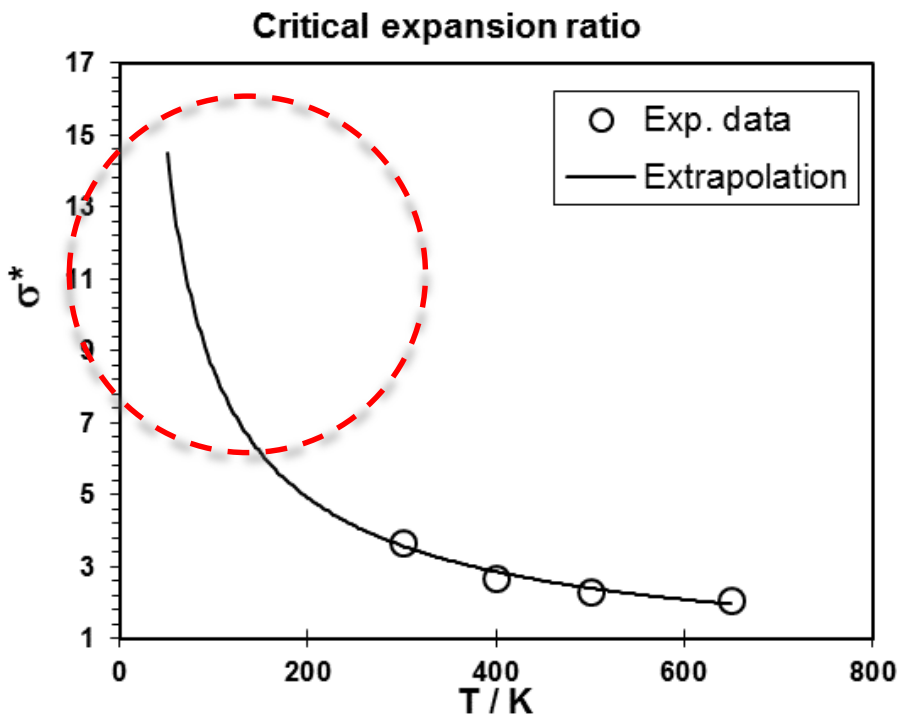




- Lack of fundamental data on combustion properties at cryogenic temperatures
  - → Dramatic changes of expansion ratio, PICC pressure and laminar flame velocity
  - → Not so big changes of TAICC

Prediction of the results

Critical expansion ratio for an effective flame acceleration



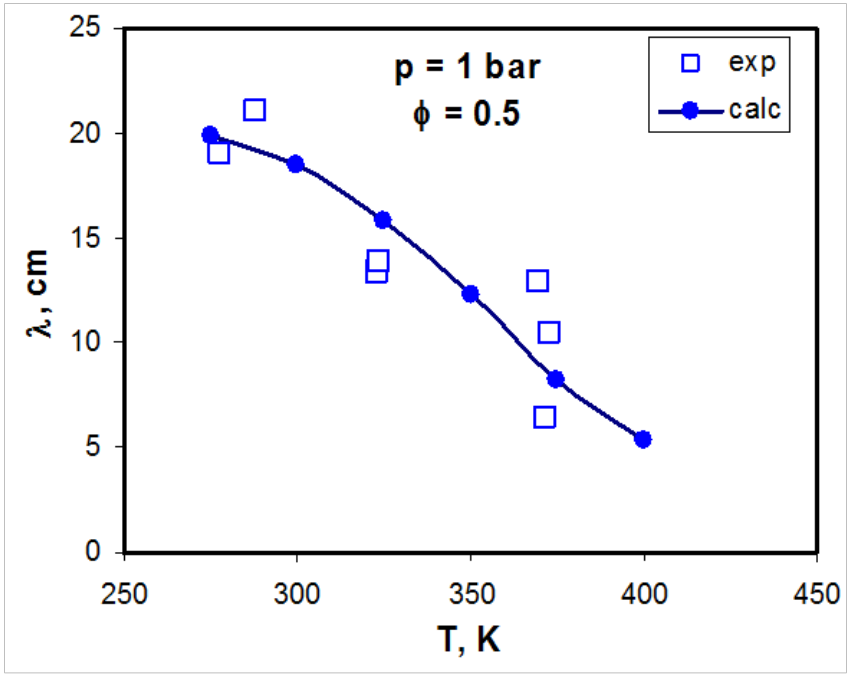
T, K	C_{H2}, %mol	σ*
300	11	3.75
200	10.34	4.92
150	10.09	6.14
100	9.58	8.49
78	9.13	10.67
50	8.60	13.89

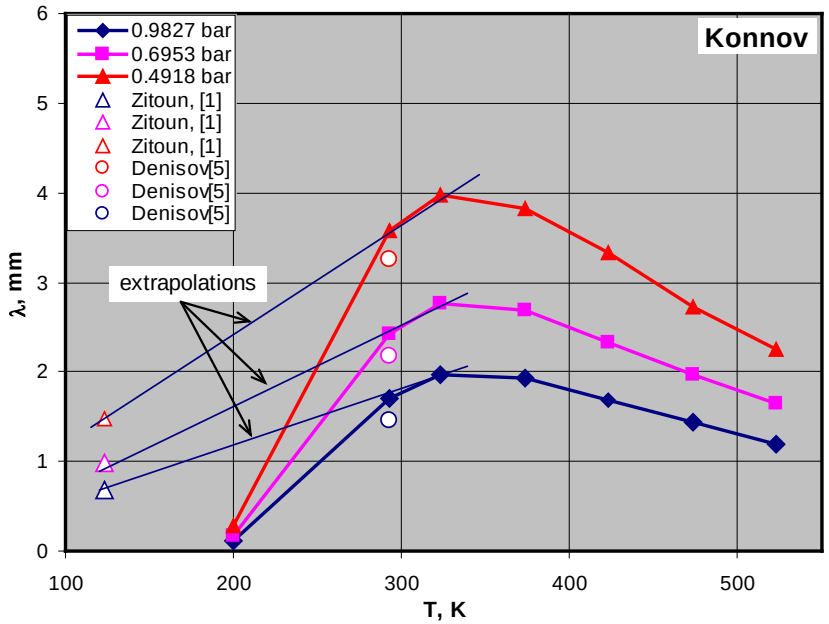
- Lack of fundamental data on combustion properties at cryogenic temperatures
  - → Too far extrapolation to be properly predicted
  - → Cannot be theoretically predicted up to now
  - → Experiments should be done

Prediction of the results

Detonation cell size (7λ criterion)

Hydrogen-air

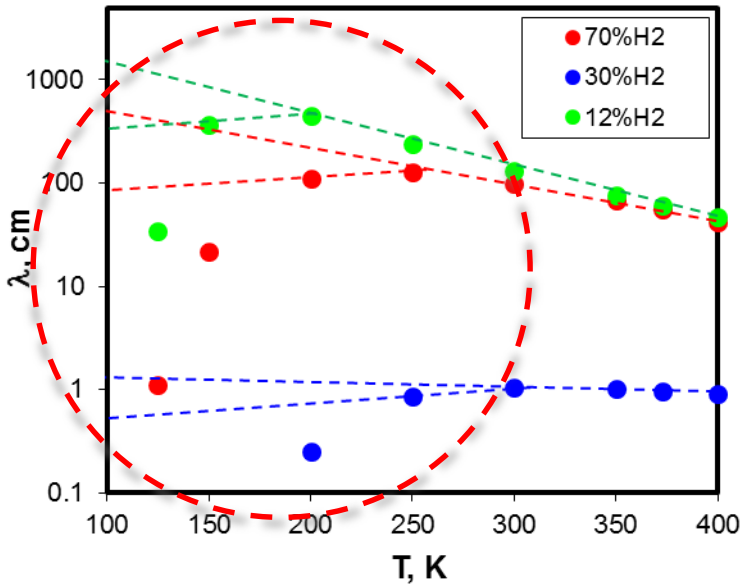




- Lack of fundamental data on combustion properties at cryogenic temperatures
  - → Too far extrapolation to be properly predicted
  - → Experiments should be done (sooted plates technique)

Prediction of the results

Detonation cell size (7λ criterion)



Temperature, T (K)	Detonation cell width λ, cm		
	Hydrogen concentration, %vol.		
	12	30	70
373	61	0.97	55
300	131	1.06	99
250	240	0.85	127
200	450	0.79	112
150	372	0.63	100
100	316	0.50	79

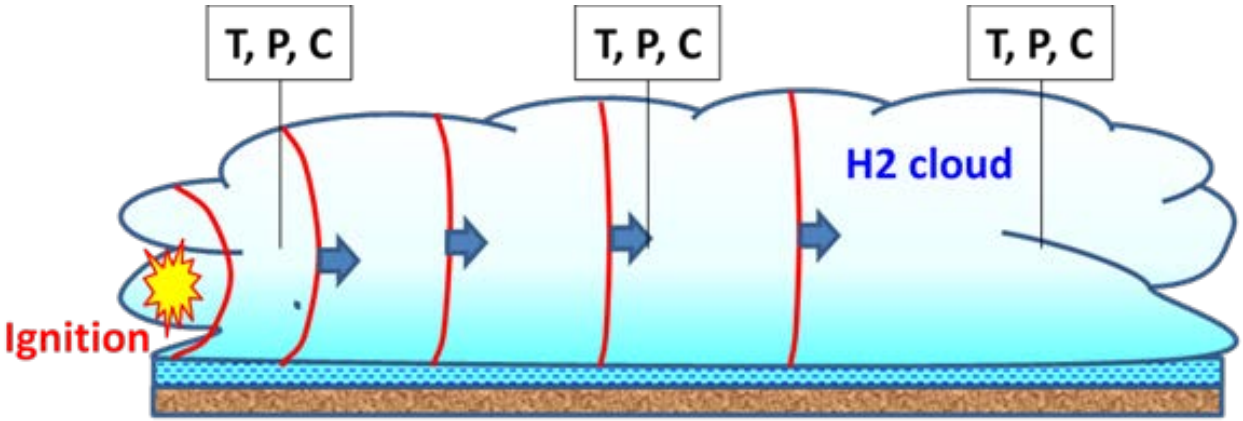
- Lack of fundamental data on combustion properties at cryogenic temperatures
  - → Too far extrapolation to be properly predicted
  - → Could be roughly predicted by numerical tools (CELL_H2)
  - → Experiments should be done (sooted plates technique)

Flame propagation over a spill of LH2

- Objectives
  - To evaluate a danger of flame propagation over a spill of LH2 in presence of inverse vertical hydrogen concentration gradient at cryogenic.
- Measurements
  - Local hydrogen concentration (an array 5x6 units)
  - Vertical temperature profile (3-5 thermocouples)
  - Dynamic pressure sensors (5 sensors)
  - Photodiodes (10 sensors)
  - Ion probes (10 sensors)
  - Axial temperature along the system (5-10 sensors)
  - A high speed video combined with BOS technique (2-3 cameras)
- Variables
  - 3 hydrogen concentration gradients
  - 3 layer thicknesses
  - 3 blockage ratios (0, 30 and 60%)

Experimental facility

HYKA A1 (V = 100 m^3)



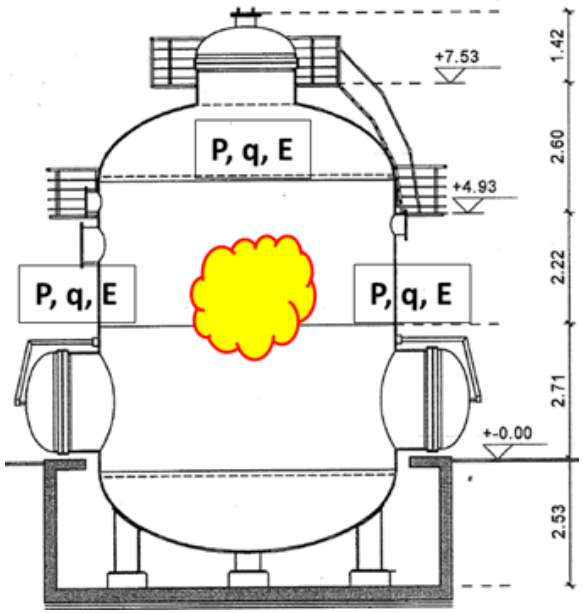
- Experimental procedure
  - The tests will be performed in a half open box 9x3 m2 with a height above 2 m inside the HYKA-A1 vessel (110 m3).
  - Natural hydrogen concentration gradient as above the LH2 will be created based on hydrogen evaporation rate measured within E3.4 experiments (WP3)
  - The natural temperature profile will optionally be created
  - The mixture should be ignited at the position of highest hydrogen reactivity to measure possible flame propagation velocity with and without obstacles.

BLEVE (boiling liquid expanding vapor explosion)

- Objectives
  - → To close knowledge gaps and data generation on LH2 tank rupture hazards – blast wave, fireball size, thermal radiation.
- Measurements
  - → Temperature profile (an array 5x5 thermocouples)
  - → Dynamic pressure (2-5 sensors)
  - → Heat flux (2-3 sensors)
  - → A high speed video combined with BOS technique for Rmax and lift-off dynamics (2-3 cameras)
- Variables
  - → 4 LH2 hydrogen inventory (10, 20, 50, 100 g LH2)
  - → 4 initial pressures (1, 2, 5, 10 bar).

Experimental facility

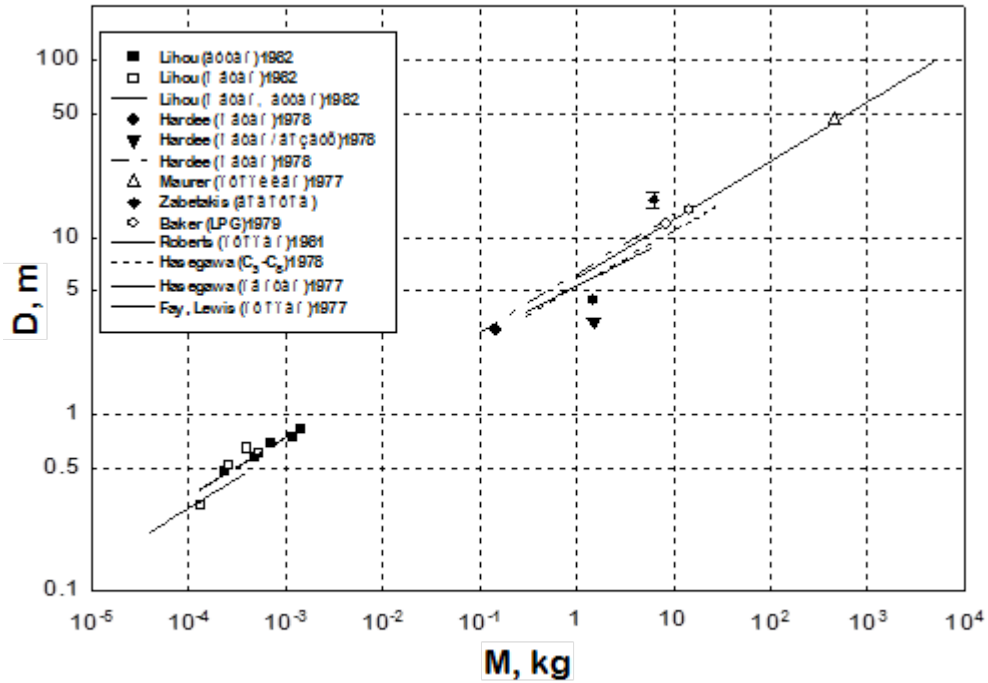
HYKA A2 (V = 220 m³)



- Experimental procedure
  - ➔ The tests will be performed inside the HYKA-A2 vessel (220 m3).
  - ➔ A pressurized liquid hydrogen inventory of different amount (<100 g) will be dispersed and ignited simultaneously

Expected results

Maximum radius of fireball



$$D=5.33\cdot M^{0.327}$$

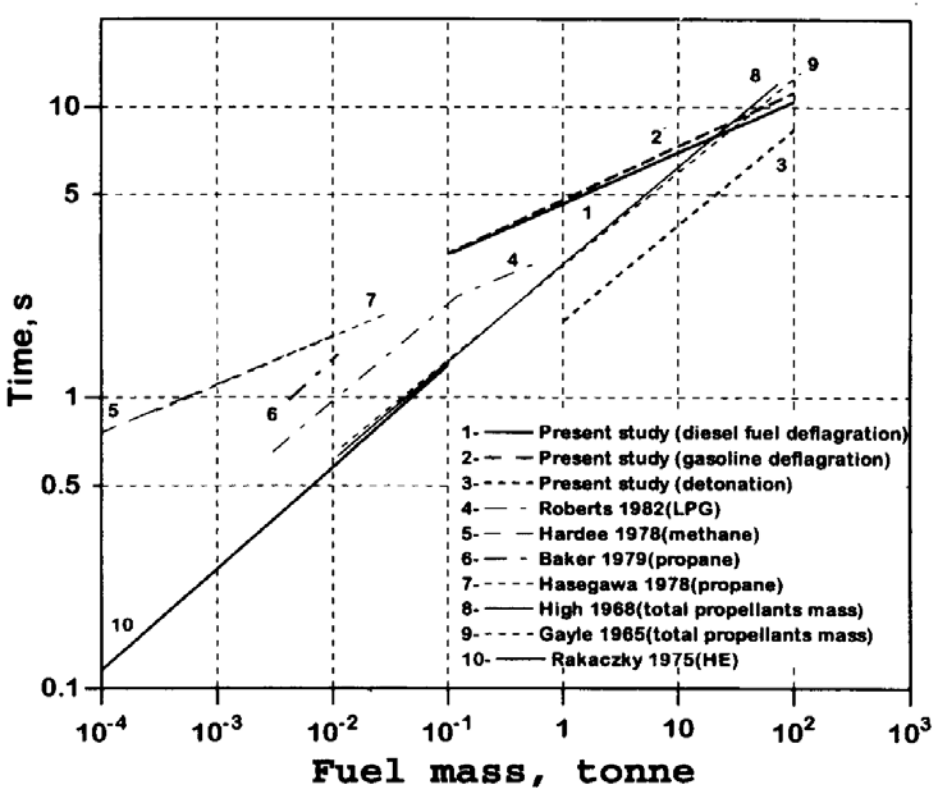
$$t_d = 0.45\cdot M_f^{1/3}.$$

$$E = 8.085\cdot M_f.$$

- Lack of fundamental data on fireball characteristics at cryogenic temperatures
  - → Behaves as BLEVE
  - → Experiments should be done

Expected results

Characteristic time for fireball



$$R = A \cdot M^{1/3}$$

$$H = D \cdot M^{1/3}$$

$$t = B \cdot M^{1/6}$$

BLEVE (Detonation, Sonic flame

$$t = B \cdot M^{1/3}$$

- Lack of fundamental data on fireball characteristics at cryogenic temperatures
  - → Behaves as BLEVE
  - → Experiments should be done

PRESLHY

Thank you!

AIR LIQUIDE

KIT

ΔΗΜΟΚΡΙΤΟΣ

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