Dynamic Modeling of the Pressure Increase in LHe Cryostats in Case of Incidents

C. Heidt, S. Grohmann

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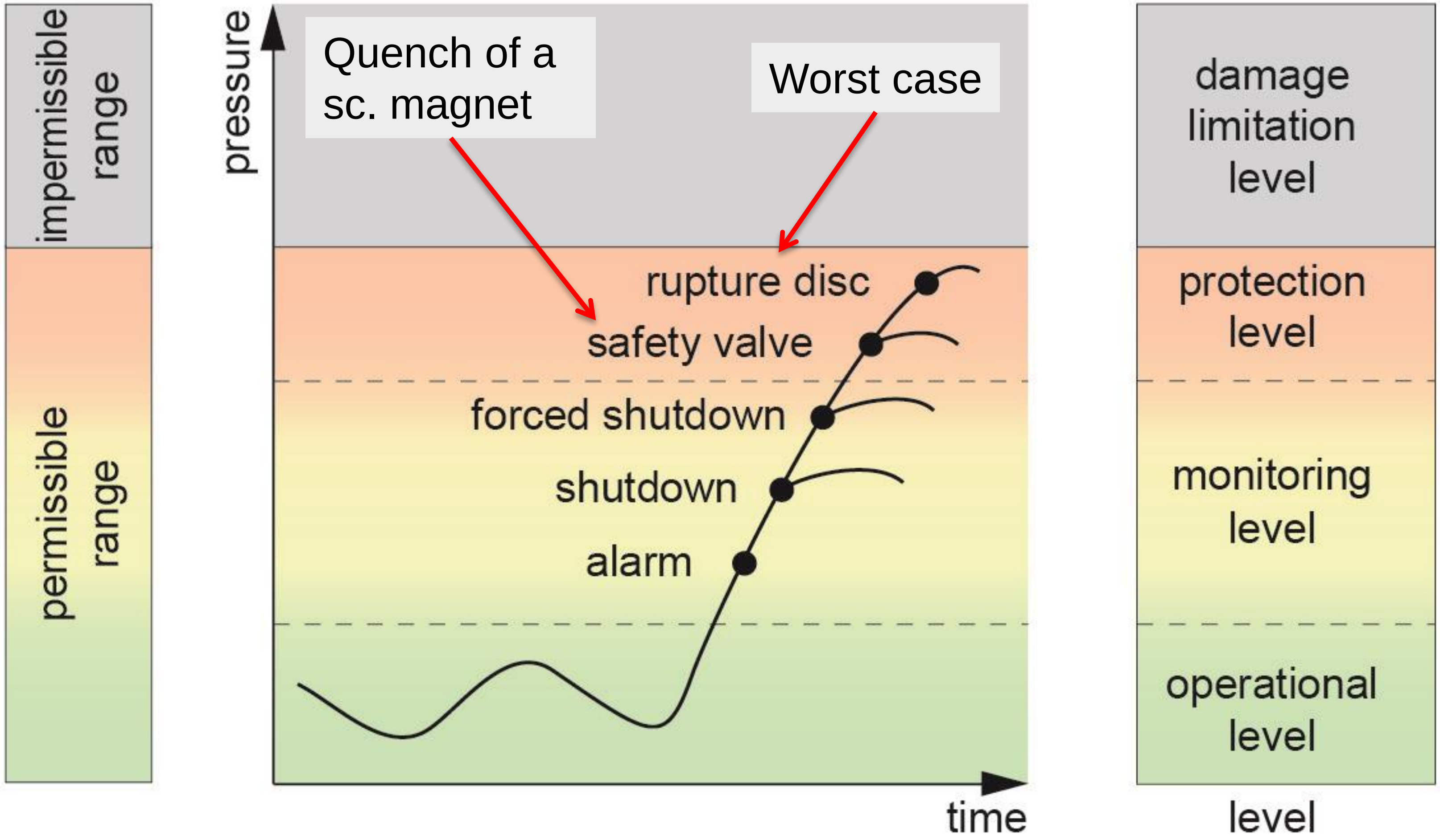
INSTITUTE FOR TECHNICAL PHYSICS
INSTITUTE FOR TECHNICAL THERMODYNAMICS AND REFRIGERATION

Outline

- Motivation Dynamic Modeling
- Model Development & Solution
- Heat and Mass Transfer
- Comparison Model - Experiment
- Conclusion & Outlook

Safety Concept



[1] DIN SPEC 4683:2015-04: *Cryostats for liquefied helium – Safety devices for protection against excessive pressure;*
[2] S. Grohmann, M. Süßer: Conceptual Design of Pressure Relief Systems for Cryogenic Application, 2014 *AIP Conf. Proc.* **1573**, 1581-1585

State of the Art

- **Sizing** of safety valves [3]: $A_0 = f(\dot{m}_{\mathrm{Out}}),\ \dot{m}_{\mathrm{Out}} = f(\dot{q})$
- **Worst case** often venting of insulating vacuum with atm. air
- EN13648 [4]: not considering **process dynamics** $\rightarrow \boldsymbol{\dot{q}_{\mathrm{max}} = \mathrm{const.}}$
  - Lehmann/Zahn [5]: $\dot{q}_{\mathrm{max}} = 3.8\ \mathrm{W/cm^2}$
  - Cavallari et al. [6]: $\dot{q}_{\mathrm{max}} = 4\ \mathrm{W/cm^2}$
- **Possible oversizing** of safety valves
  - Implications on spending, space and helium leakage
  - Unstable operation → reduced relief flow capacity (*pumping, chattering*)
- **Objective:** Dynamic model linking all sub-processes

[3] ISO 4126-7 Safety devices for protection against excessive pressure –Part 7: Common data, German version pr EN ISO 4126-7:2011

[4] EN 13648-3 Cryogenic vessels - Safety devices for protection against excessive pressure - Part 3: Determination of required discharge Capacity and sizing, German version EN 13648-3:2002

[5] Lehmann W and Zahn G, Safety aspects for LHe cryostats and LHe containers, 1978 *Proc. Int. Cryog. Eng. Conf*. **7** 569-579

[6] Cavallari G, Gorin I, Güsewell D and Stierlin R, Pressure protection against vacuum failures on the cryostats for LEP SC cavities, 1989 *Proc. 4th Workshop on RF Superconductivity* **1** 781-803

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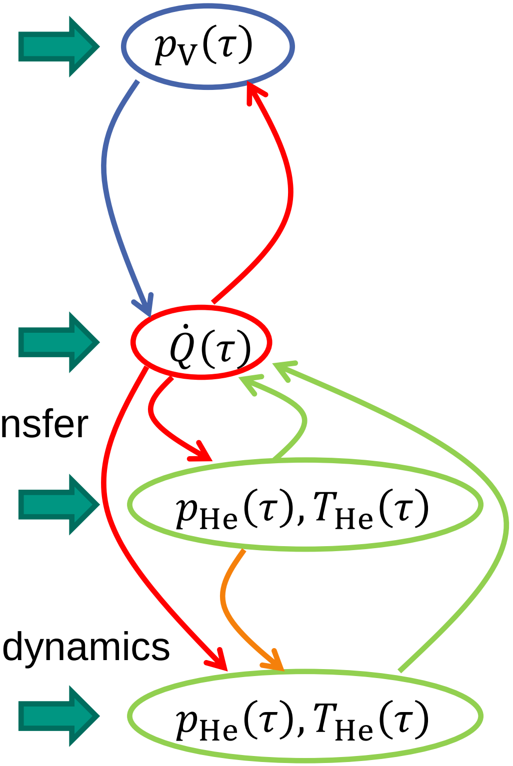
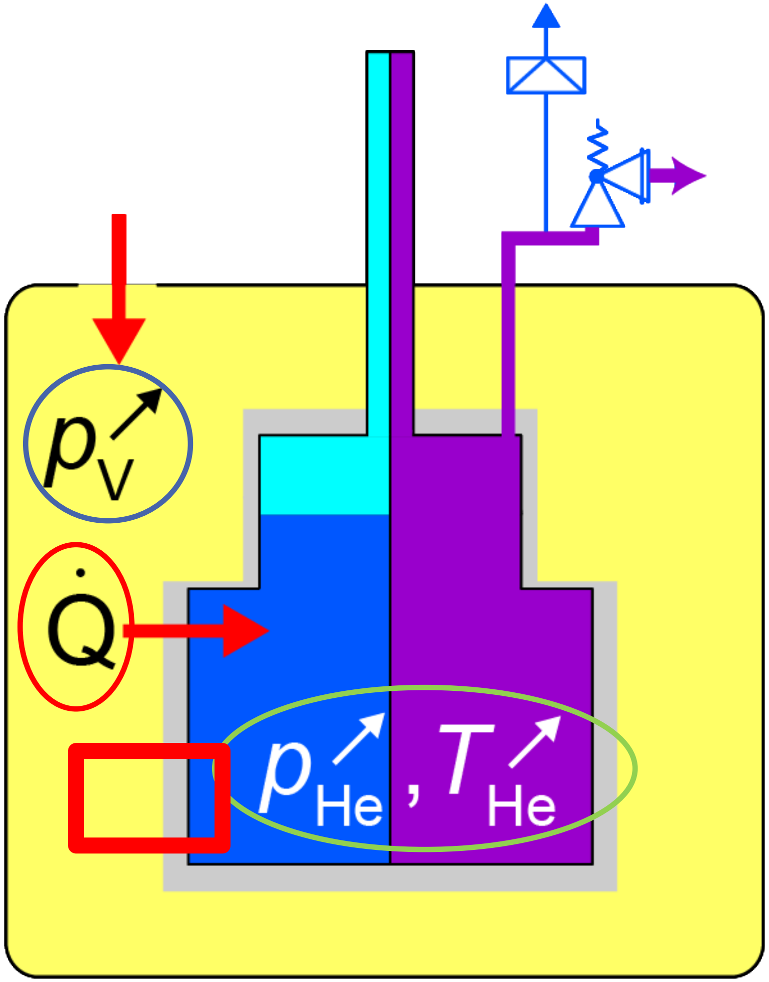
Model Development & Solution [4]

- Vacuum space
  - Ideal gas law
  - Ideal gas flow through orifice
- Transition
  - Heat and mass transfer
- Closed inner vessel
  - Isochoric process
  - First law of thermodynamics
- Open inner vessel
  - Isobaric process
  - First law of thermodynamics

➢ Simultaneous solution of ODEs





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[4] Heidt, C., Grohmann, S., Süßer, M., Modeling the Pressure Increase in Liquid Helium Cryostats after Failure of the Insulating Vacuum, 2014 *AIP Conf. Proc.* **1573** 1574-1580

Model Development & Solution [4]

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  - **Heat and mass transfer**
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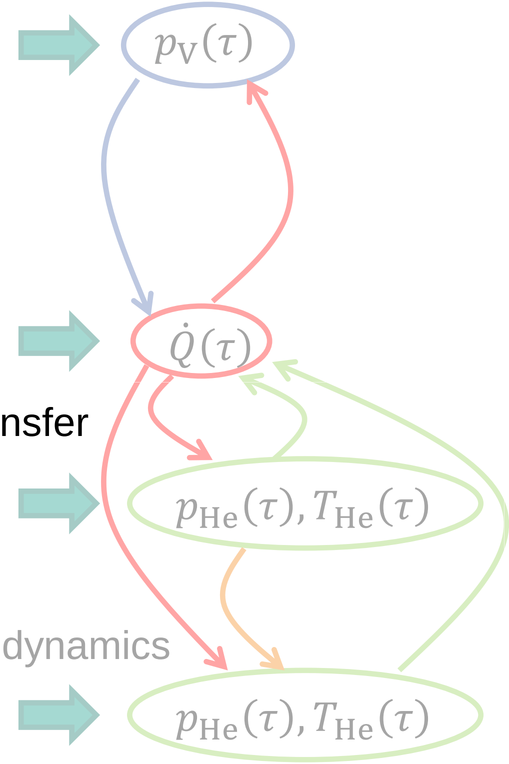
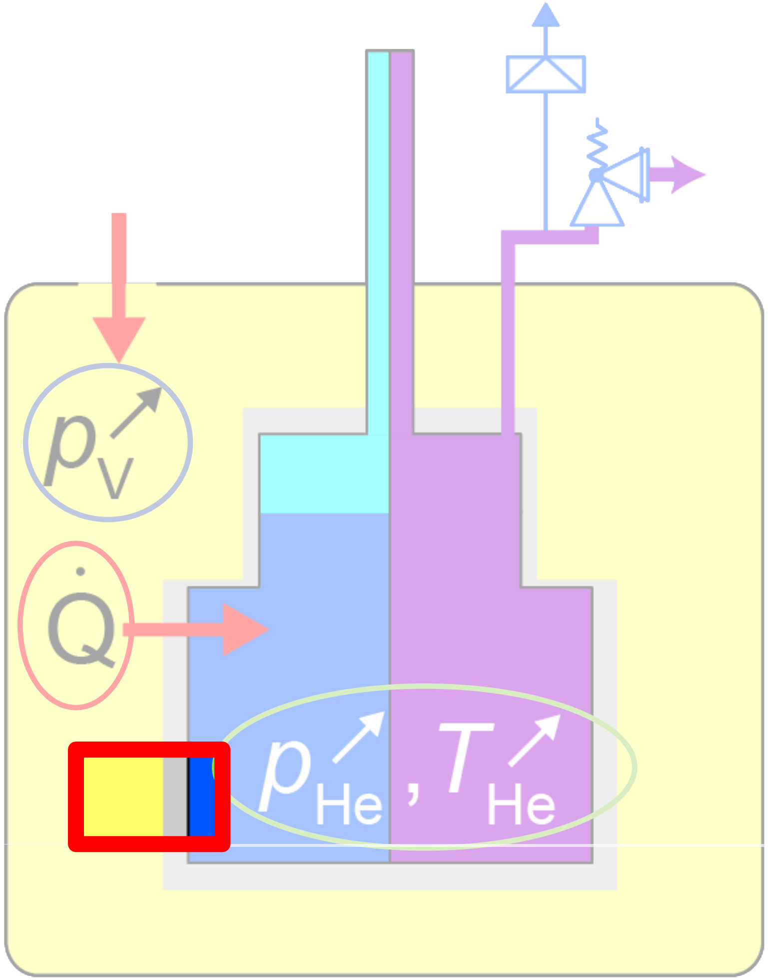


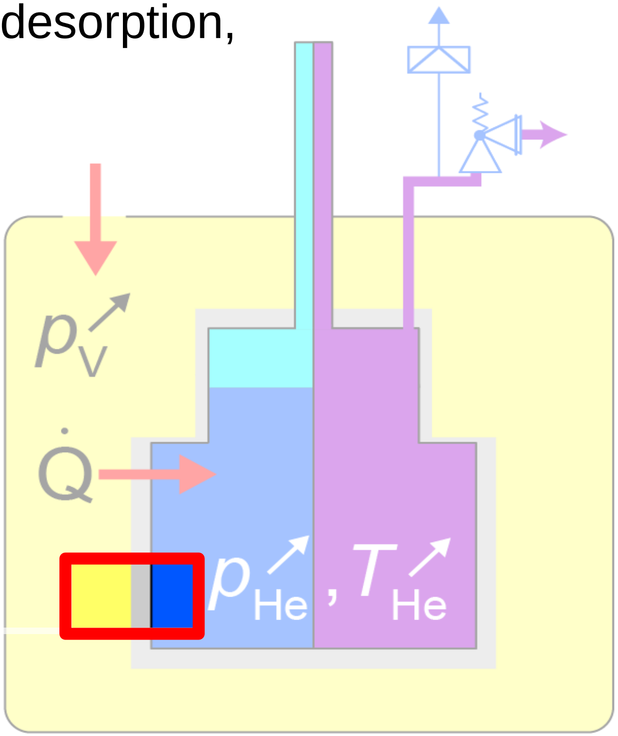


[4] Heidt, C., Grohmann, S., Süßer, M., Modeling the Pressure Increase in Liquid Helium Cryostats after Failure of the Insulating Vacuum, 2014 *AIP Conf. Proc.* **1573** 1574-1580

Heat and Mass Transfer

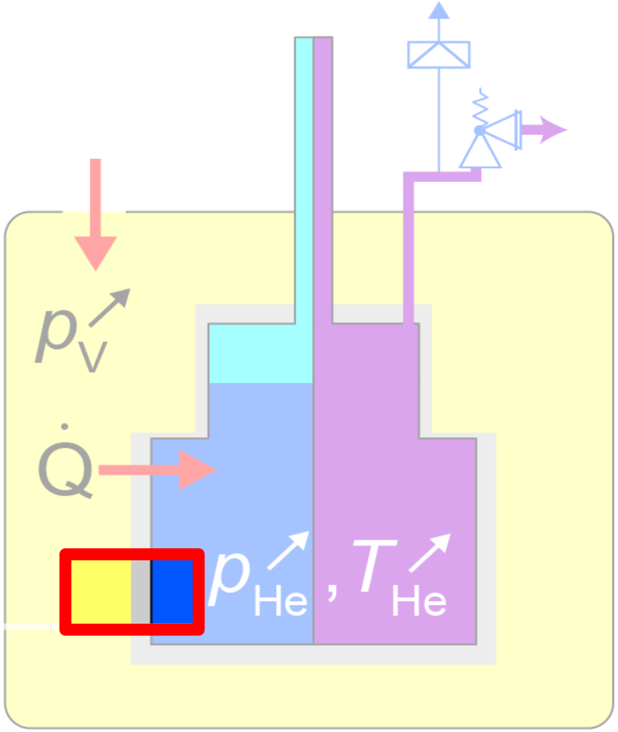
- Purely analytical approach not feasible
  - Gas flow in vacuum space, pressure gradients → $f(x,\tau)$
  - Temperature gradients on inner vessel surface → $f(x,\tau)$
  - Simultaneous processes: diffusion, adsorption/desorption, VLS phase changes → $f(x,\tau)$
  - Sticking of air on cold surface → $f(x,\tau)$
  - Solid air density, heat conductivity, layer thickness, composition → $f(x,\tau)$
  - …

➢ Fitting necessary



Deposition of Air on Cold Surface [5]

- Calculation based on kinetic theory: *Knudsen-Langmuir-Hertz*
  - $\dot{m}_{\mathrm{dep}} = A_{\mathrm{Cr}} \cdot (I_{\mathrm{C}} - I_{\mathrm{E}})$
  - Condensation: $I_{\mathrm{C}} = \alpha_{\mathrm{C}} \cdot \frac{p_{\mathrm{V}}}{\sqrt{T_{\mathrm{V}}}} \cdot \frac{1}{\sqrt{2\pi\, R_{\mathrm{Air}}}}$
  - Evaporation: $I_{\mathrm{E}} = \alpha_{\mathrm{E}} \cdot \frac{p_{\mathrm{Sat}}(T_{\mathrm{W}})}{\sqrt{T_{\mathrm{W}}}} \cdot \frac{1}{\sqrt{2\pi\, R_{\mathrm{Air}}}}$
- Coefficients $\alpha_{\mathrm{C}}, \alpha_{\mathrm{E}}$
  - $\alpha_{\mathrm{C}}, \alpha_{\mathrm{E}} = f(T_{\mathrm{V}}, T_{\mathrm{W}}, p_{\mathrm{V}}, p_{\mathrm{Sat}}(T_{\mathrm{W}}), \ldots)$
  - $\alpha_{\mathrm{C}} = \alpha_{\mathrm{E}}$ at equilibrium
  - $0 \leq \alpha_{\mathrm{C}}, \alpha_{\mathrm{E}} \leq 1$
  - $T_{\mathrm{W}} \uparrow$: $\alpha_{\mathrm{C}} \downarrow$, $\alpha_{\mathrm{E}} \uparrow$



[5] Haefer, R, Cryopumping – Theory and Practice, 1989 *Monographs on Cryogenics* ***4*** Clarendon Press, Oxford

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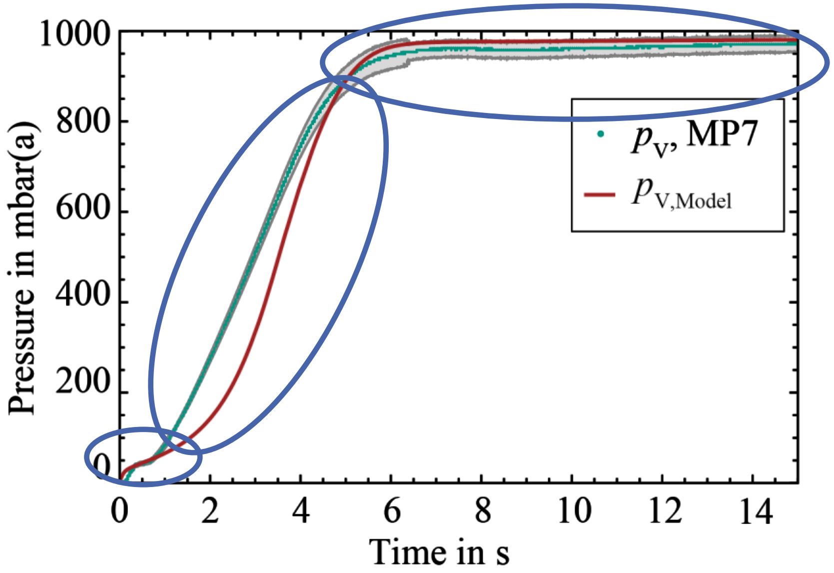
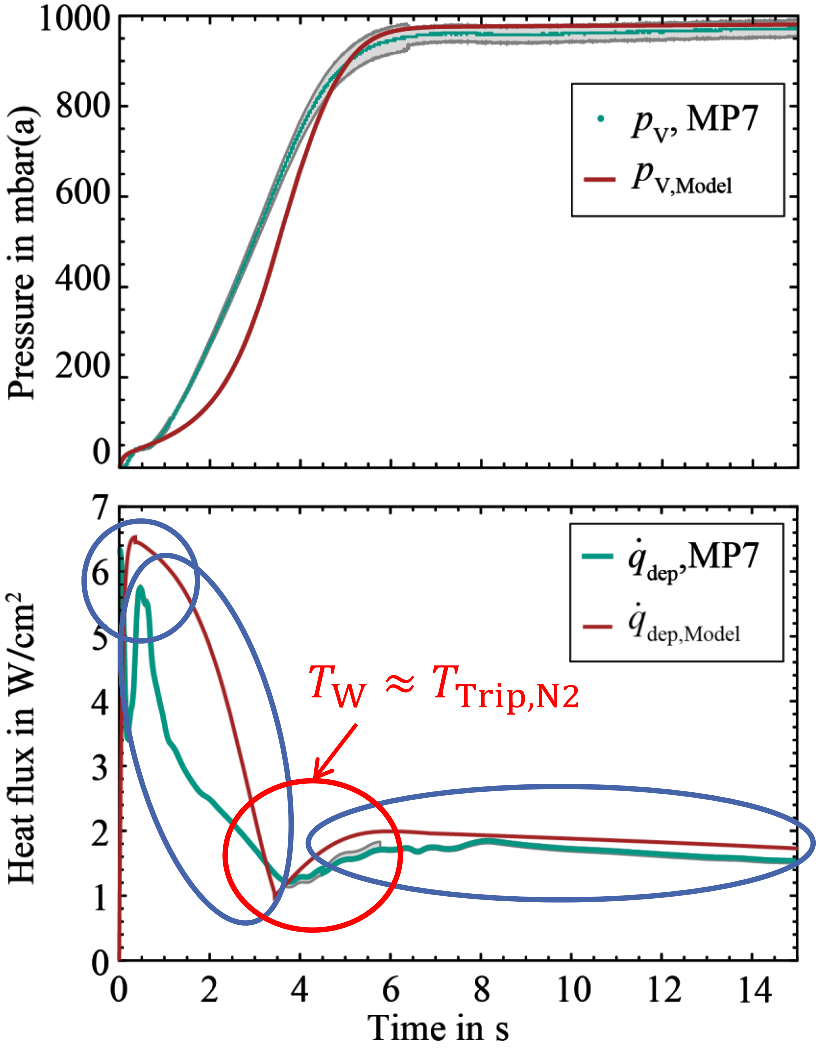
Comparison Model - Experiment



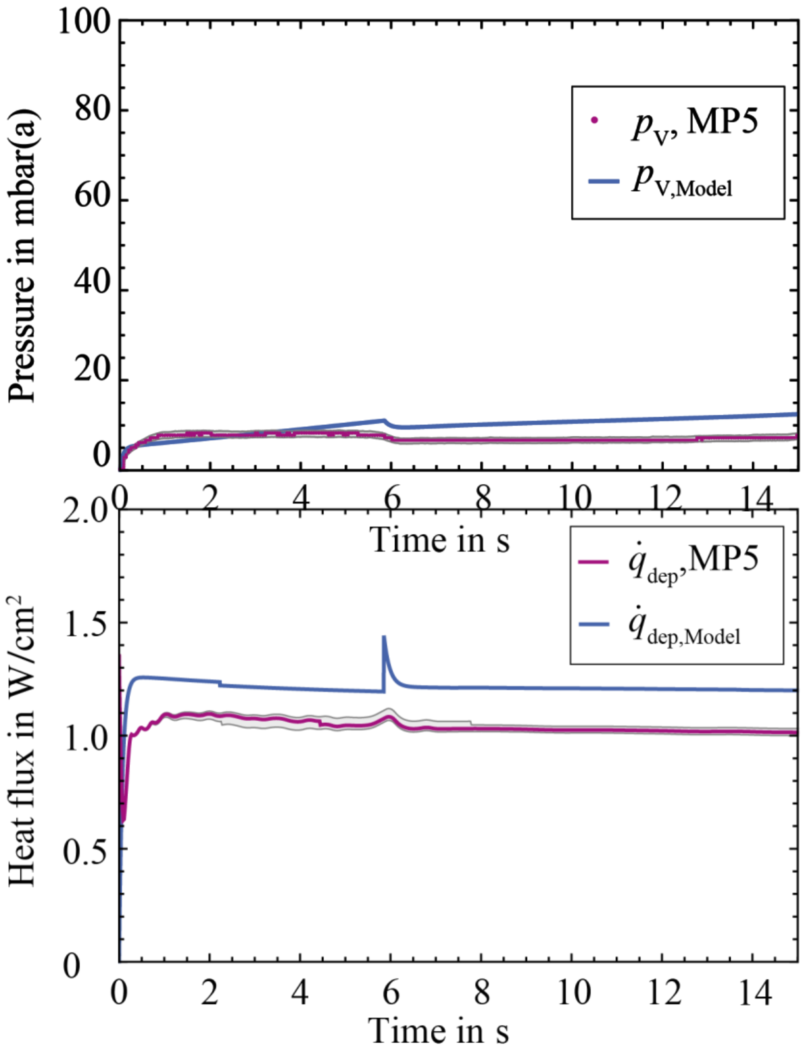
- Experimental data MP7
  - $d_\mathrm{Vent} = 30\ \mathrm{mm}$
  - $p_0 = 6\ \mathrm{bar(g)}$
- Model
  - $\dot{m}_\mathrm{dep} \sim \left(\alpha_\mathrm{C} \cdot \frac{p_\mathrm{V}}{\sqrt{T_\mathrm{V}}} - \alpha_\mathrm{E} \cdot \frac{p_\mathrm{Sat}(T_\mathrm{W})}{\sqrt{T_\mathrm{W}}}\right)$
  - $\alpha_\mathrm{C}, \alpha_\mathrm{E} = \begin{cases} \mathrm{const.}, & T_\mathrm{W} < 20\ \mathrm{K} \\ \mathrm{linear}, & \alpha_\mathrm{C}\downarrow, \alpha_\mathrm{E}\uparrow \\ \mathrm{const.}, & T_\mathrm{W} > T_\mathrm{Trip,N2} \end{cases}$
  - Fit $T_\mathrm{W} = f(T_\mathrm{Cr})$

Comparison Model - Experiment



- Experimental data MP7
  - $d_{Vent} = 30$ mm
  - $p_0 = 6$ bar(g)
- Model
  - $\dot{m}_{dep} \sim \left(\alpha_C \cdot \frac{p_V}{\sqrt{T_V}} - \alpha_E \cdot \frac{p_{Sat}(T_W)}{\sqrt{T_W}}\right)$
  - $\alpha_C, \alpha_E = \begin{cases} \text{const.}, & T_W < 20\text{ K} \\ \text{linear}, & \alpha_C \downarrow, \alpha_E \uparrow \\ \text{const.}, & T_W > T_{Trip,N2} \end{cases}$
  - Fit $T_W = f(T_{Cr})$
  - $T_W \approx T_{Trip,N2}$: $s \to l$ air
    - $\alpha_C \downarrow, \alpha_E \uparrow, \frac{p_{Sat}(T_W)}{\sqrt{T_W}} \uparrow$ ➡ $\dot{m}_{dep} \downarrow$
    - $\frac{p_V}{\sqrt{T_V}} \uparrow$ ➡ $\dot{m}_{dep} \uparrow$

Comparison Model - Experiment



- Experimental data MP5
  - $d_{Vent} = 12.5\ \mathrm{mm}$
  - $p_0 = 2\ \mathrm{bar(g)}$
- Model
  - $\dot{m}_{dep} \sim \left(\alpha_C \cdot \frac{p_V}{\sqrt{T_V}} - \alpha_E \cdot \frac{p_{Sat}(T_W)}{\sqrt{T_W}}\right)$
  - $\alpha_C, \alpha_E = \begin{cases} \text{const.}, & T_W < 20\ \mathrm{K} \\ \text{linear}, & \alpha_C \downarrow, \alpha_E \uparrow \\ \text{const.}, & T_W > T_{Trip,N2} \end{cases}$
  - Fit $T_W = f(T_{Cr})$

➢ **Good correspondence**

Conclusions & Outlook

- Inclusion of simple fit $T_{\mathrm{W}} = f(T_{\mathrm{Cr}}), \alpha_{\mathrm{C}}(T_{\mathrm{W}}), \alpha_{\mathrm{E}}(T_{\mathrm{W}})$ from kinetic theory
- Good agreement between measured data and experiment for very different conditions
- Shape of heat flux and vacuum pressure increase can be explained

➢ Improvement of modeling desublimation through experiments

➢ More experiments for wall temperature fit

Thank you for your attention!

Karlsruhe Institute of Technology

The PICARD Test Facility - KIT/CERN Collaboration on Cryogenic Pressure Relief Experiments

C. Heidt[1,2], A. Henriques[3], M. Stamm[1], C. Weber[1,2], S. Grohmann[1,2]

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[1] INSTITUTE FOR TECHNICAL PHYSICS, KIT
[2] INSTITUTE FOR TECHNICAL THERMODYNAMICS AND REFRIGERATION, KIT
[3] EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH (CERN)

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