Experimental Investigation of Nonideality and Nonadiabatic Effects under High Pressure Releases

Kuznetsov M., Pariset S., Friedrich A., Stern G., Jordan T.
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
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

- 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)

- 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)
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

- 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
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 $\Delta T = 40K$
  - 1-mm nozzle $\Delta T = 60K$
  - 2-mm nozzle $\Delta T = 120K$
  - 4-mm nozzle $\Delta T = 170K$
Scaling of transient discharge pressures

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

- \( p^+ = p(t)/p_0 \) - dimensionless pressure;
- \( t^+ = t/t_{\text{char}} \) - characteristic release time;
- \( t_{\text{char}} = V/(A \cdot c_0) \) - 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

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

- 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 \( \gamma \) 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 \( p_{\text{end}} = 3 \text{ bar} \) to remain in the choked flow regime, but even further the difference is rather small.

\[ p^+ = p(t)/p_0 \text{ - dimensionless pressure;} \]
\[ t^+ = t/t_{\text{char}} \text{ - characteristic release time;} \]
\[ t_{\text{char}} = \sqrt{V/(A \cdot c_0)} \text{ - characteristic release time} \]
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