ELVHYS 3rd workshop on
"Progress in modelling and development of fuelling / bunkering procedures"

DISCHA: Tool for discharge and tank to tank transfer simulations

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Outline

- Introduction
- DISCHA features
- Recent Validation
  - Emptying of an LH2 tank due to boil-off
  - Self pressurization of LH2 tanks
- Tank to tank transfer predictions
  - Filling of an LH2 truck from a stationary tank at 5 bars

Introduction

- DISCHA tool for
  - Physical properties at single phase and two-phase conditions
  - Discharge calculations
  - Tank to tank transfer calculations
- DISCHA development / validation in previous EC projects
  - NET-Tools

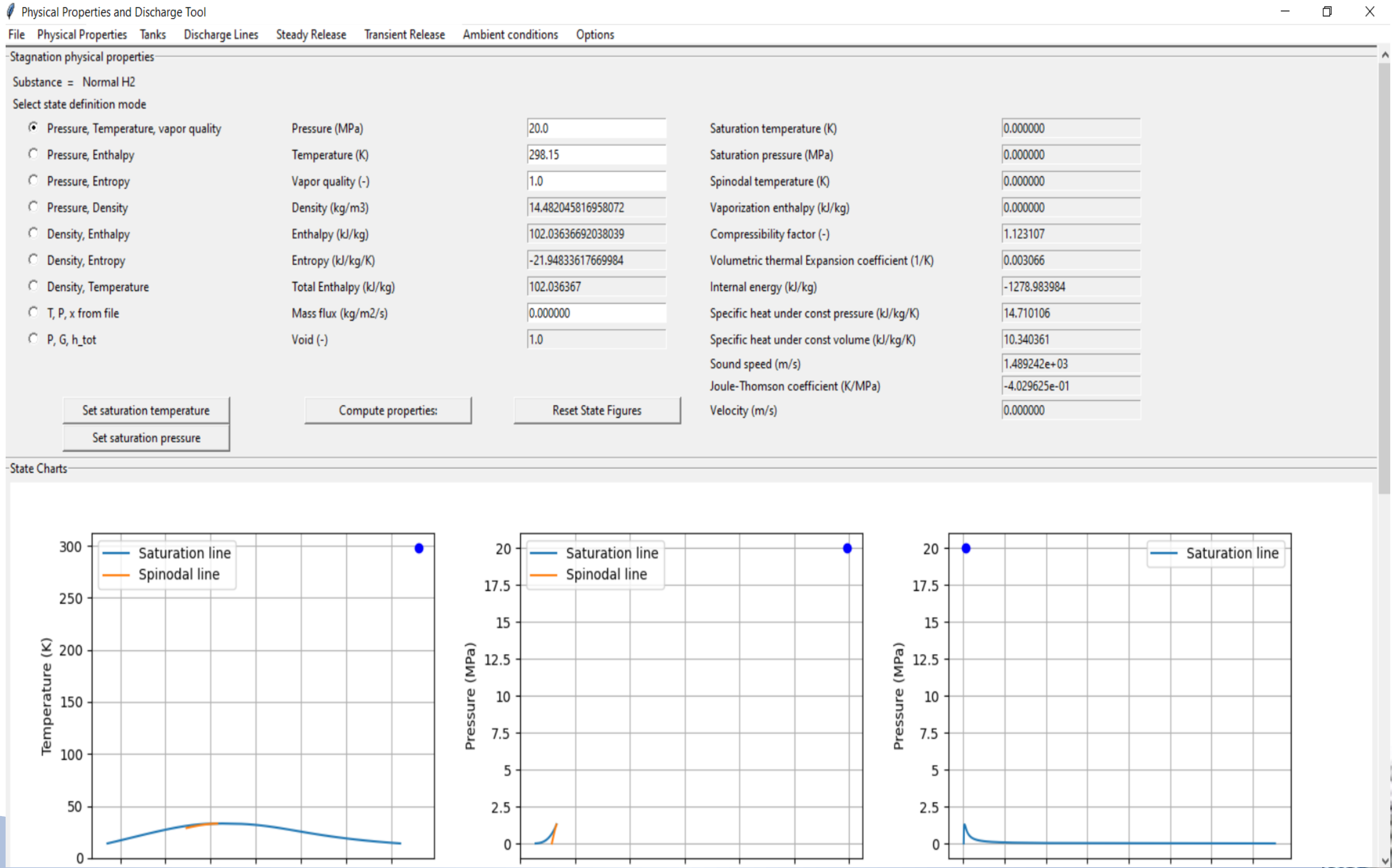
    NET-Tools_Venetsanos
  - PRESLHY

    PRESLHY_Venetsanos.mp4 PRESLHY_Venetsanos.pdf
  - HyTunnel-CS

    HyTunnel-CS_D4.4.pdf

DISCHA features (1)

- GUI (Python), Main code (Fortran)



DISCHA features (2)

- Substances
  - Normal H_2, Para-H_2, CH_4, CO_2, H_2O, NH_3, O_2, N_2, He
- Single phase EoS
  - Helmholtz free energy, SRK, PR, RKMC, Abel-Noble, Ideal gas
- Two-phase modelling
  - Ideal mixture of liquid and vapor phase
  - HEM
  - HRM, DEM mainly for H_2O
- Various input modes for thermodynamic state definition
  - Pressure + temperature + vapor quality
  - Pressure + (enthalpy or entropy or density or internal energy)
  - Density + (internal energy or entropy)
  - …

DISCHA features (3)

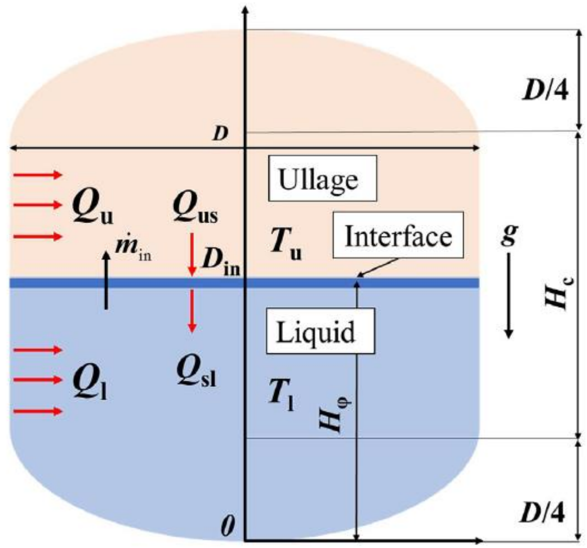
- Discharge / tank to tank transfer calculations
  - Arbitrary network of tanks connected by transfer lines.
  - A transfer line either connects 2 tanks or connects a tank with the ambient environment
  - No direct connection between different lines (branches).

DISCHA features (4)

- Tank modelling
  - Single zone
    - Liquid and vapor phases share the same (sat) temperature
    - Transient mass and energy equations for the entire tank volume.
  - Multizone
    - Two distinct volumes (liquid below, vapor above) separated by one interface
    - Liquid phase subcooled or saturated
    - Vapor phase superheated or saturated
    - Liquid-Vapor Interface saturated
    - Various models for evaporation/condensation through the interface
    - Transient mass and energy equations for the vapor phase
    - Transient mass and energy equations for the liquid phase
  - Wall heat transfer
    - Time-dependent energy equation within tank walls.
    - Different material layers within tank walls

Evaporation/Condensation model

$$\dot{q}_{VS} - \dot{q}_{SL} = \dot{m}_{evap}\left(h_{sat,V} - h_{sat,L}\right)$$



$$\dot{q}_{VS} = K_V a_{VS}\left(T_V - T_{Sat}\right) \qquad \dot{q}_{SL} = K_L a_{SL}\left(T_{Sat} - T_L\right)$$

$$Nu_{VS} \equiv \frac{a_{VS} D}{\lambda_{VS}} = 0.27 Ra_{VS}^{1/4}$$ Mc Adams

$$Nu_{SL} \equiv \frac{a_{SL} D}{\lambda_{SL}} = 2.5\left\{\ln\left\{1.0 + \frac{2.5}{0.527 Ra_{SL}^{0.2}}\left(1.0 + \left(\frac{1.9}{\Pr_{SL}}\right)^{0.9}\right)^{2/9}\right\}\right\}^{-1}$$ Nellis & Klein

$K_V = K_L = 0.1$ Account for non-equilibrium

Wang H.R. et al., Modeling and thermodynamic analysis of thermal performance in self-pressurized liquid hydrogen tanks, IJHE, 47 (2022)

DISCHA features (5)

- Discharge/transfer line modelling
  - Conservation equations
    - Steady state momentum and energy balance
    - Line resistance, area change, wall heat transfer both for single phase and two-phase conditions
    - Transient internal energy equation within pipe walls.
  - Choked flow
    - Calculated using general Possible-Impossible-Flow (PIF) algorithm
    - Discretization along discharge line is necessary (refine grid near pipe exit !!!)
    - Mach = 1 at exit is an output result not a BC
  - Fictitious nozzle
    - 7 available models

DISCHA validation

Emptying of an LH2 tank due to boil-off

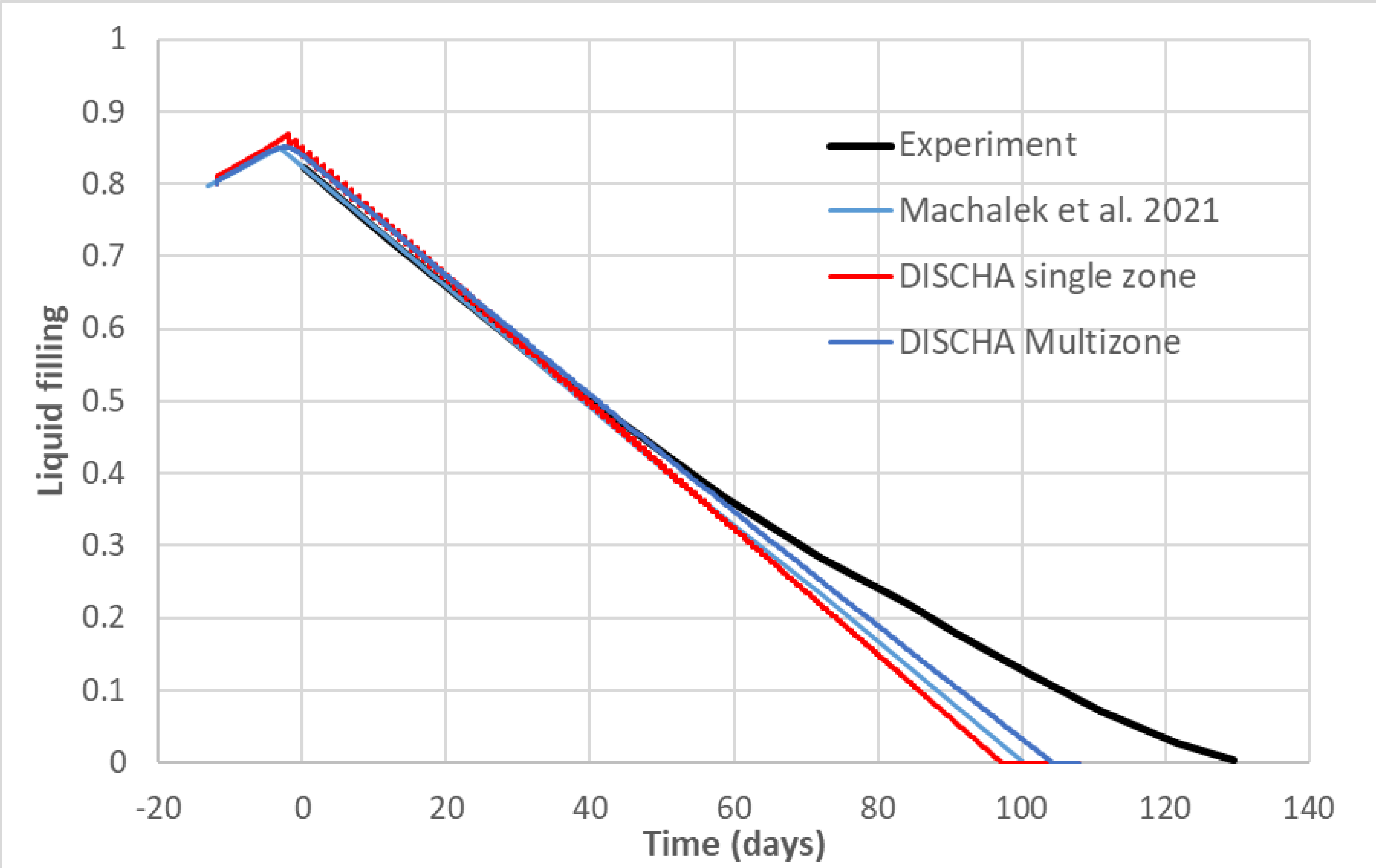
Emptying of an LH2 tank due to boil-off

- Experiments
  - From Lawrence Livermore National Laboratories, see also Machalek et al., ICHS-9, 2021.
- System
  - Tank
    - Vertical cylindrical tank 2 m diameter, 3.97 m height, 12.47 m^3 volume.
    - 11.1 mm inner steel + 50.8 mm MLI vacuum + 8.3 mm outer steel walls
    - 80% initial LH2 fill
  - Line
    - 5 mm PRV, opens at 3.1 bar and closes at 2.9 bar

Material	Inner steel	MLI	Outer steel
Conductivity	3	2e-4	15
Specific heat	25	0.1	450
Density	8050	0.1	8050

Machalek et al., Influence of non-equilibrium conditions on liquid hydrogen storage tank behavior, 9th Int. Conf. on Hydrogen Safety, 21-23 Sept. 2021, Edinburgh, UK

Emptying of an LH2 tank due to boil-off

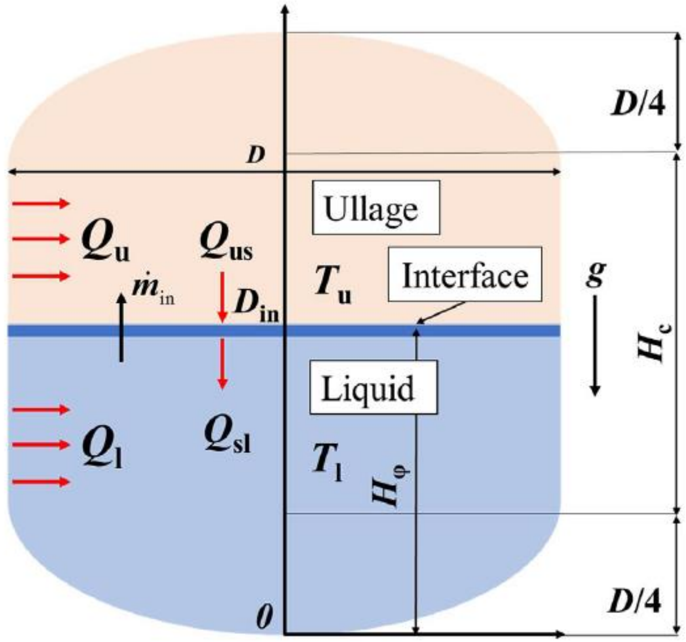


DISCHA validation

Self pressurization of LH2 tanks

Self-pressurization of LH2 tanks

- Experiments
  - NASA multipurpose hydrogen test bed (MHTB) tank experiments see Hastings et al., (2003) and related modeling by Wang et al. (2022).
- System
  - Tank volume 18.09 m^3,
  - tank diameter D = 3.05 m
  - Cylindrical height H_c = 1.525 m
  - No venting



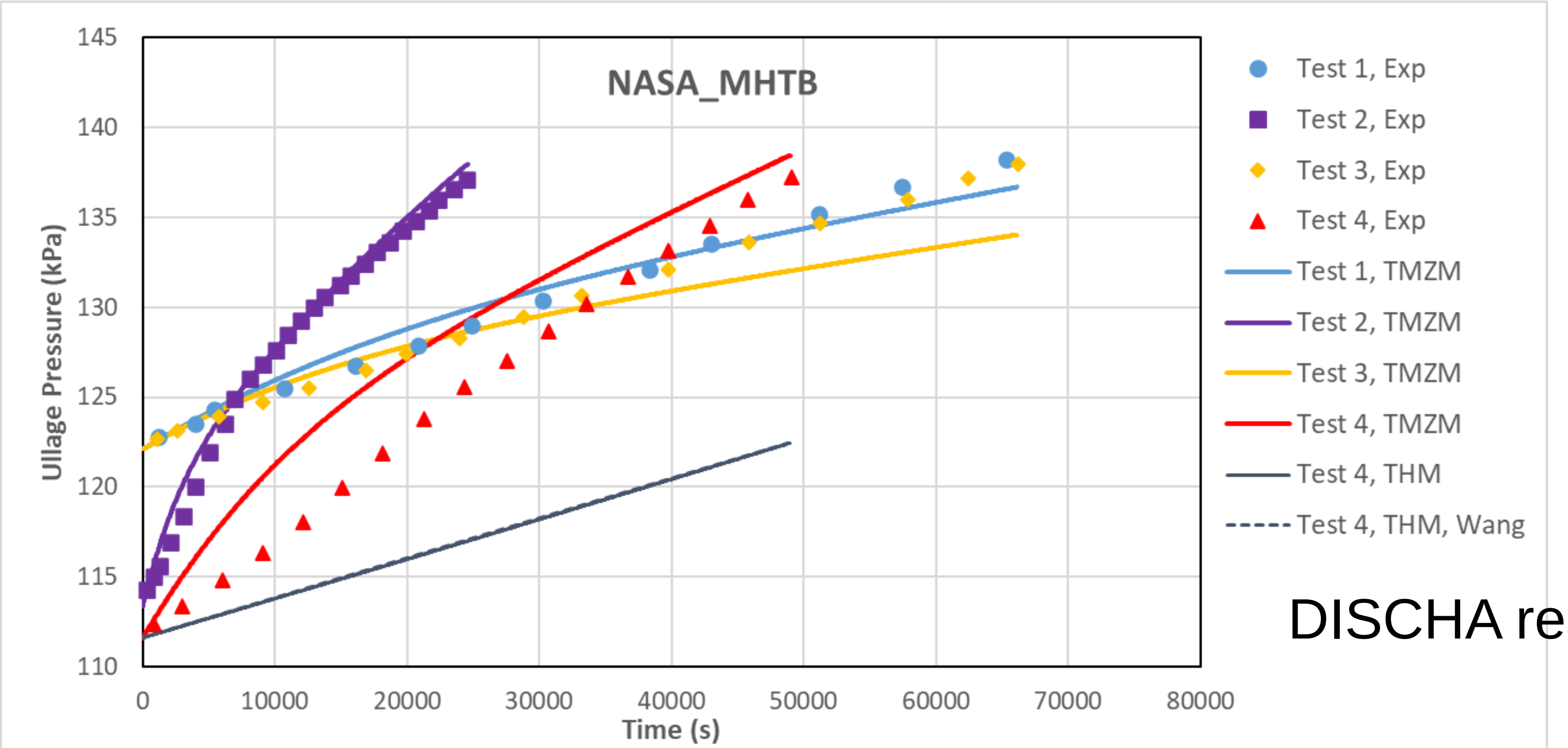
Hastings et al., Spray bar zero-gravity vent system for on orbit liquid hydrogen storage. NASA TM-12926 (2003)

Wang H.R. et al., Modeling and thermodynamic analysis of thermal performance in self-pressurized liquid hydrogen tanks, IJHE, 47 (2022)

Self-pressurization of LH2 tanks

Table 1 – Experimental results of MHTB tank [23].

Number	φ	Initial pressure (kPa)	Terminated pressure (kPa)	Holding time (s)	Q_{tot} (W)
#1	25%	122.1	137.8	66,100	18.8
#2	90%	113.3	137.1	24,560	71.3
#3	50%	122.1	137.8	66,115	18.7
#4	50%	111.6	137.2	48,970	51.8



$$\frac{\dot{q}_V}{\dot{q}_L} = 0.5$$

DISCHA results

Tank to tank transfer

Filling of an LH2 truck from a stationary tank

Tank to tank transfer

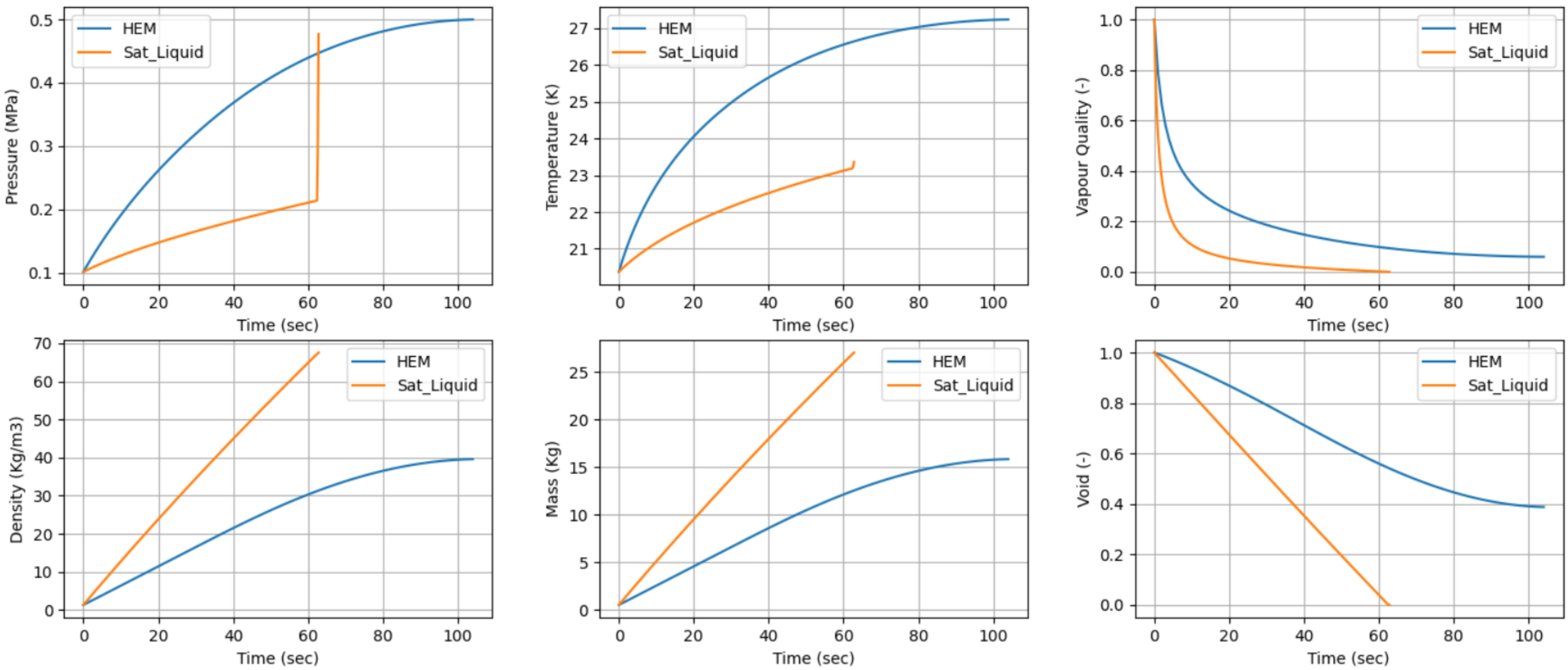
- Scope of work:
  - Simulate the filling of an LH2 truck from a stationary tank
  - Effect of tank model (single zone or multizone)
  - Effect of transfer line evaporation model (HEM or saturated liquid)
  - Is filling eventually stopped by unwanted pressure increase in the target tank?
  - Provide pre-test support for ELVHYS tank to tank transfer experiments at DLR
  - Provide a validated tool for tank to tank transfer simulations

Tank to tank transfer

- System Components:
  - Supply tank 12 m^3 (5 bars, sat LH_2)
  - Transfer line (30 m, 2.54 cm) + (5 cm, 10mm) nozzle
  - Receiving tank 0.4 m^3 (1 atm, sat GH2) without vent
  - All components are considered adiabatically isolated.
- Models:
  - Constant pressure for supply tank
  - HEM or Sat_Liquid for transfer line
  - Single zone or Multizone for receiving tank

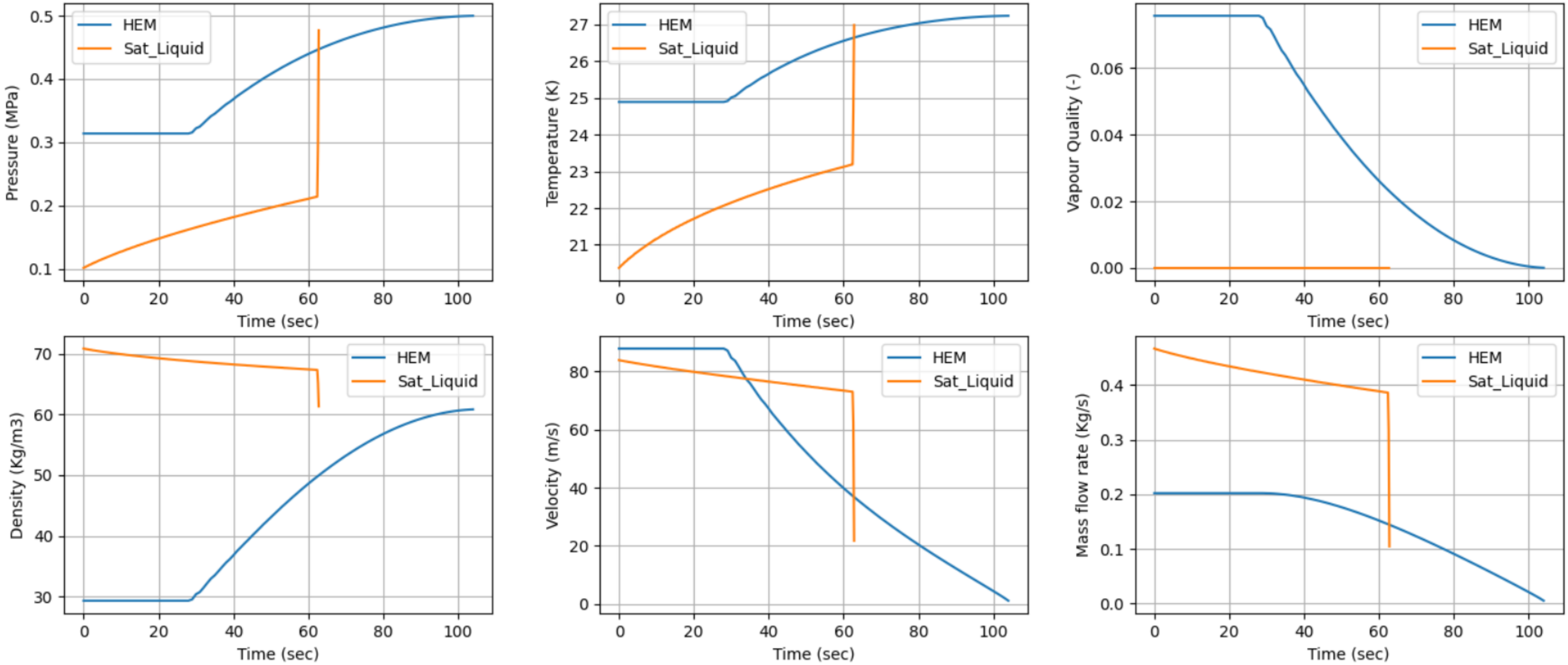
5 bars, single zone

Predicted conditions in receiving tank



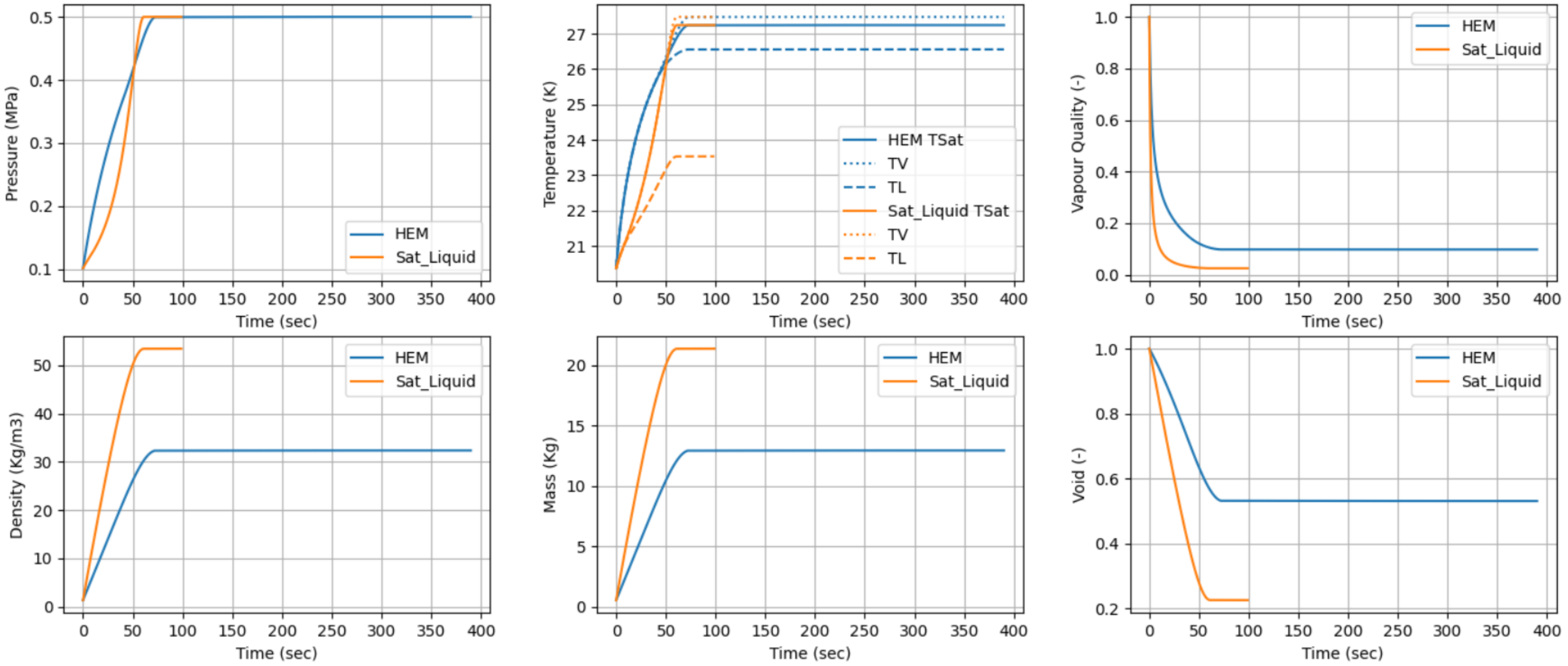
5 bars, single zone

Predicted conditions at transfer line exit



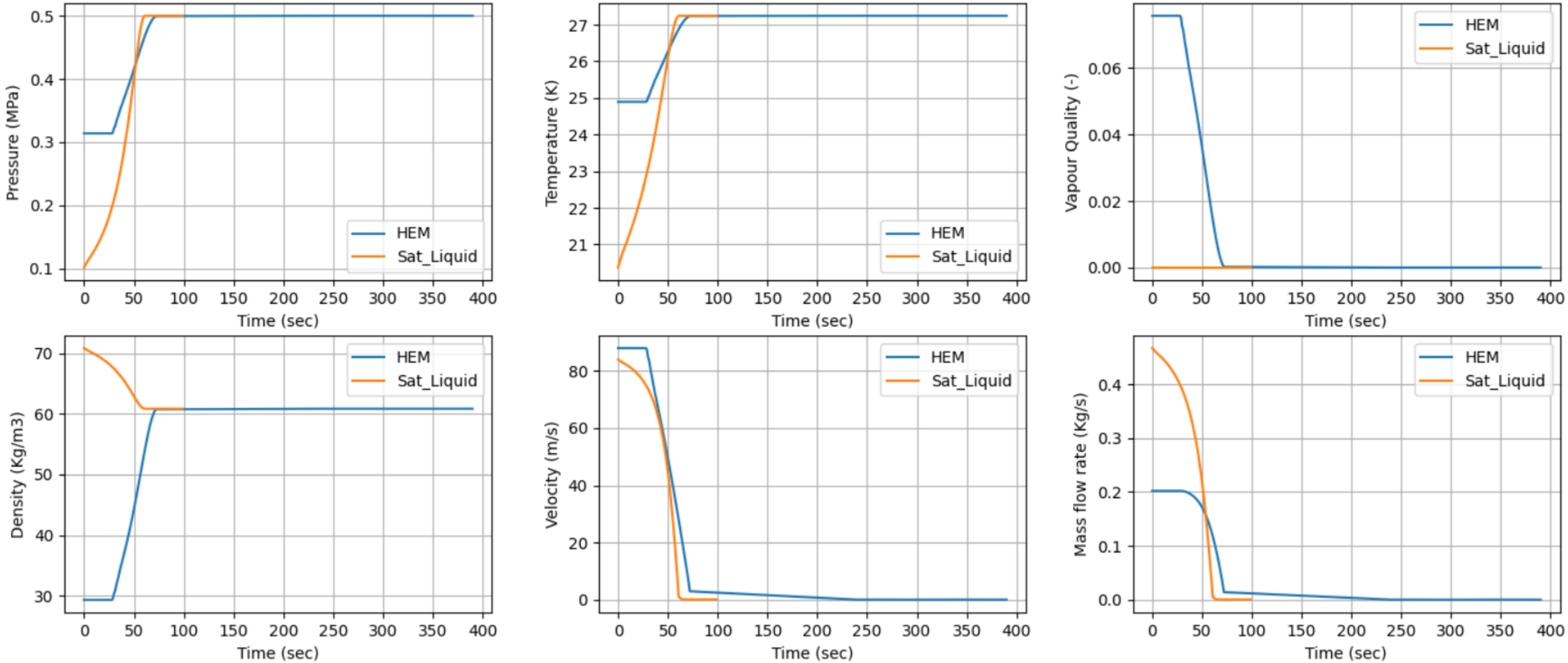
5 bars, Multizone

Predicted conditions in receiving tank



5 bars, Multizone

Predicted conditions at transfer line exit



Conclusions

- DISCHA validation
  - Reasonable agreement against LLNL LH2 boiloff tests and NASA MHTB pressurization tests
- Tank to tank transfer simulations at 5 bars
  - Single zone tank model
    - ⇒61% fill with HEM in transfer line
    - ⇒100% fill with Saturated liquid in transfer line
  - Multizone tank model
    - ⇒47% fill with HEM in transfer line
    - ⇒77% fill with Saturated liquid in transfer line
  - Multizone model gives lower tank fill compared to single zone
  - Saturated liquid in transfer line gives higher fill compared to HEM

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ELVHYS

Thank you for your attention

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