International Conference on Hydrogen Safety (ICHS)

"Progress in safety of hydrogen technologies and infrastructure:
enabling the transition to zero carbon energy"

September 9-11, 2013 Brussels - Belgium

Experimental Investigation of Nonideality and Nonadiabatic Effects under High Pressure Releases

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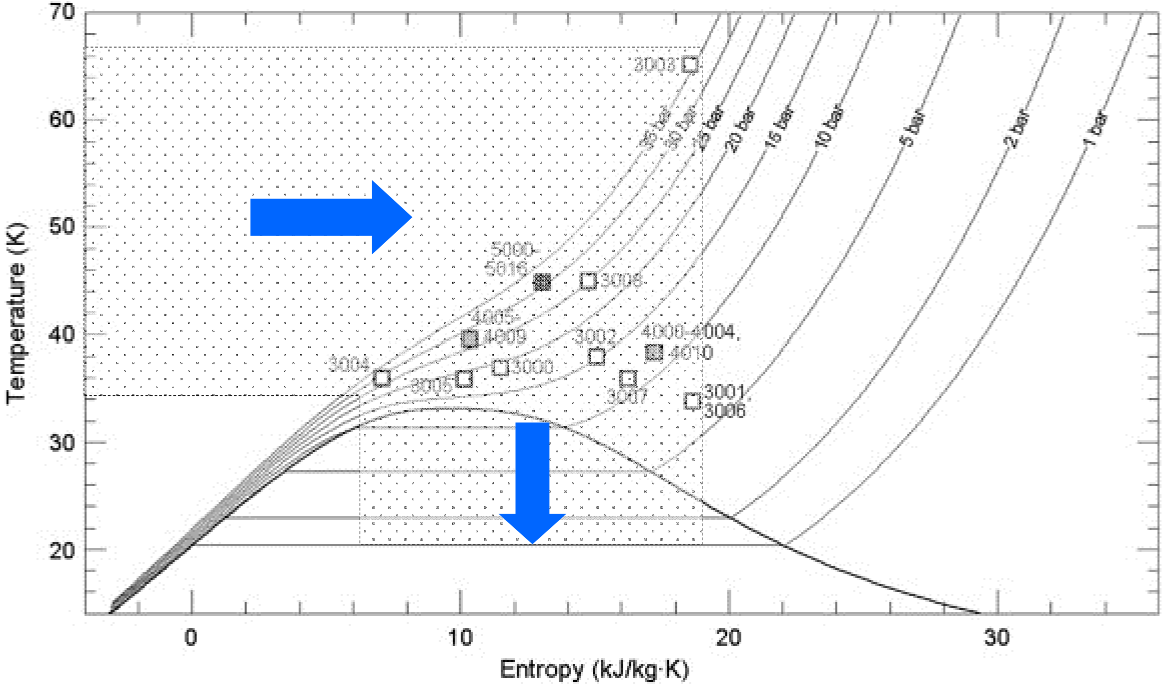
Background

The problem is related to the high pressure hydrogen releases in order to evaluate proper dynamics of the discharge and characteristic discharge time

Temperature – entropy (T-S) – diagram of state of real para-hydrogen (NIST+icefuel data)



- Problems to be solved: nonideality of the blow-down process (two-phase flow); non adiabatic character of the discharge process

Blow down mass flow rate

Solution of Bernoulli equation (integral form):

$$\dot{m} = C_D \cdot A_2 \cdot \max\left\{ \rho_2 \left[-2\left(\frac{p_1}{\rho_1}\right) \int_1^{\frac{p_2}{p_1}} \left(\frac{\rho_2}{\rho_1}\right)^{-1} d\left(\frac{p_2}{p_1}\right) \right]^{\frac{1}{2}} \right\}$$

1, u – upstream conditions
2, d – downstream conditions

$$C_D = \frac{\dot{m}_{\exp}}{\dot{m}_{theor}}$$

$$\dot{m} = C_D A_2 \begin{cases} \left\{ \gamma_u p_u \rho_u \left(\frac{2}{\gamma_u + 1}\right)^{\frac{\gamma_u + 1}{\gamma_u - 1}} \right\}^{\frac{1}{2}}; & \frac{p_d}{p_u} \le \left(\frac{2}{\gamma_u + 1}\right)^{\frac{\gamma_u}{\gamma_u - 1}} \\ \left\{ p_u \rho_u \frac{2\gamma_u}{\gamma_u - 1} \left[\left(\frac{p_d}{p_u}\right)^{\frac{2}{\gamma_u}} - \left(\frac{p_d}{p_u}\right)^{\frac{\gamma_u + 1}{\gamma_u}} \right] \right\}^{\frac{1}{2}}; & \frac{p_d}{p_u} > \left(\frac{2}{\gamma_u + 1}\right)^{\frac{\gamma_u}{\gamma_u - 1}} \end{cases}$$

critical (chocked) flow

subcritical flow

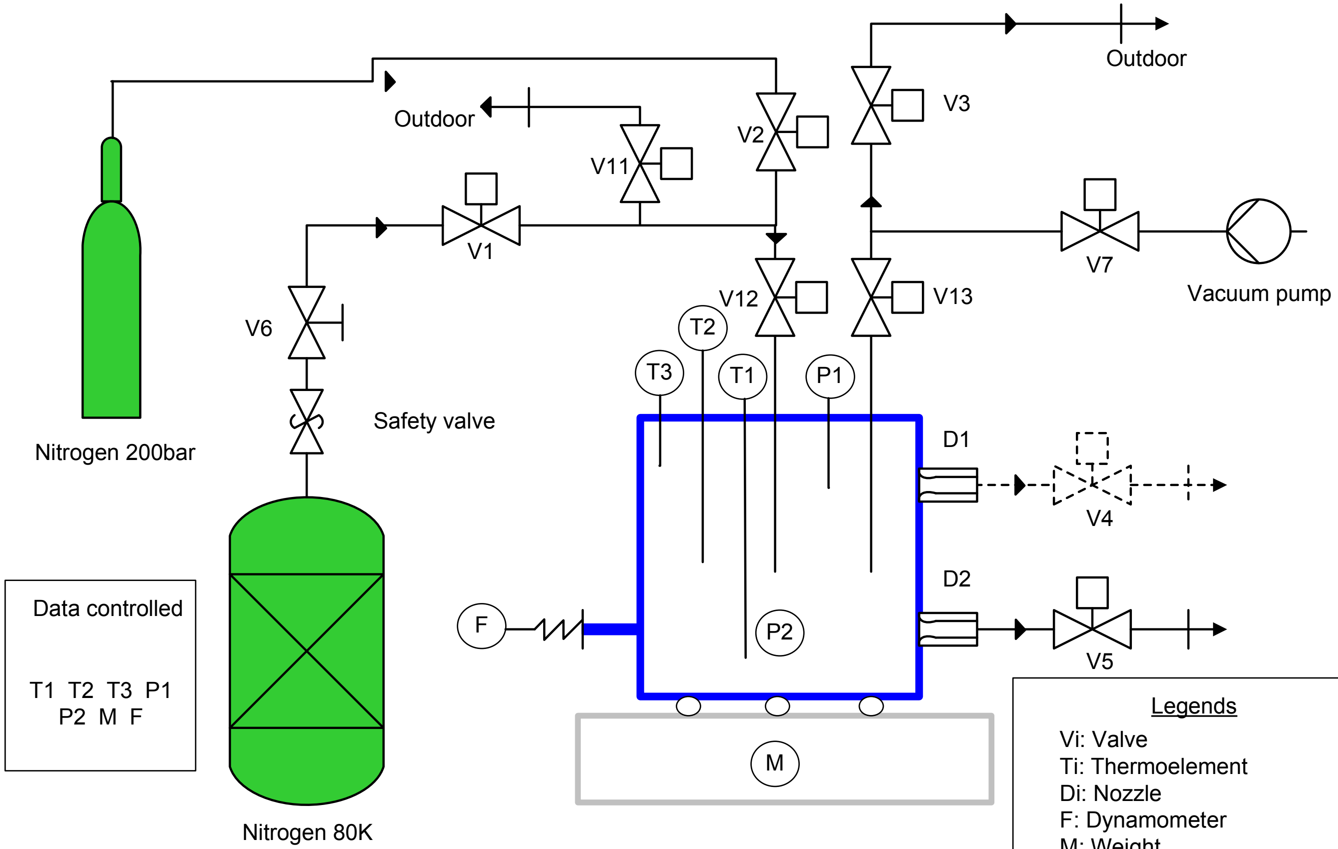
- The idea is to properly calculate the blow down mass flow rate for high pressure releases
- Validation against experiments to evaluate the C_D taking into account nonideality (two phase) and non adiabatic character of blow down process

Objectives

- The objective of current work is to obtain detailed experimental data on the high-pressure releases in wide range of initial pressures and nozzle diameters to take into account nonideality of the process.
- In order to simplify the conditions for two-phase flow and for safety reasons, nitrogen will be used instead of the pressurized hydrogen.
- With this work, a capability of numerical and theoretical models for high pressure hydrogen releases will be validated against time-dependent experimental data

Experimental facility

A gaseous system of DISCHA facility for transient two-phase blow-down tests with gaseous nitrogen instead of hydrogen



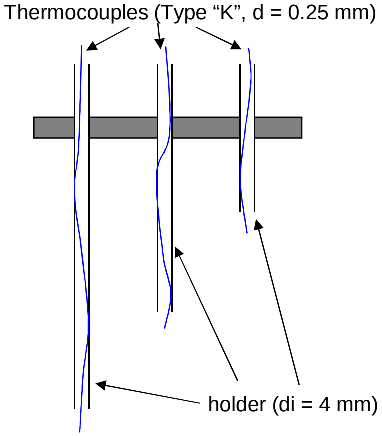
Legends

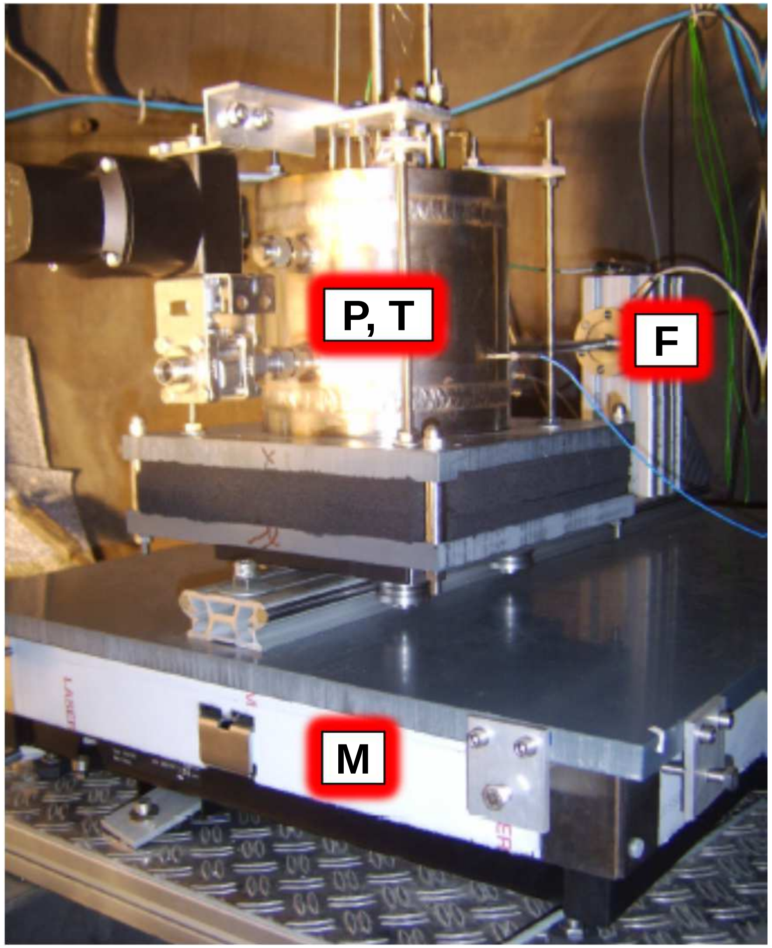
Vi: Valve
Ti: Thermoelement
Di: Nozzle
F: Dynamometer
M: Weight
Pi: Pressure sensor

Size of internal volume:	2.81 dm^3
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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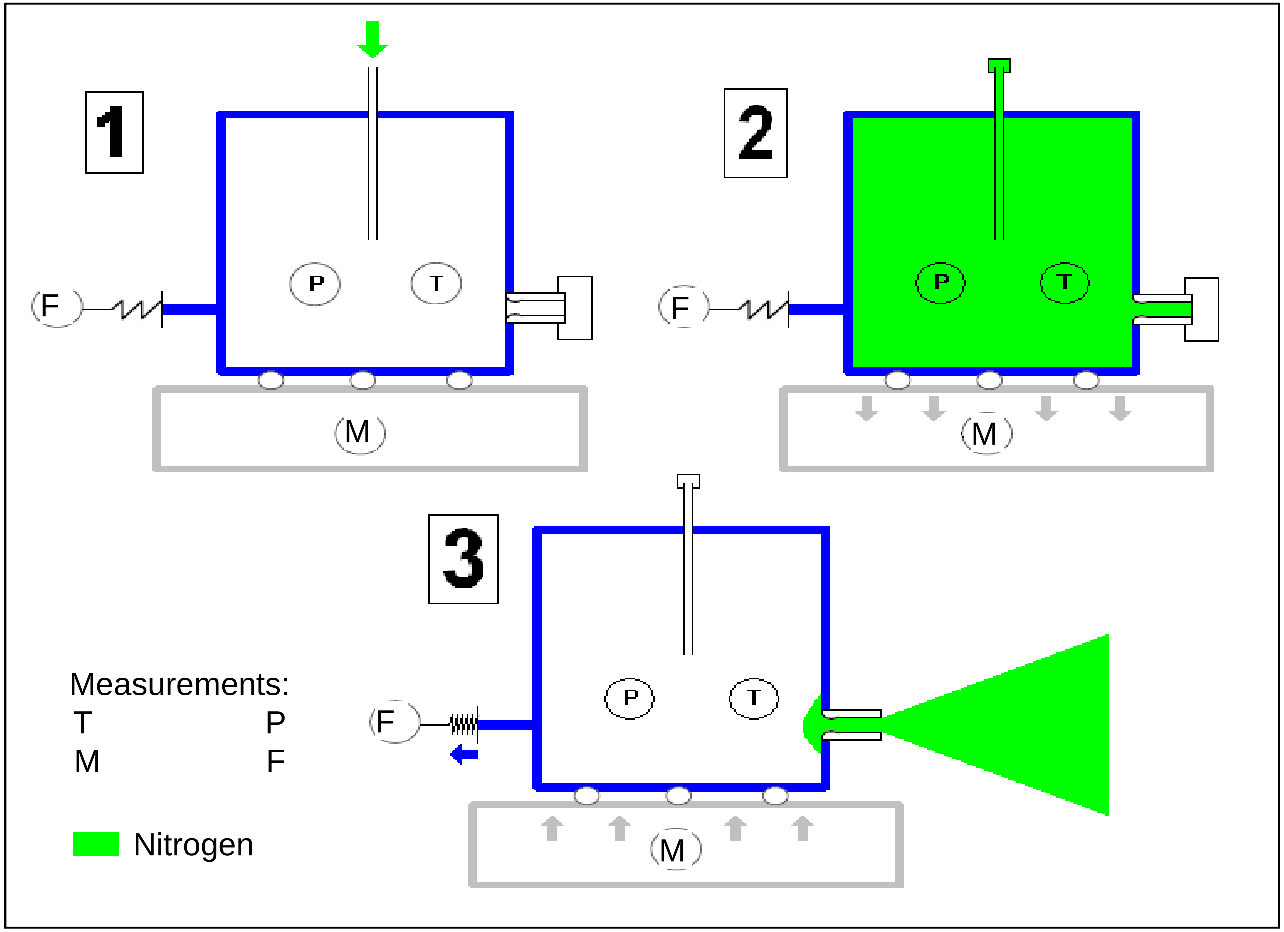
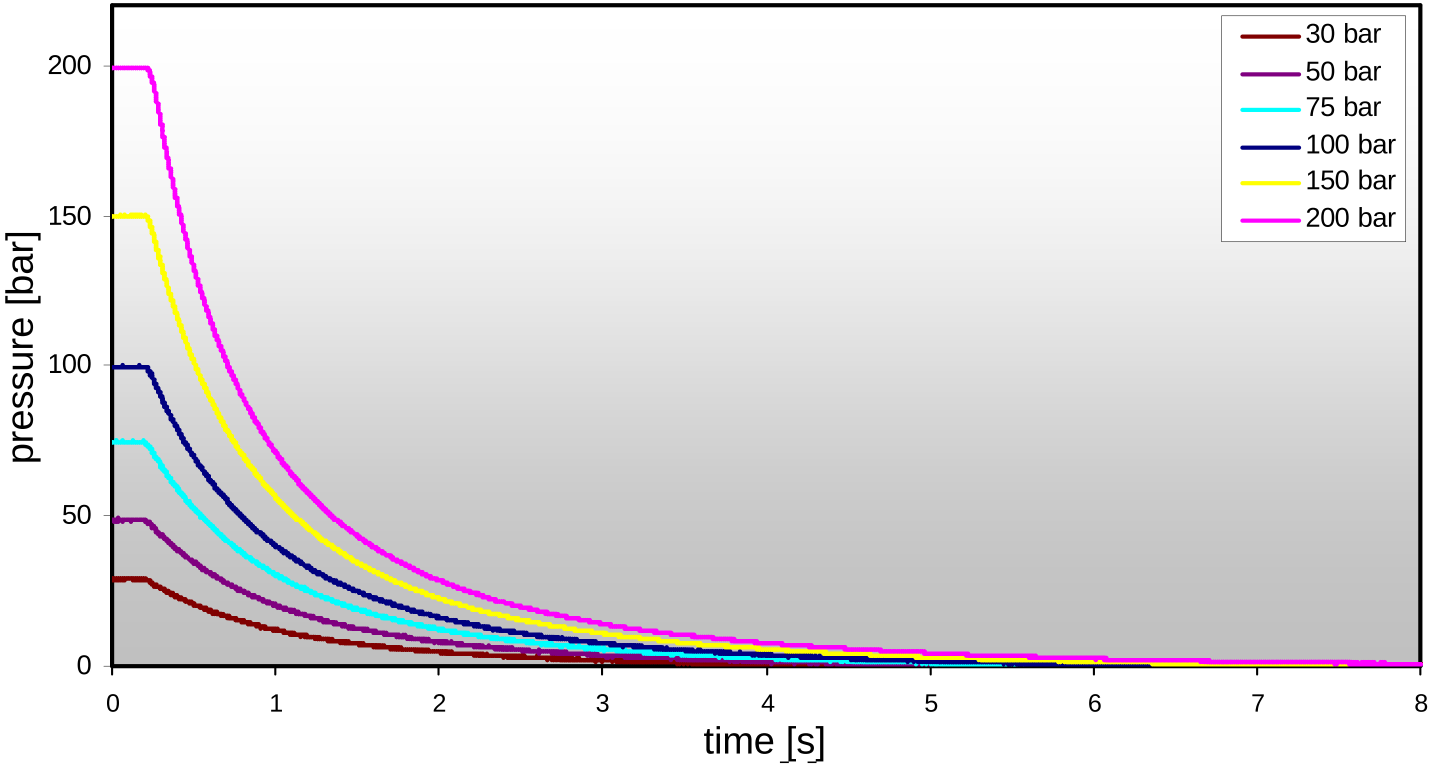
Test procedure



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

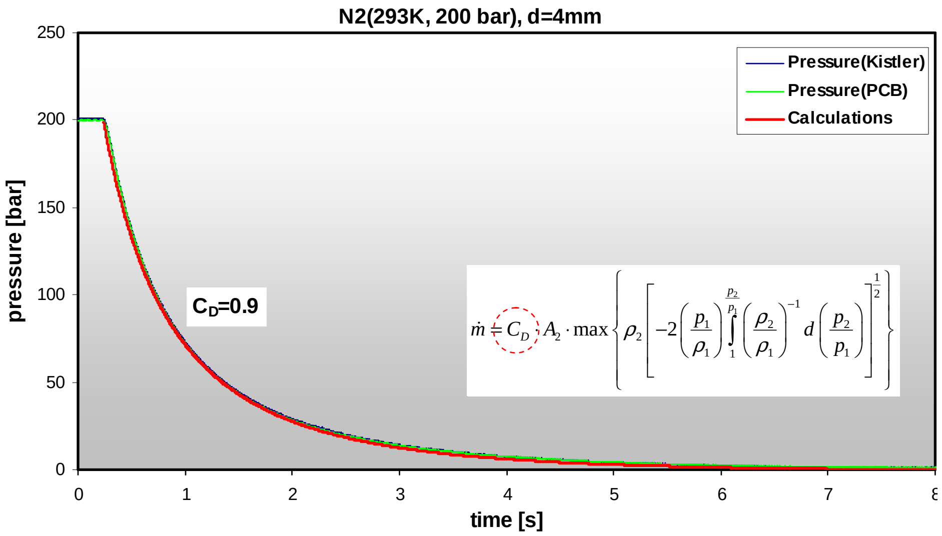
- Simultaneous temperature, pressure, force and weight measurements provide independent measurements of mass flow rate

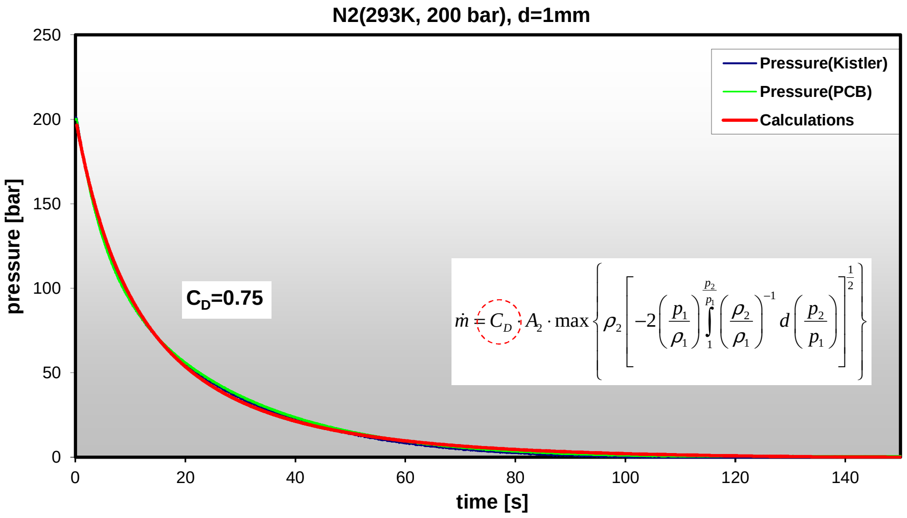
Experimental results: pressure dynamics



- Very good reproducibility of the pressure behavior
- Characteristic pressure discharge time changes from 8 sec for 4-mm nozzle to 600 sec for 0.5-mm nozzle almost independent of initial pressure

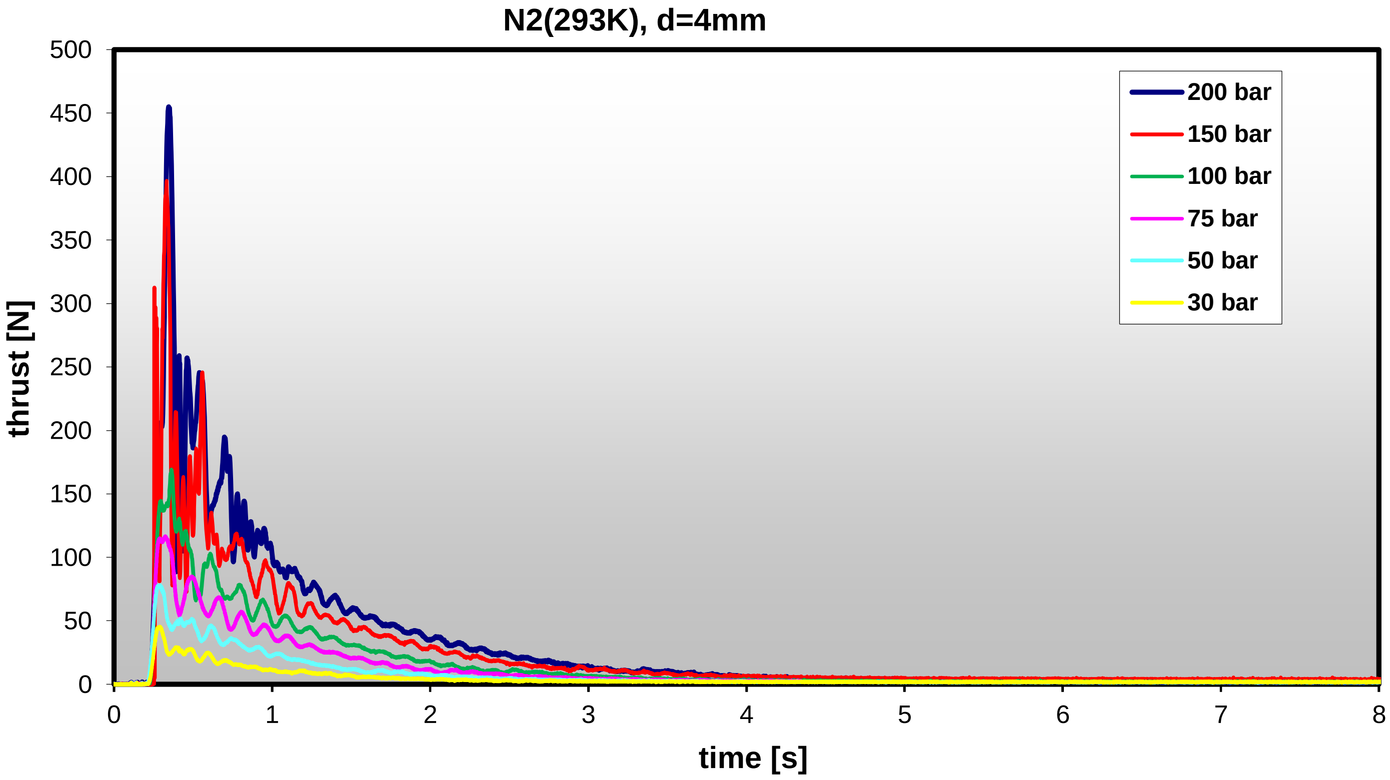
Calculations: a comparison with pressure measurements





- Very good agreement of experimental data and theoretical calculations
- The discharge coefficient changes from 0.9 to 0.75 with nozzle diameter decrease from 4 to 1 mm inner diameter

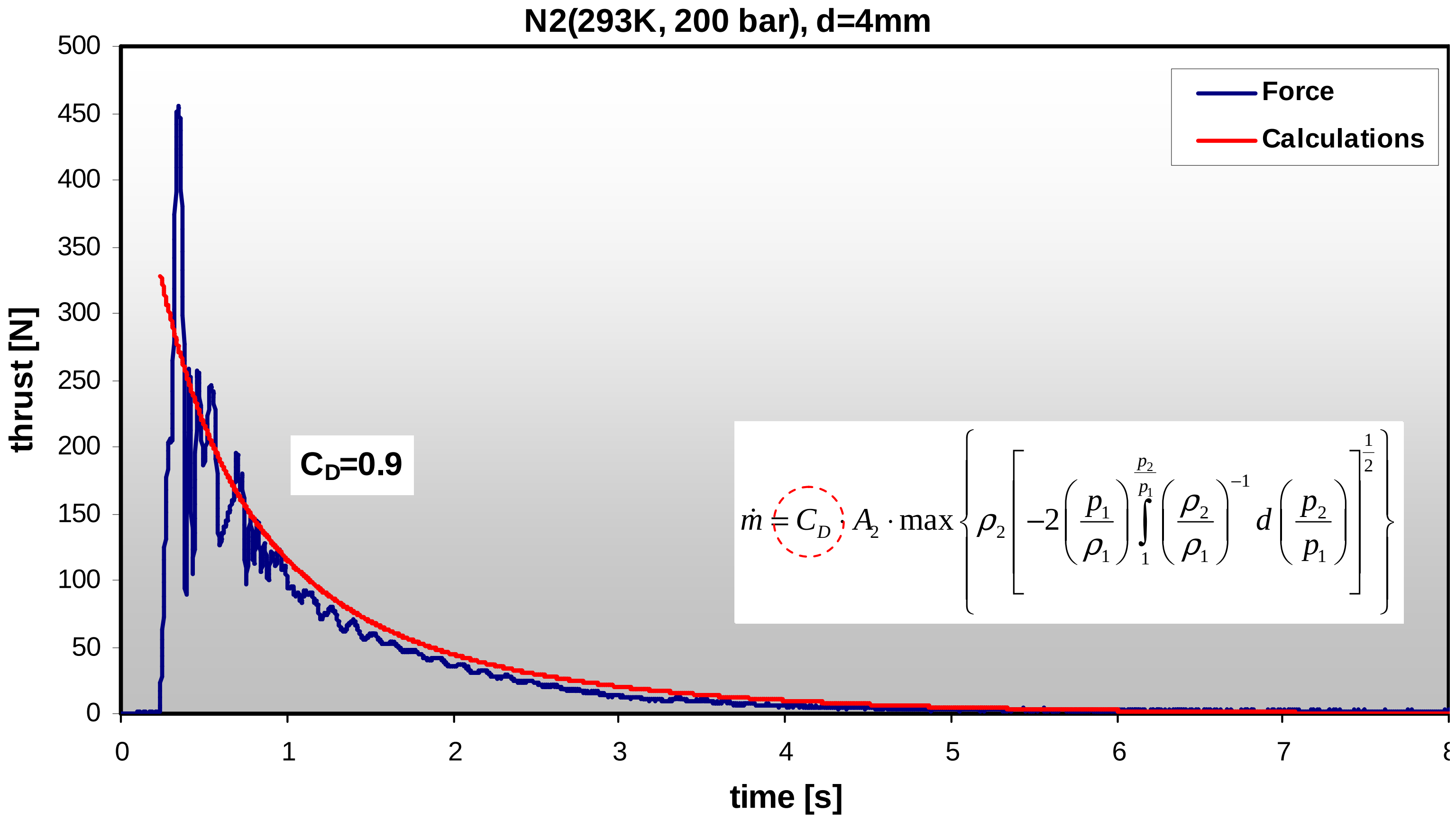
Experimental results: thrust measurements



- Experimental dependencies of thrust data vs. time behave according to the initial pressure
- Some oscillating process was observed due to mechanical vibration of the system

Calculations: a comparison with thrust measurements

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

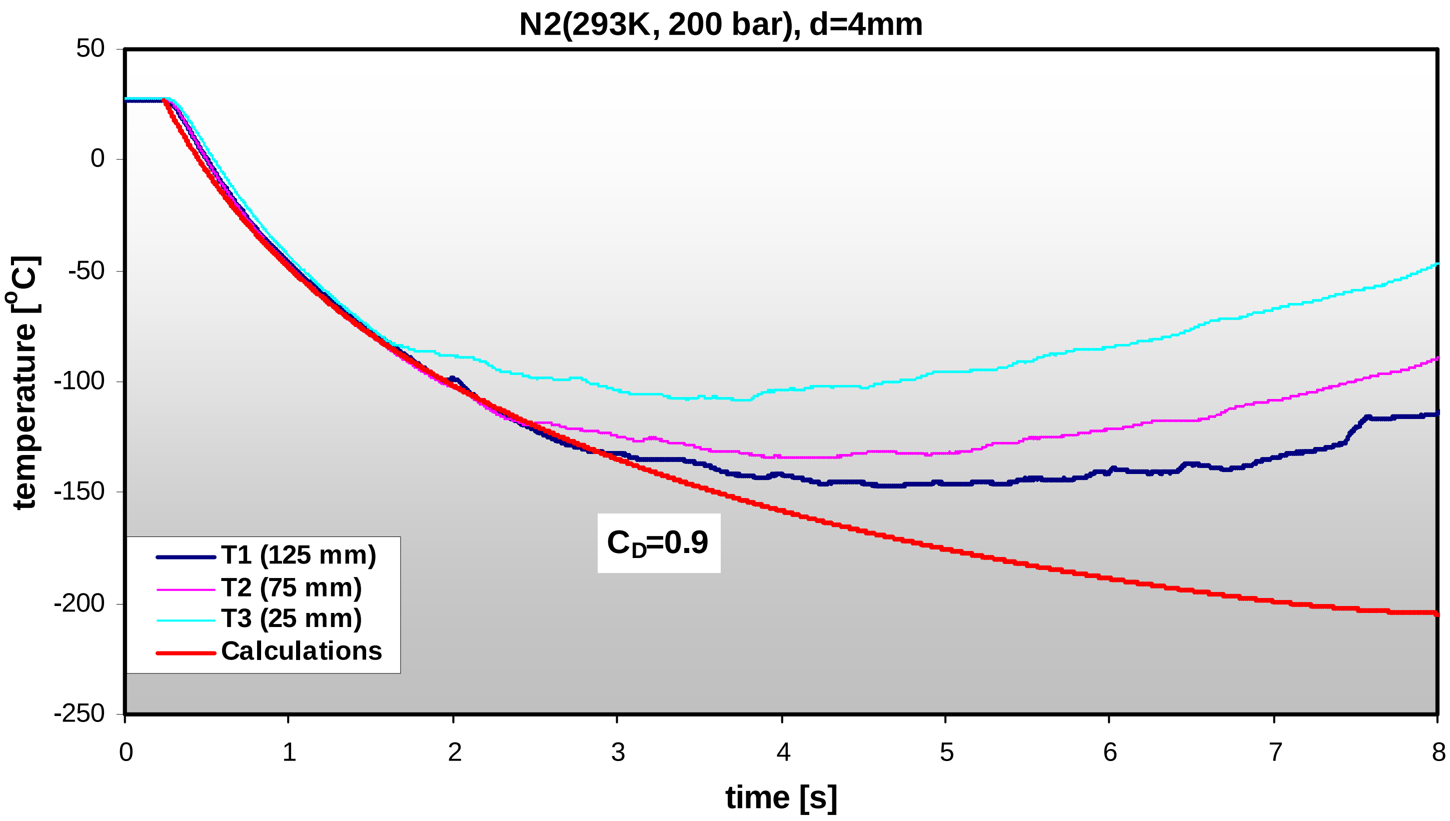


N2(293K, 200 bar), d=4mm

$$\dot{m} = C_D A_2 \cdot \max\left\{\rho_2\left[-2\left(\frac{p_1}{\rho_1}\right)\int_1^{\frac{p_2}{p_1}}\left(\frac{\rho_2}{\rho_1}\right)^{-1} d\left(\frac{p_2}{p_1}\right)\right]^{\frac{1}{2}}\right\}$$

- Experimental data on thrust measurements fit very well with theoretical calculations using the same discharge coefficient as for pressure dynamics

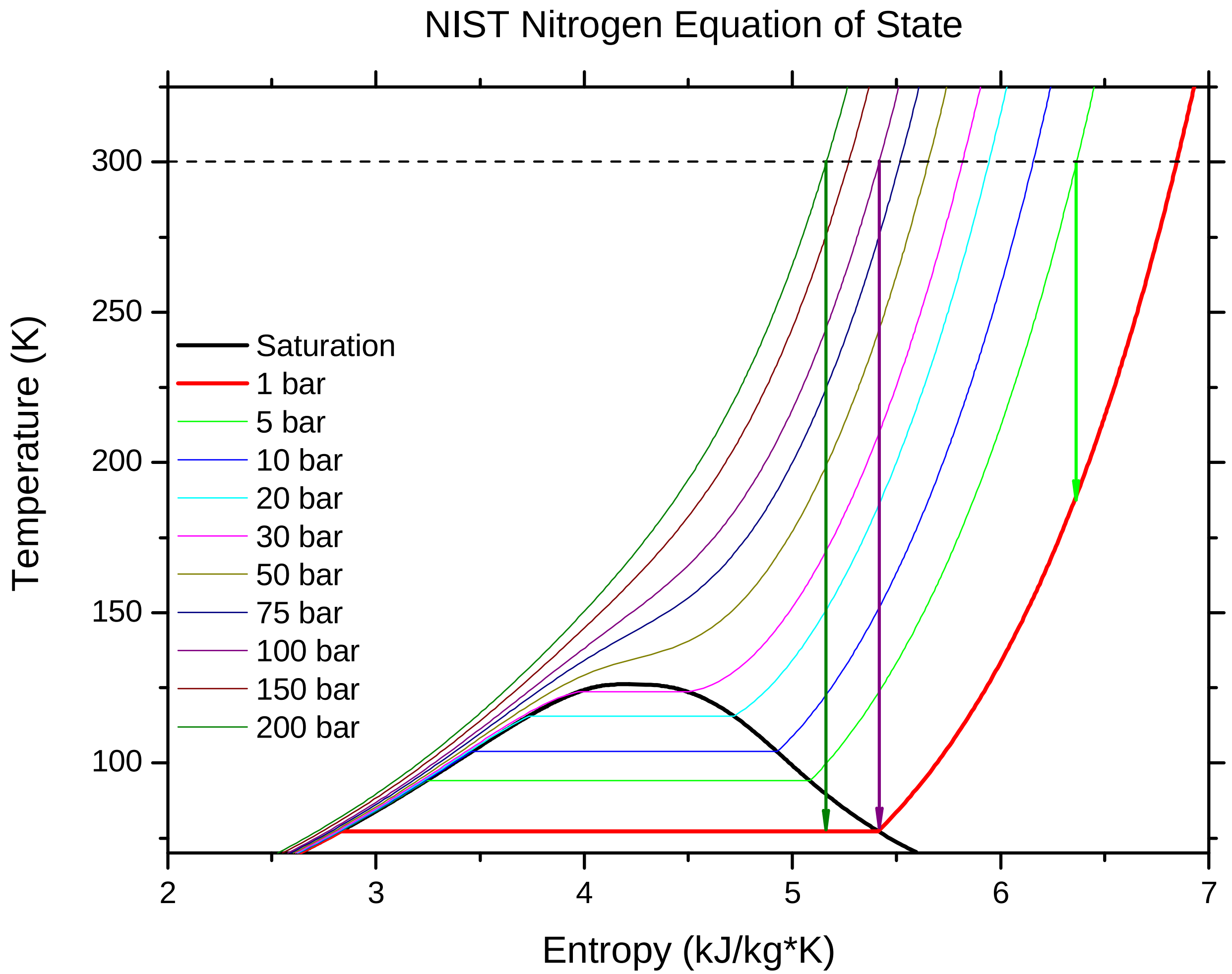
A comparison of experimental temperature measurements and calculations



- 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

Experimental data analysis

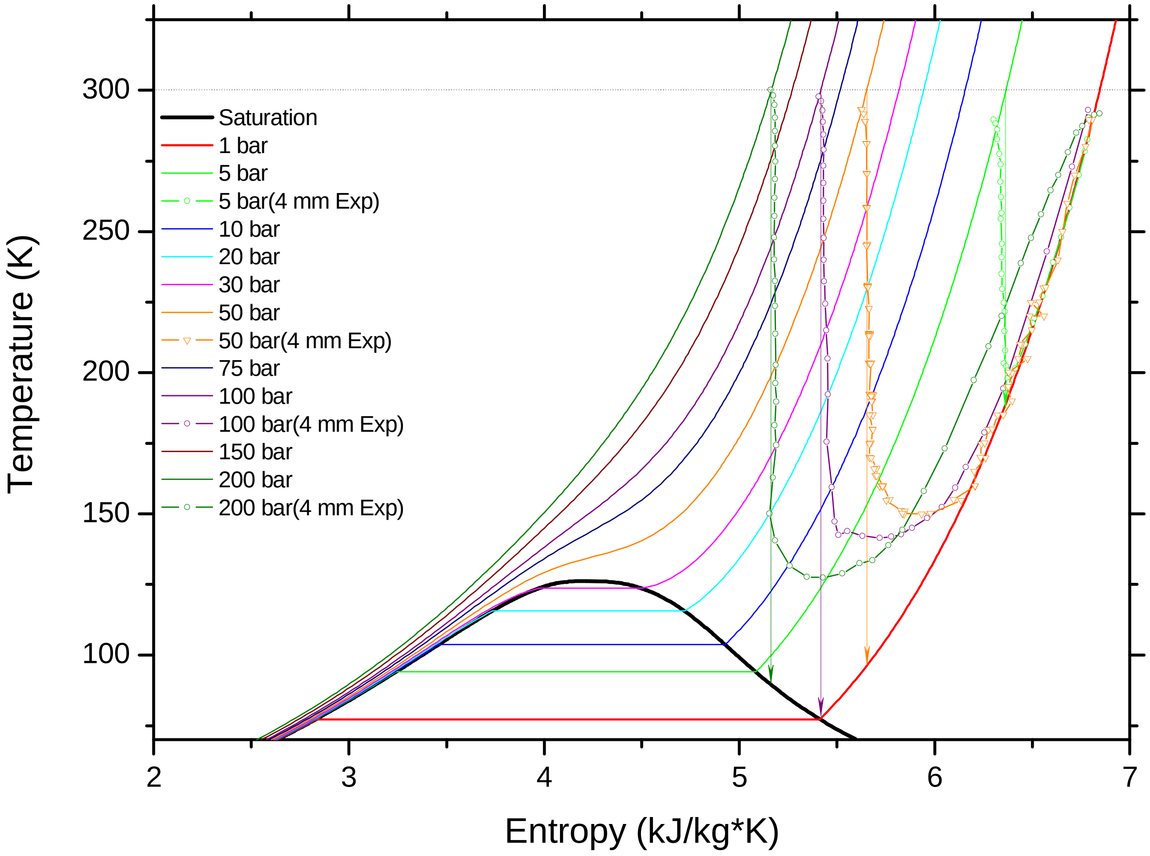
Temperature – entropy (T-S) – diagram of state of real nitrogen (NIST)



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

Experimental data analysis

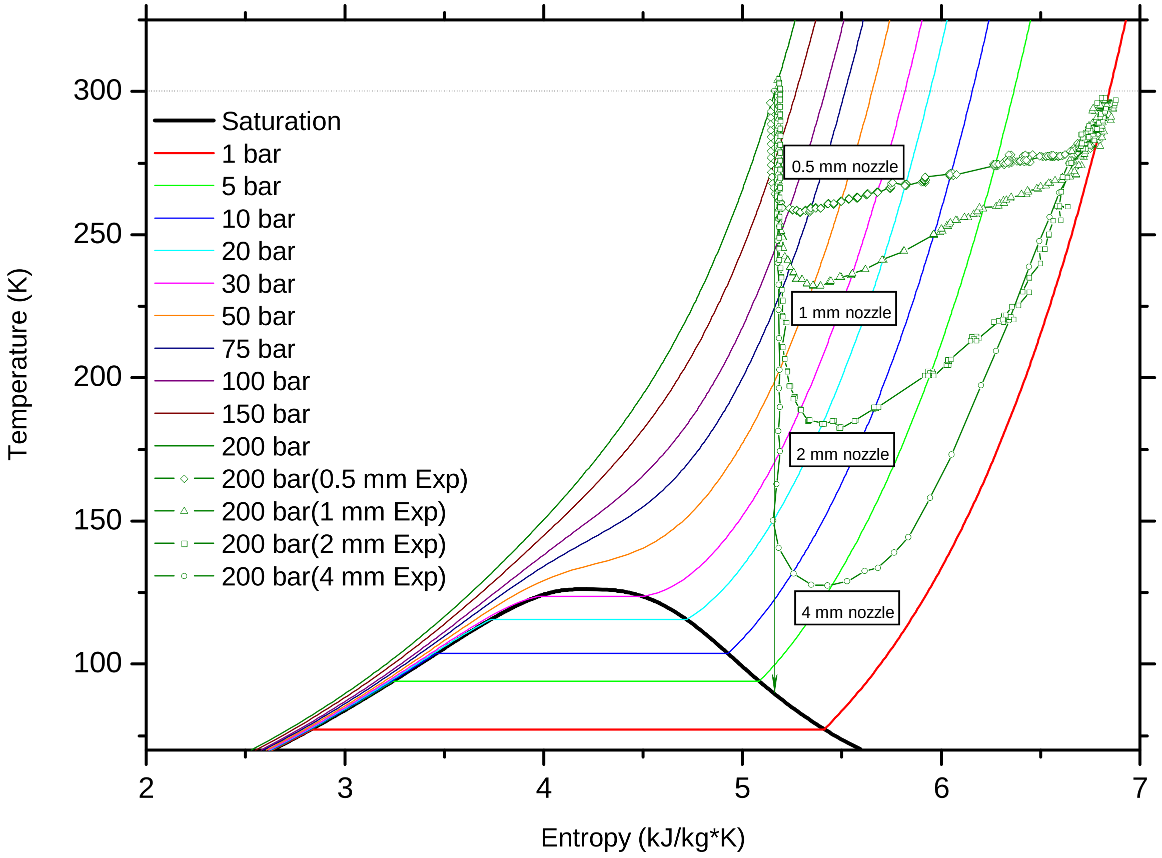
Real nitrogen release at different initial pressures (4-mm nozzle)



- 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

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 $\Delta T = 40$K ; 1-mm nozzle $\Delta T = 60$K ;
  2-mm nozzle $\Delta T = 120$K ; 4-mm nozzle $\Delta T = 170$K ;

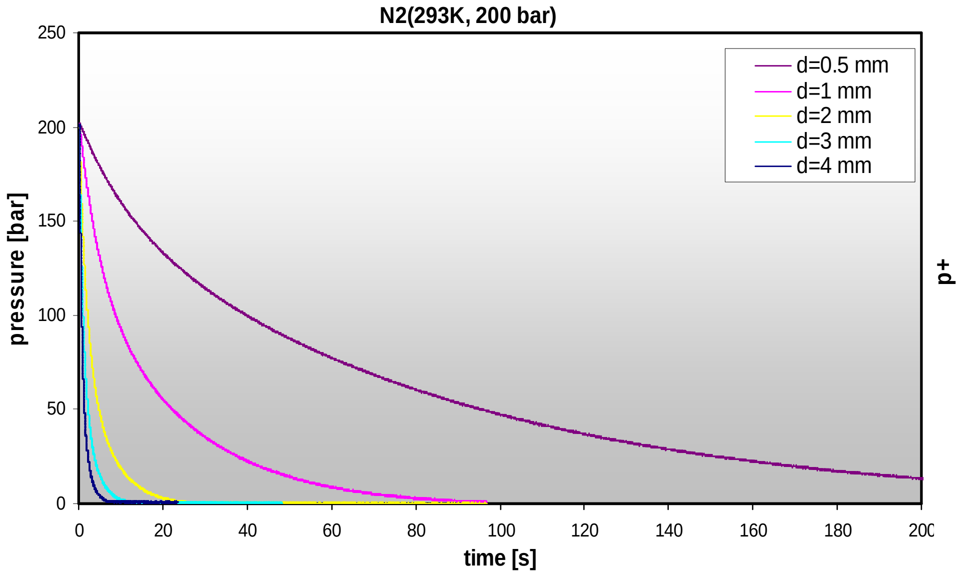
Scaling of transient discharge pressures

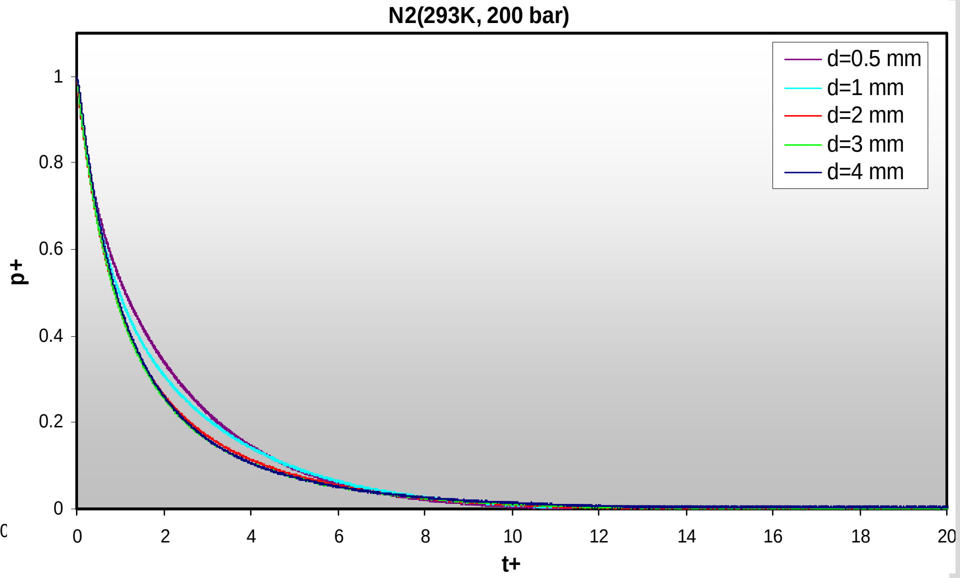
$$p^{+}=\left[1+\left(\frac{\gamma-1}{2}\right)\left(\frac{\gamma+1}{2}\right)^{\frac{-(\gamma+1)}{2(\gamma-1)}}\cdot t^{+}\right]^{\frac{-2\gamma}{\gamma-1}}$$

$p^+ = p(t)/p_0$ - dimensionless pressure;

$t^+ = t/t_{char}$ - characteristic release time;

$t_{char} = V/(A\cdot c_0)$ - characteristic release time





- Scaling by dimensionless p^+ and t^+ results in very good agreement of the tests with different initial pressures for the nozzle diameter more than 2 mm.
- There is some difference appears for smallest nozzle diameters due to the above discussed heat transfer effects and the discharge time. The slowest experiments (0.5 and 1 mm nozzles) show the highest values for $p^+(t^+)$.

Scaling of transient discharge pressures

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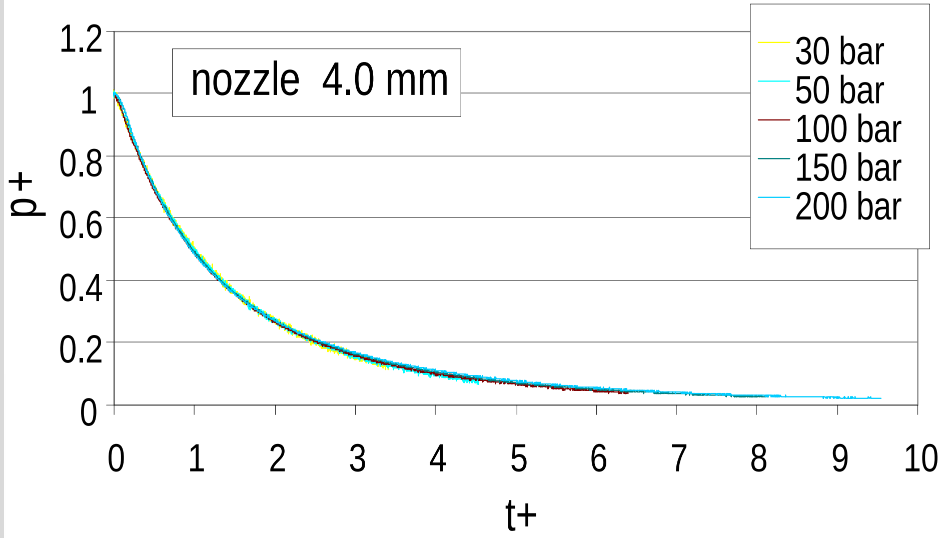

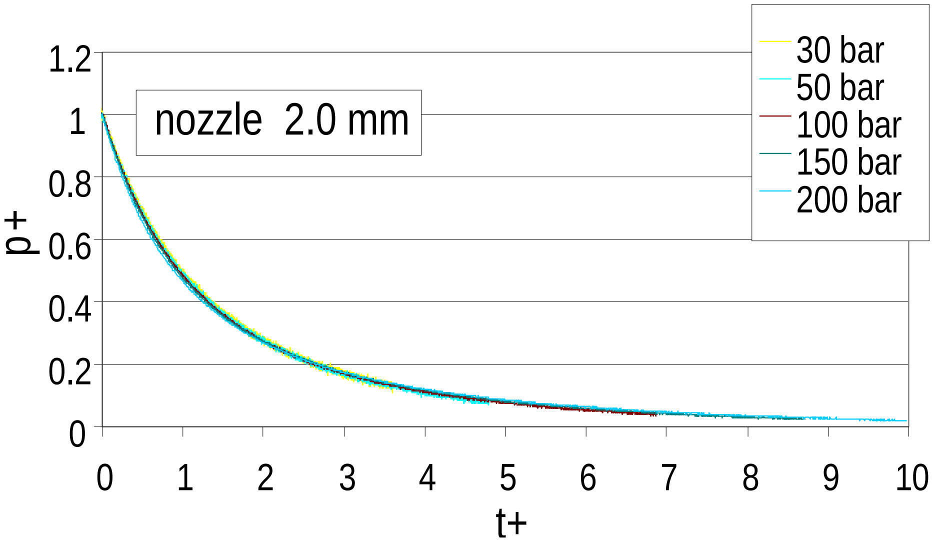

- Characteristic time t^+ includes the sound speed of the gas c_0 in its initial state p_0/T_0, which varies significantly with the initial pressure.
- Independent of that the scaling equation was originally derived for ideal gases with constant γ and constant sound speed c_0 during the blow-down process it allows a very good scaling of the present non-ideal high-pressure discharge experiments with nitrogen
- The measured pressures $p^+(t^+)$ were scaled well from the initial pressure p_0 down to p_{end} = 3 bar to remain in the choked flow regime, but even further the difference is rather small

Conclusions

- A small-scale facility for transient discharge of cryogenic nitrogen was fabricated and tested with gaseous nitrogen as an inert hydrogen substitute. Different orifice sizes (0.5, 1, 2, 3, 4 mm) and initial N2 pressures (30 – 200 bar) were investigated.
- The measured time-dependent data for vessel discharge pressure, thrust, discharge mass flow, and gas temperatures could be well reproduced using the NIST database for the real gas equation-of-state of nitrogen. This verification for nitrogen also assures the EOS for hydrogen, which is based on the same methodology.
- The newly developed critical discharge analysis method for a pure substance predicts correctly the transient blow-down of a high-pressure gas system. The measured pressure histories could be scaled very well using initial pressure and sound speed of the gas, vessel volume and nozzle area as characteristic quantities.
- New results about the heat transfer effects in blow-down of gaseous high-pressure systems have been obtained. For relatively small nozzle diameter and lower initial pressure the heat from surrounding may completely eliminate the two-phase scenario of high pressure release.
- The facility is ready for extension of the experiments to liquid nitrogen and investigation of cryogenic two-phase discharge in a future phase