PRESLHY

Work Package 3 / Release & Mixing

GA Meeting, 16-18 Oct 2018, Paris

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Pre-normative REsearch for Safe use of Liquid HYdrogen

KIT
Karlsruher Institut für Technologie
Air Liquide
HEALTH & SAFETY LABORATORY
hySafe
INTERNATIONAL ASSOCIATION FOR HYDROGEN SAFETY
INERIS
ΔΗΜΟΚΡΙΤΟΣ
Pro-Science
Ulster University
WARWICK
THE UNIVERSITY OF WARWICK

WP3 / Overview (DoW)

- Partners / PMs

NCSRD	KIT	PS	AL	HSL	INERIS	UU	UWAR	Total
12	2	8	2	9	2	4	3	42

- Implementation
  - 3.1 – Theory and Analysis (NCSRD, all)
  - 3.2 – Simulations (NCSRD, KIT, UU, UWAR, INERIS)
  - 3.3 – Experiments (KIT, PS, HSE, INERIS)

PRESLHY WP3 Release and Mixing		Leader	Month																																			
Task			1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36
3.1	Theory and Analysis	NCSRD																		D3.1																		
3.2	Simulations	NCSRD																																				D3.2
3.3	Experiments	KIT																																				D3.3
E3.1	Small Discharge	KIT/PS					S				E		D3.4																							
E3.4	Pool Dispersion	KIT/PS												S					E		D3.5																	
E3.5	Rainout	HSE													S						E			D3.6														

Overview of experiments (link to WP2)

LH2 / LHe two-phase expanded releases

Experiment	Reference	Spill volume (L)	Spill duration (s)	Flow Rate (kg/s)	Wind (m/s)	Tank pressure (bar)	Humidity (%)	Diameter (cm)	L/min
NASA-6 / US	Witcofski and Chirivella (1984)	5700	35	11.5	2.2 at 10 m	6.9	29	15.2	
INERIS Lhe / FR	Proust et al. (2001)	560-880	34-71	1.5 and 2.1	2 to 5.5 at 3m		84-90		
BAM / GE	L. Marinescu-Pasoi, B. Sturm (1994)	650	120	0.4	≤ 1 m/s	7	97		
HSL / UK	Hooker et al. (ICHS-4, 2011)	305	305	0.07	3 at 2.5m	2	64	2.63	60

Subcooled liquid / Gaseous / Supercritical UnderExpanded Releases

Performed by	Reference	Storage P (bar)	Storage T (K)	Diameter (mm)
NASA / US	Simoneau and Hendricks (1979)	12.9 to 58.9	27.2 to 32.3	2.934
KIT / GE	Veser et al. (2011)	5 to 60	80 and 35	1, 2 and 4
KIT / GE	Xiao et al. (2012)	8.25 and 32	80	1 and 2
KIT / GE	Friedrich at al. (2012)	7 to 35	35 to 65	0.5 and 1.0
SANDIA / US	Hecht and Panda (2018)	2 to 5	48 to 63	1 and 1.25
SANDIA / US	Panda and Hecht (2018)	6		0.75-1.25
ISAS / JPN	Kobayashi et al. (IJHE, 2018)	900	50-300	0.2, 0.4, 0.7, 1.0
ISAS / JPN	Kobayashi et al. (IJHE, 2018)	200-850	50-300	0.2, 0.4, 0.7
Nagasaki R&D / JPN	Nakamichi et al. (Cryogenics, 2008)	4		0.5 to 2.0

Gaps / Weak points related to cryogenic H_2 release and dispersion (link to WP2)

- Gaps
  - No experiments for under-expanded release & dispersion from LH_2 storage (saturated or sub-cooled conditions)
  - No Blowdown
  - No BLEVE
  - No droplet size measurements
  - No velocities or fluctuations
  - Very limited structure of two-phase jets close to the release (e.g. Sandia, 2017, 2018)
- Weak points in many past experiments
  - Release momentum not measured
  - Uncertainty on the discharge rates
  - Large variability or limited info about meteorological conditions
  - Only few concentrations and temperatures

WP3 / NCSRD activities

- Release modeling (engineering tools)
  - A.G. Venetsanos, Homogeneous Non-Equilibrium Two-Phase Choked Flow Modeling, **accepted for publication to IJHE**, Oct. 2018
  - Estimations of vapor quality for two-phase releases from measured quantities
  - Single and two-phase Fanno flow modeling (**on-going**)
- Dispersion modeling (CFD)
  - Simulations of Hecht and Panda (2018) experiments (**on-going**)

Table 1 – Experimental conditions in this work.

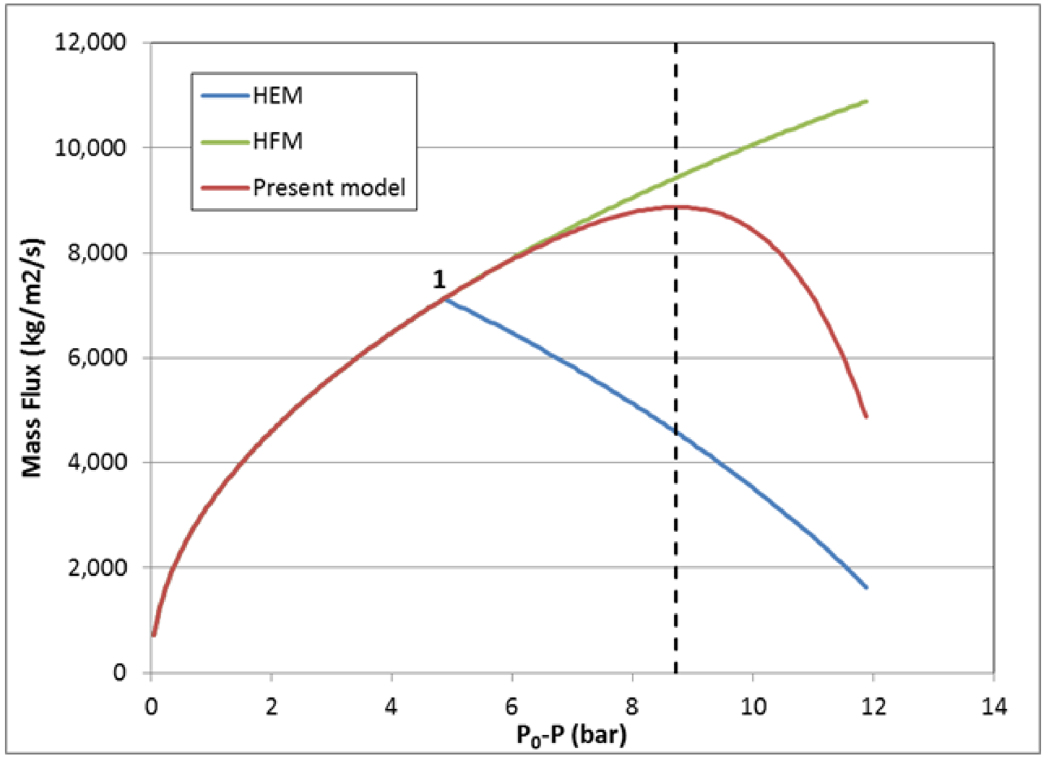
T_{noz} (K)	P_{noz} (bar_{abs})	d_{noz} (mm)	$n_{heights}$	T_{throat} (K)	P_{throat} (bar_{abs})	ρ_{throat}	v_{throat} (m/s)
58	2.0	1.0	4	43.5	0.972	0.55	544.5
56	3.0	1.0	4	41.9	1.457	0.86	533.3
53	4.0	1.0	4	39.6	1.940	1.22	516.4
50	5.0	1.0	5	37.4	2.422	1.65	498.2
61	2.0	1.25	6	45.7	0.973	0.52	558.9
51	2.5	1.25	2	38.2	1.215	0.79	508.4
51	3.0	1.25	6	38.2	1.457	0.95	507.5
55	3.5	1.25	3	41.2	1.699	1.03	527.6
54	4.0	1.25	2	40.4	1.940	1.20	521.6

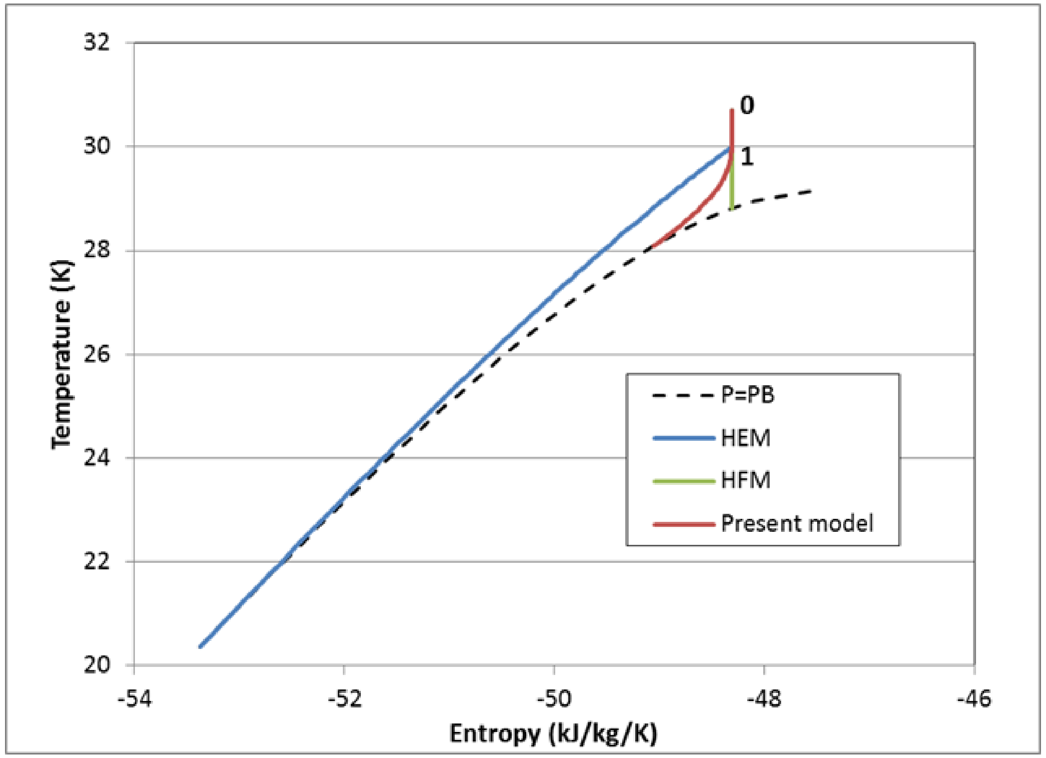
HEM / HNEM Two-Phase Choked Flow Modeling

- HEM isentropic expansion
  - Sound speed discontinuity at the location where the isentropic meets the saturation curve (point 1)
  - Partly responsible for underestimation of mass flow rates
  - Implications on the choked flow calculation algorithm
  - Available in NET-TOOLS e-Lab
- New HNEM for isentropic expansion in the bubbly flow regime (low x)
  - Accounts for liquid superheat T_L-$T_{SAT}(P)$ assuming $T_V=T_{SAT}(P)$
  - Assumes constant non-equilibrium parameter $n = (T_L(P)-T_{SAT}(P))/(T_1-T_{SAT}(P))$
  - Determines n by requiring sound speed continuity at point 1
  - Validated against NASA, Simoneau and Hendricks (1979) tests using NIST EoS
  - Can be used with any EoS that accounts for metastable conditions
  - Easy to implement once HEM pressure iterative algorithm is available
  - Plan to be used as an option in NET-TOOLS e-Lab

HEM / HNEM Two-Phase Choked Flow Modeling Examples

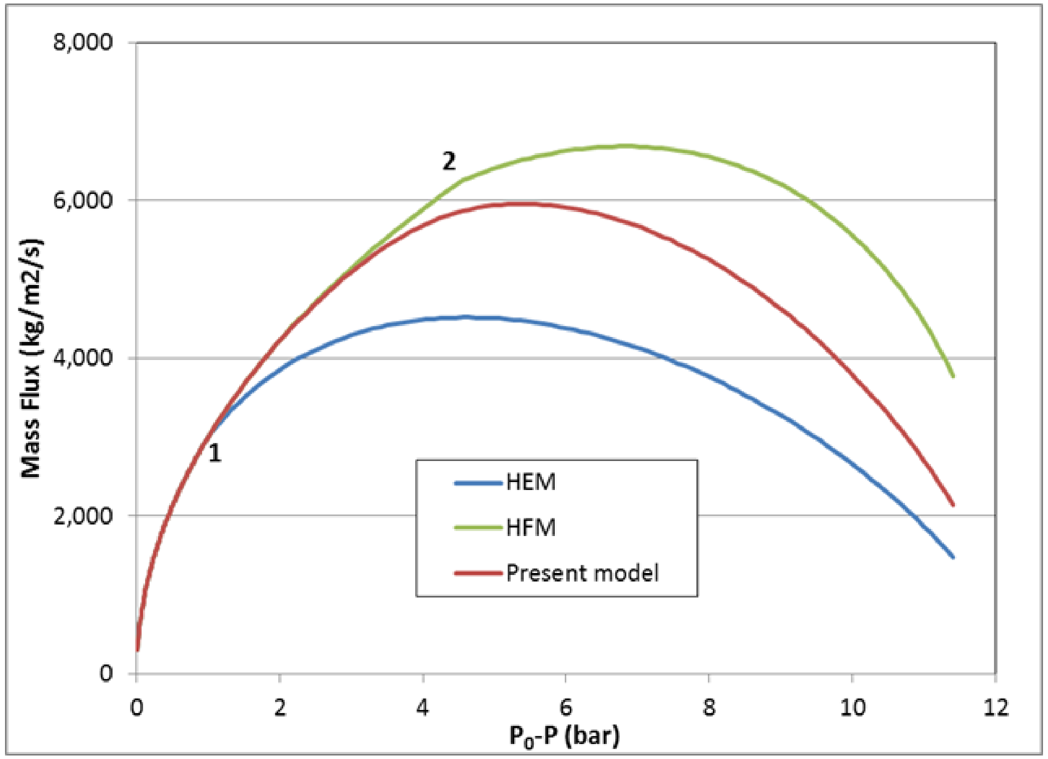
- NASA test 1197 (P_0=12.9 bar, T_0=30.7 K)

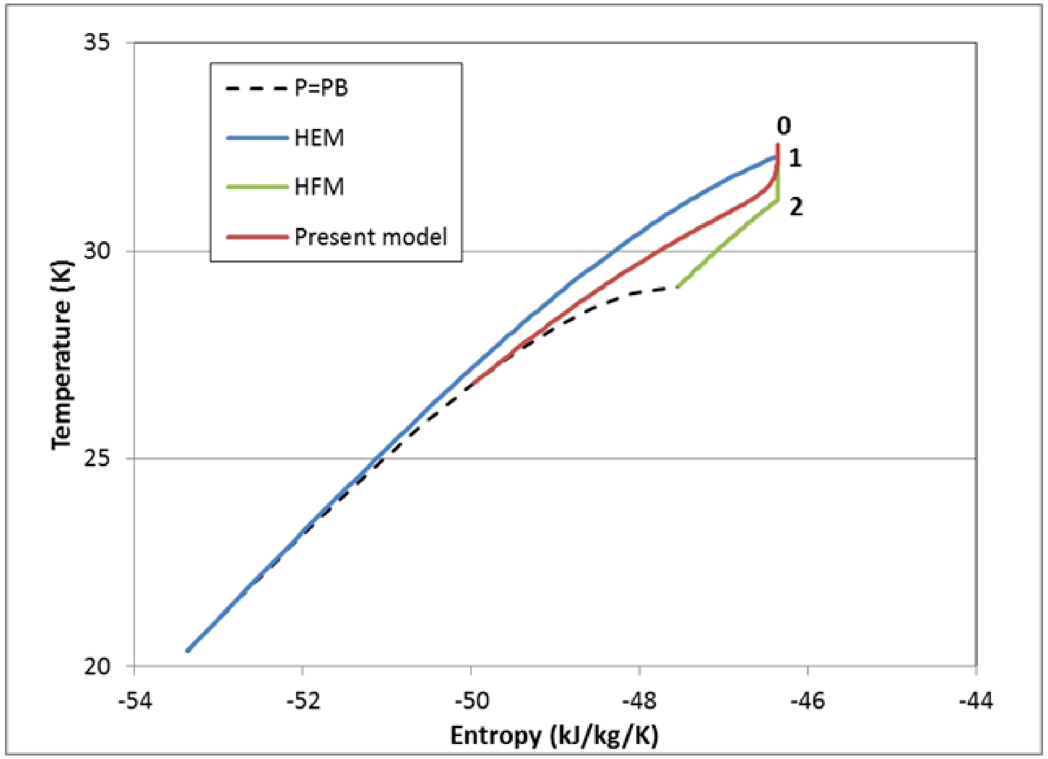




HEM / HNEM Two-Phase Choked Flow Modeling Examples

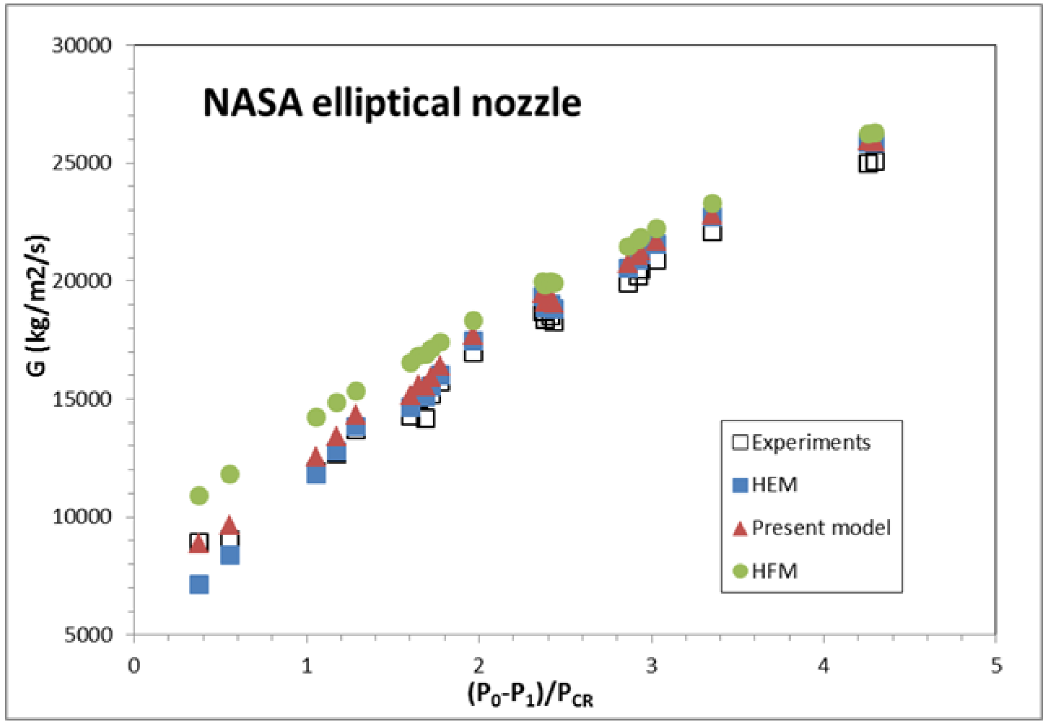
- Hypothetical test (P_0=12.43 bar, T_0=32.55 K)

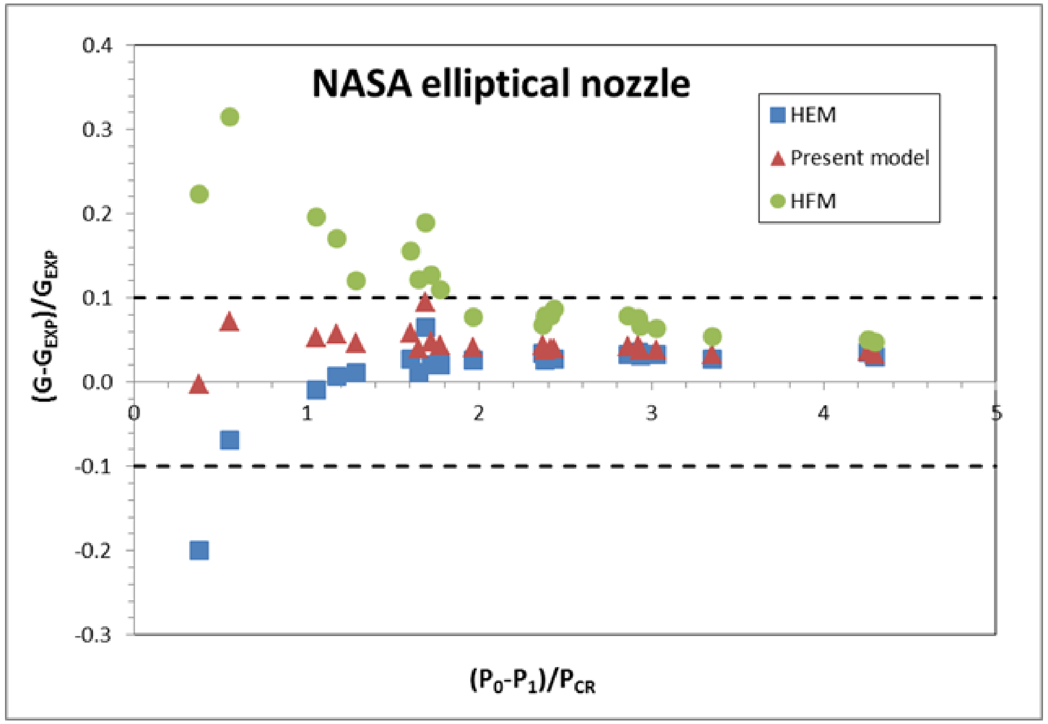


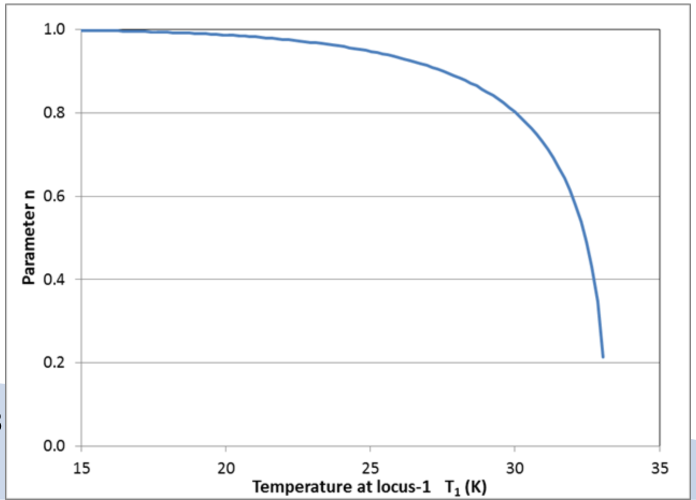


HNEM Two-Phase Choked Flow Modeling

- Validation against NASA, Simoneau and Hendricks (1979) tests using NIST EoS (normal H_2)







Estimation of vapor quality (x) for two-phase releases (1/2)

- Measured quantities
  - mass flow rate ṁ
- Assumptions
  - Expanded conditions at exit => $P = P_{amb}$
  - Homogeneous Equilibrium conditions => $T = T_{sat}(P)$
  - No area changes => Constant mass flux $G = \dot{m}/A = \rho * u$
  - Constant total enthalpy $h_t = h + u^2/2 = h_0$ (Fanno flow assumption)
- Analytical solution

$$Ax^2 + Bx + C = 0$$

$$A = \frac{[G(v_V - v_L)]^2}{2}, \quad B = (h_V - h_L) + G^2 v_L (v_V - v_L), \quad C = \frac{(G v_L)^2}{2} + h_L - h_0$$

- Examples
  - HSL tests Hooker et al. (ICHS-4, 2011)
  - Nasa-6, Witcofski and Chirivella (1984)

Test	P0 (bar)	Pamb (bar)	MFR (kg/s)	Diam (cm)	G (kg/m2/s)	X_exit
HSL	2	0.101325	0.07	2.63	130.4	6.16E-02
NASA-6	6.9	0.101325	11.5	15.2	633.755	0.250991

Estimation of vapor quality (x) for two-phase releases (2/2)

- Measured quantities
  - Thrust & mass flow rate & wall exit temperature
- Assuming homogeneous exit conditions
  - From mass flow rate & thrust we can directly get exit density and exit velocity
- Assuming homogeneous equilibrium exit conditions
  - We can calculate exit vapor quality x and exit pressure P from:

$$T_L = T_V = T \qquad P = P_{SAT}(T) \qquad \frac{1}{\rho} = \frac{x}{\rho_V(T,P)} + \frac{1-x}{\rho_L(T,P)}$$

- Assuming homogeneous non-equilibrium exit conditions and that T_L=T and validity of new HNEM, then we can calculate x and P from:

$$T_L = T \qquad T_V = \frac{T_L - nT_1}{1-n} \qquad P = P_{SAT}(T_V) \qquad \frac{1}{\rho} = \frac{x}{\rho_V(T_V,P)} + \frac{1-x}{\rho_L(T_L,P)}$$

Some remarks for planned experiments

- Release modeling needs
  - Detailed geometrical description of the release line from storage to exit location
  - Show all area changes
  - Specify all items that cause pressure changes (pipes, bends, orifices, nozzles, etc.)
  - For each pipe element
    - Internal Diameter
    - pipe length
    - Internal roughness
    - Pipe thickness
    - Pipe material
    - Insulation (if any)

WP3 / Activities

- KIT / PS
  - Design of tests E3.1, E3.4 (presentation by PS)
- HSL
  - Design of tests E3.5 (presentation by HSL)
- INERIS
  - Sharing of old LHe experiments is expected
  - Excluded tests
    - test 0 for no humidity info
    - tests 1,2 for too large wind variation
    - tests 7-9 for no H1, H2, L info
  - Tests 3 and 6 selected for validation

Issue n°	duration (s)	Mass flow rate (kg/s)	Wind speed (m/s) at 3 m height	Humidity (%)	Temp (°C)	H1 (m)	H2 (m)	L (m)
0	60	1,5	6	/	16	3	5	20
1	50	1,4	4,0±1,0	86	17	5	17	50
2	52	1,4	5,2±1,0	90	17	5	17	50
3	52	2,1	3,0±0,5	84	12	12	32	80
4	43	2,1	4,0±0,5	84	12	7	35	75
5	34	2,1	5,5±0,5	88	12	7	30	70
6	43	2,1	4,5±0,5	88	11	7	30	70
7	63	1,2	2,0±0,5	85	12			
8	65	1,2	2,0±0,5	85	12			
9	71	2,2	2,0±0,5	85	12			

L the length of the cloud on the ground
H_1 the height of the base of the cloud
H_2 the height at the top of the cloud.