





Experimental Study of R-290 Leakage Behavior

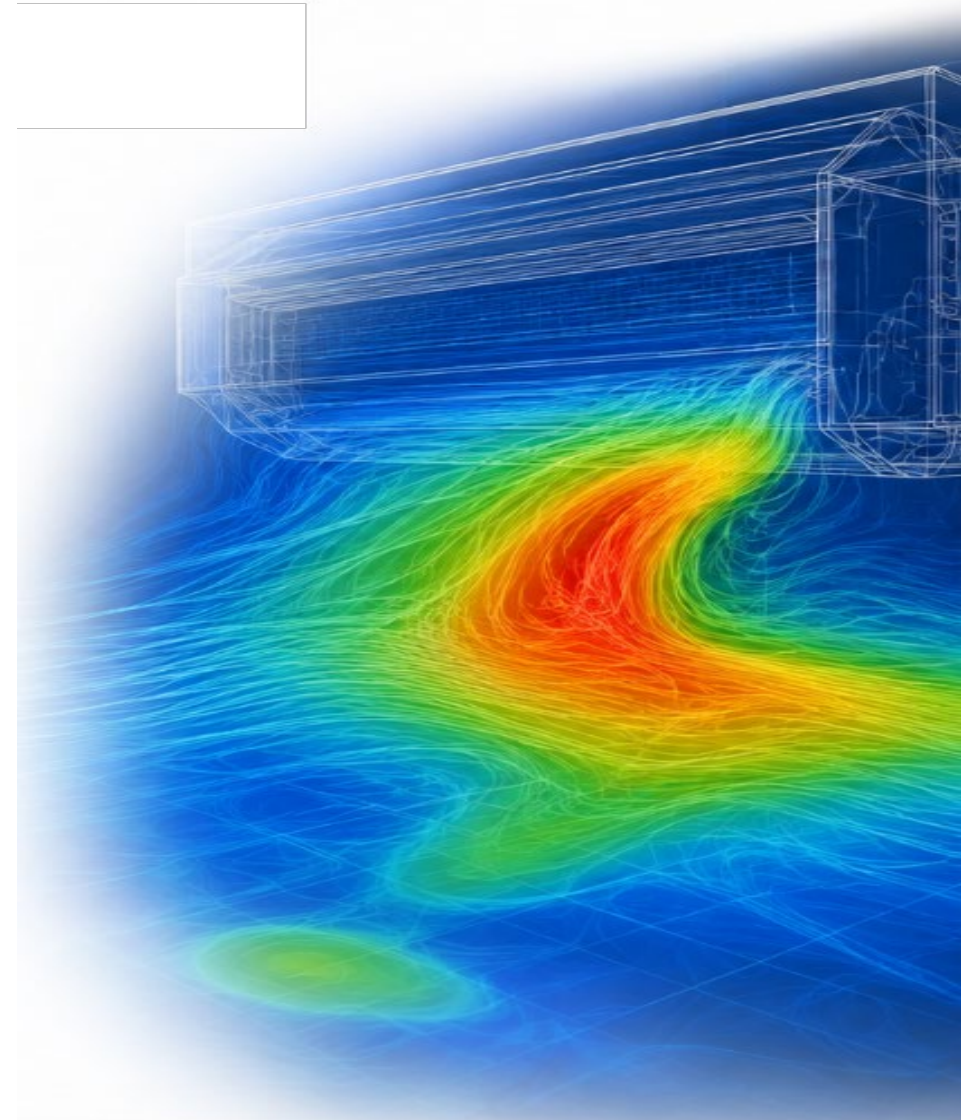
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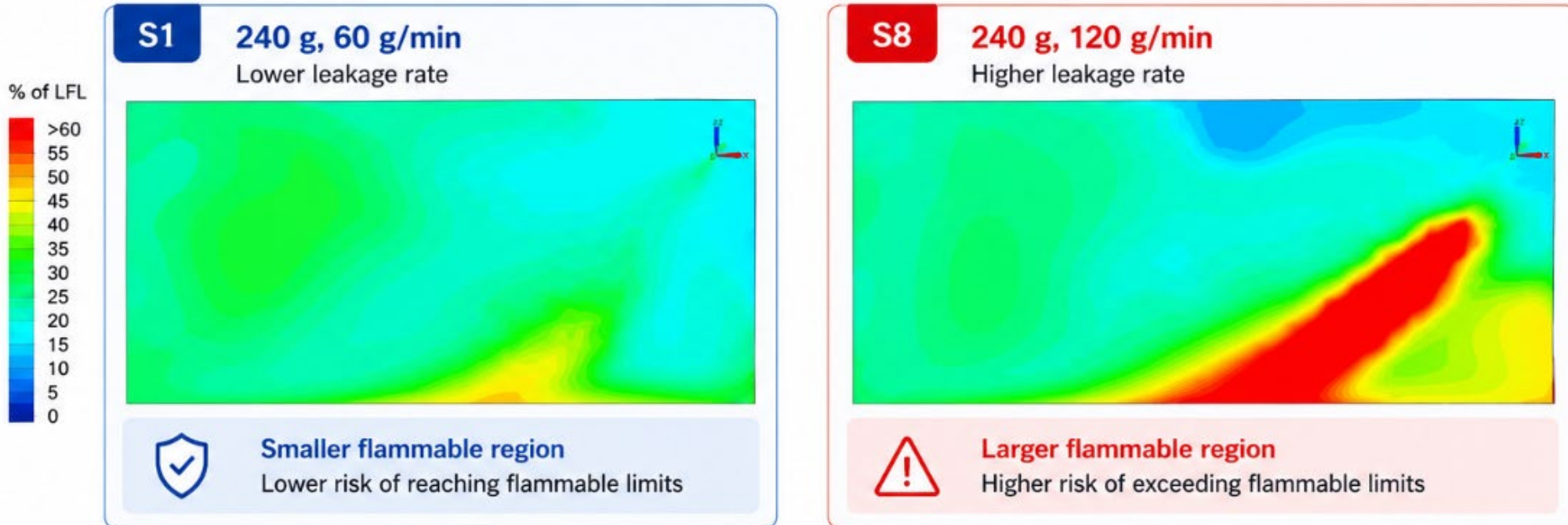
KTH Royal Institute of technology
Stockholm, Sweden

Presentation Roadmap

- 01**  Motivation
- 02**  Knowledge Gaps
- 03**  Objectives
- 04**  Experimental setup and test conditions
- 05**  Results and conclusions




Motivation



Flammability risk
Strongly depends on leakage behavior.



Safety limits & models
Leak rate assumptions affect charge limits and safety models.



Accurate leakage characterization is essential for safe use of flammable refrigerants.

Knowledge Gap



1. Conflicting conclusions: liquid vs gas leaks

Studies report inconsistent results on concentration and dispersion behavior for liquid and gas leakage scenarios.



2. Full-system tests hide fundamental physics

Complex system interactions mask the underlying physical mechanisms driving leakage and dispersion.



3. Limited experimental data with thermal visualization

Scarcity of high-quality thermal data limits validation of models and understanding of real behavior.

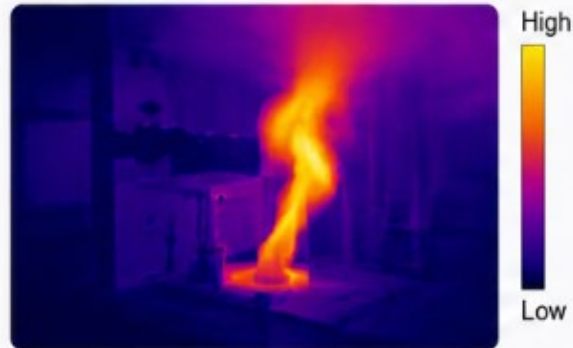
Liquid Leak



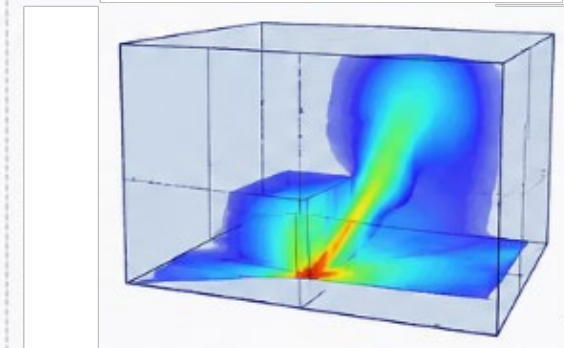
Gas Leak



Thermal Visualization (Experiment)



Full System Tests



More fundamental, controlled experiments with thermal visualization are needed to close these gaps.

Objective

01



Measure R-290 leak rates under controlled conditions

Quantify mass flow rates of R-290 leaks across a range of temperatures and pressures using a controlled experimental setup.



02



Compare liquid, vapor, and two-phase leakage behavior

Analyze and compare leakage characteristics for single-phase (liquid and vapor) and two-phase conditions to understand their impact on leakage rates.



03



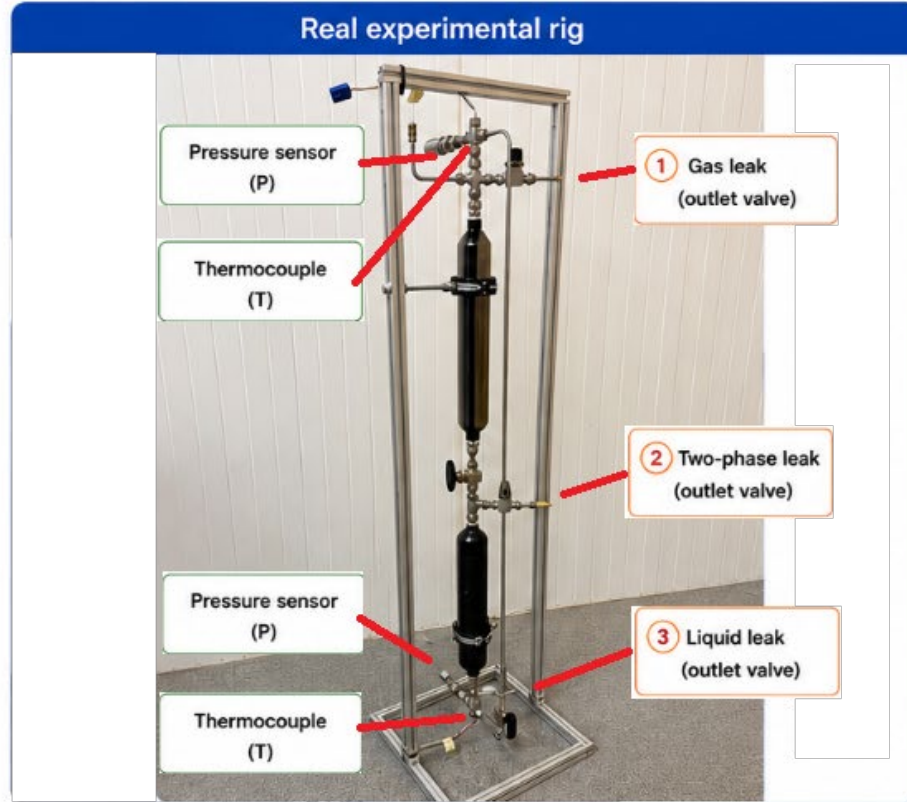
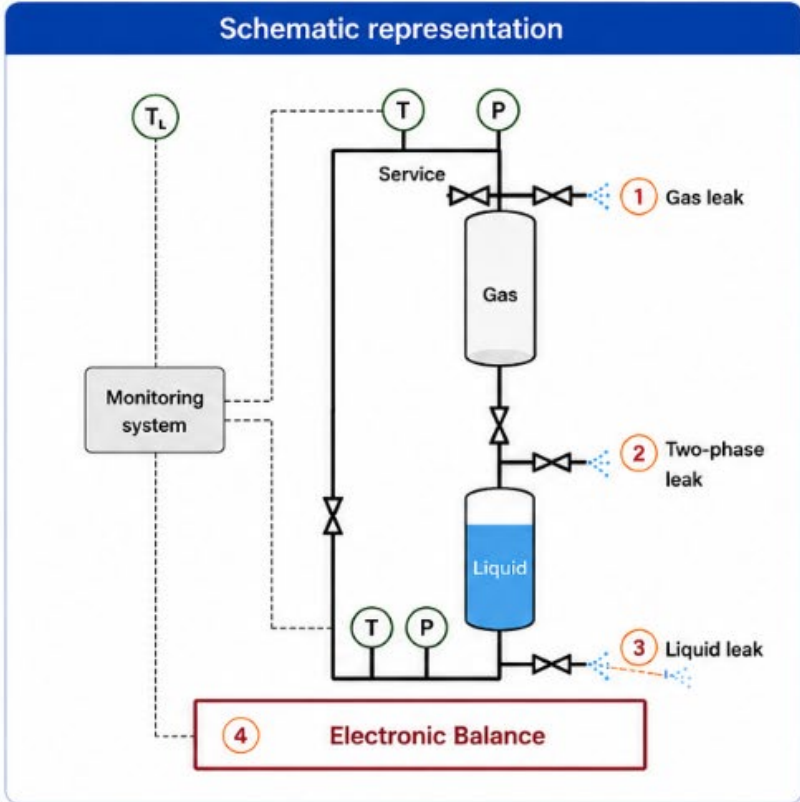
Support safety standards and Annex 64

Provide high-quality experimental data and insights to support safety standards (e.g., EN378, IEC60335-2-40) and contribute to the development of Annex 64.



These objectives aim to improve understanding of leakage behavior and support safer use of flammable refrigerants.

Experimental setup: Dual Cylinder Setup



Key measurement features



Pressure sensors (P)
Monitor system pressure and depressurization during leakage.



Thermocouples (T)
Measure temperature and cooling due to leakage and evaporation.



Leak valves
Enable controlled gas, liquid and two-phase leakage.



Electronic balance
High-accuracy mass measurement for leak rate determination.



The dual-cylinder setup enables controlled and repeatable measurements of leakage rates under different conditions.

Test Conditions



Refrigerant
R-290 (300 g)



Hole sizes
0.3 mm, 0.5 mm and 1.0 mm

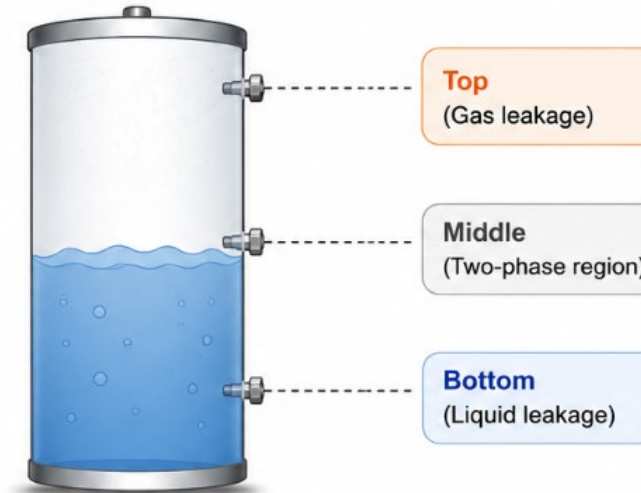


Leak positions
top (gas), middle,
bottom (liquid)

Hole size comparison

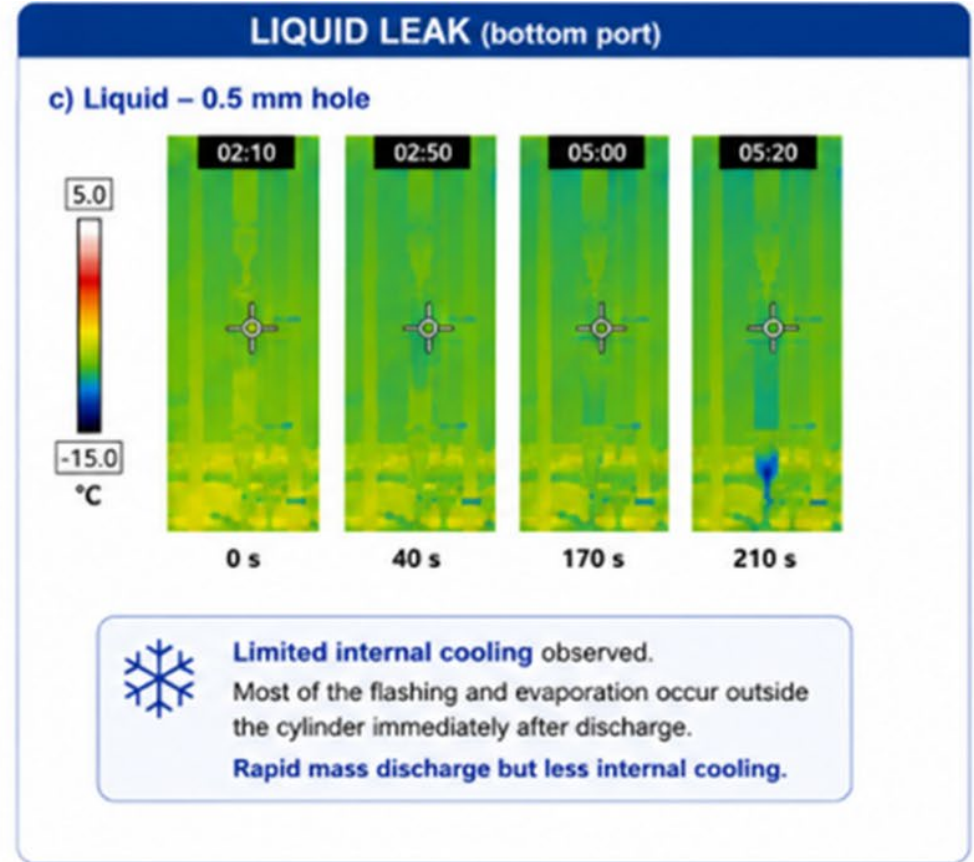
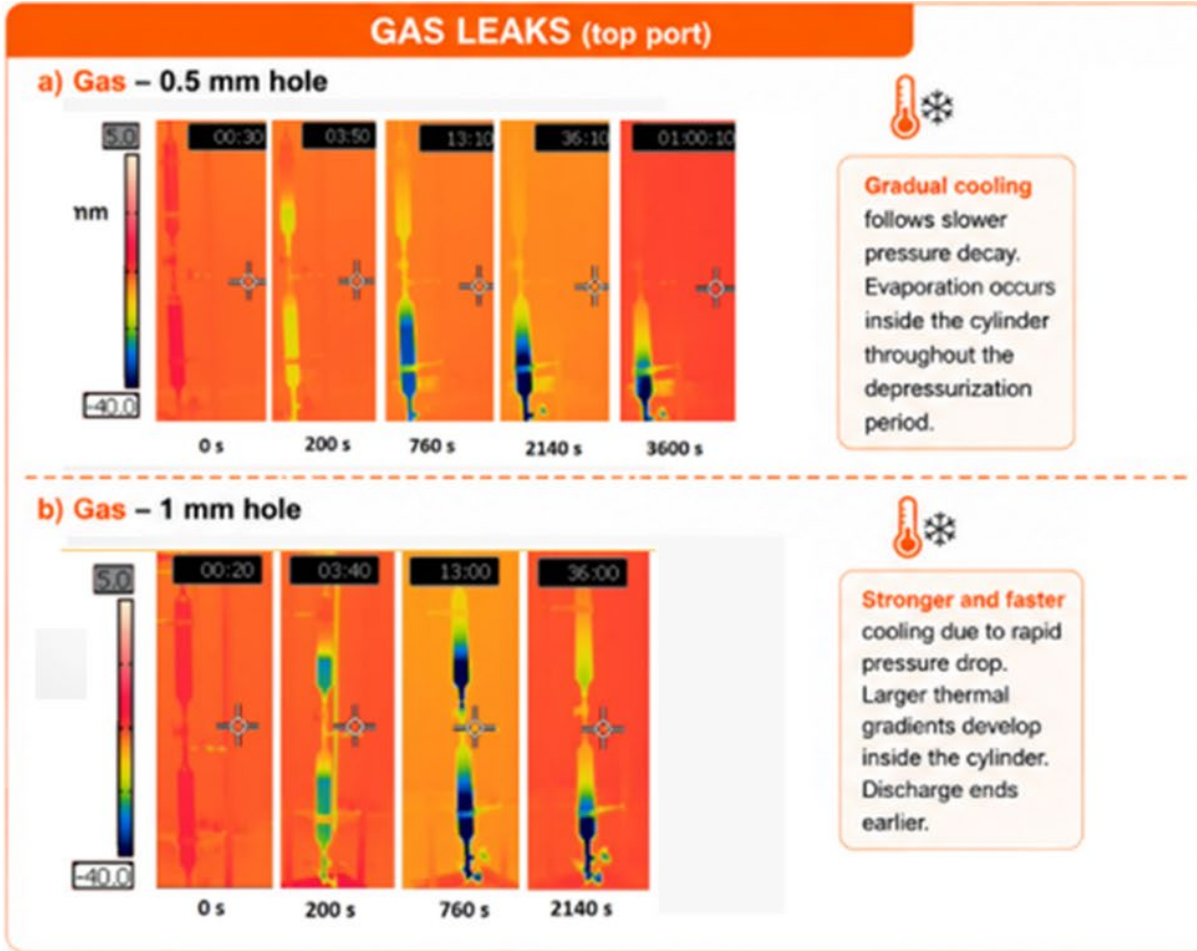


Leak position schematic



Tests conducted for different hole sizes and leak positions
to investigate the effect of leakage mode on dispersion and concentration.

IR thermography



IR results show that gas leaks produce stronger internal cooling because evaporation occurs inside the cylinder during depressurization, while liquid leaks mainly flash outside the cylinder.

Pressure Decay: Gas Leakage

Key observations



Smaller holes retain pressure longer

0.3 mm (top) shows the slowest pressure decay.



Larger holes cause faster depressurization

1 mm (top) exhibits the steepest pressure drop.



Middle vs. top location

0.5 mm (middle) decays faster than 0.5 mm (top) due to flow dynamics and mixing.

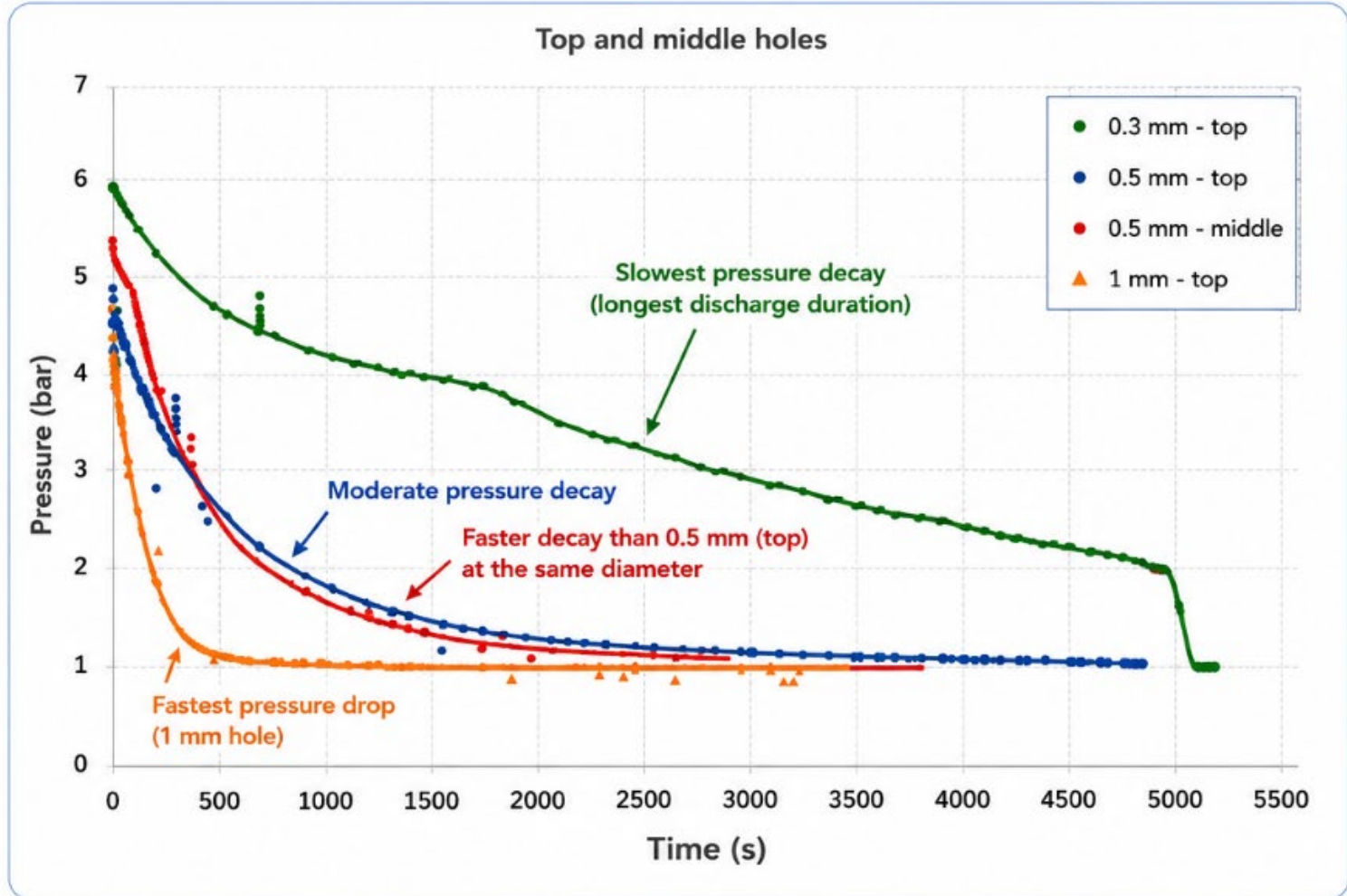


Pressure approaches atmospheric level

All cases stabilize near 1 bar as the system discharges.



Pressure decay strongly depends on leak diameter and location, which governs the transient release behavior of flammable refrigerants.



Pressure Decay – Liquid Leakage

Key observations



Smaller holes retain pressure longer

0.3 mm hole maintains higher pressure for the longest duration.



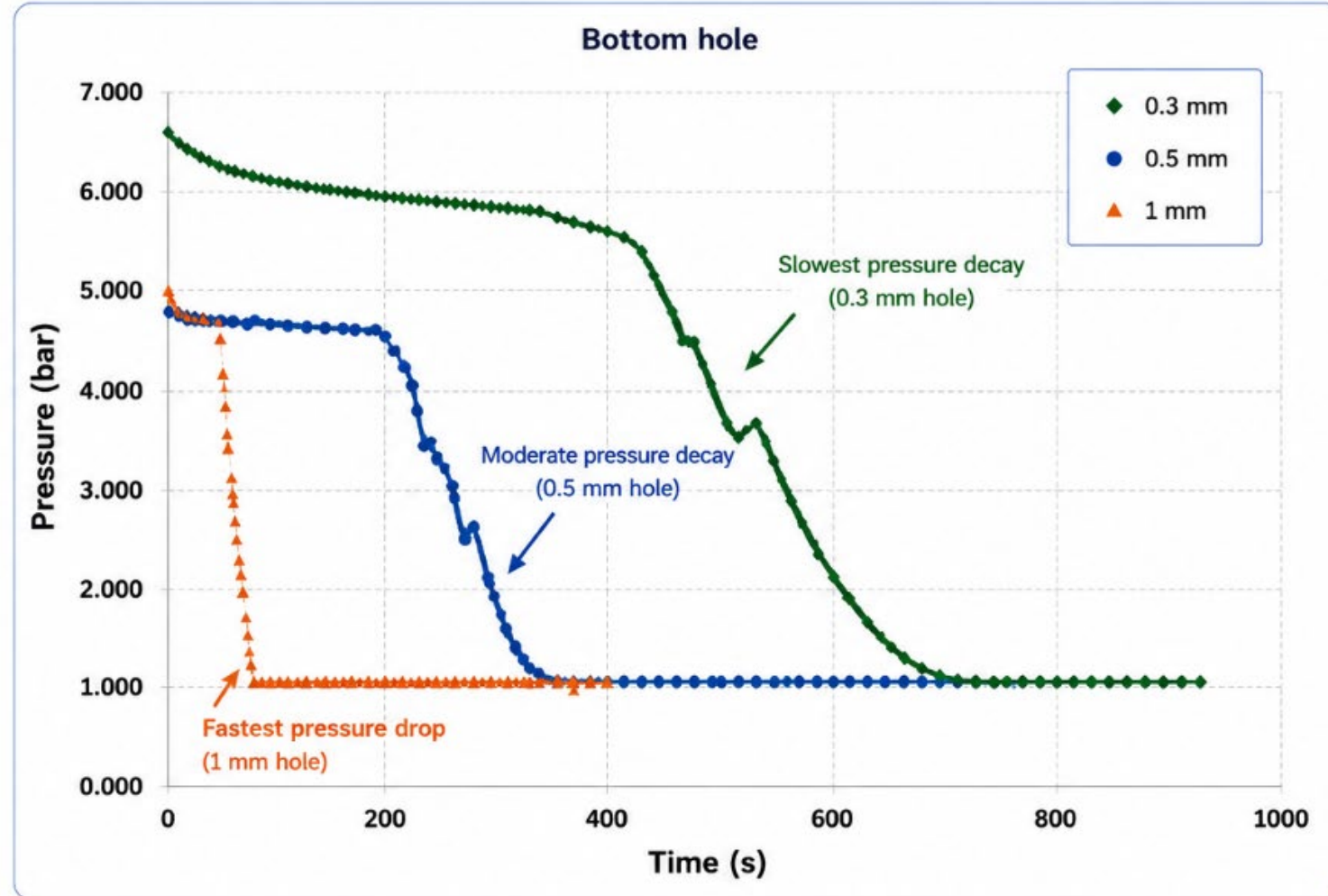
Larger holes cause faster depressurization

1 mm hole shows the steepest and earliest pressure drop.



Pressure stabilizes near atmospheric level

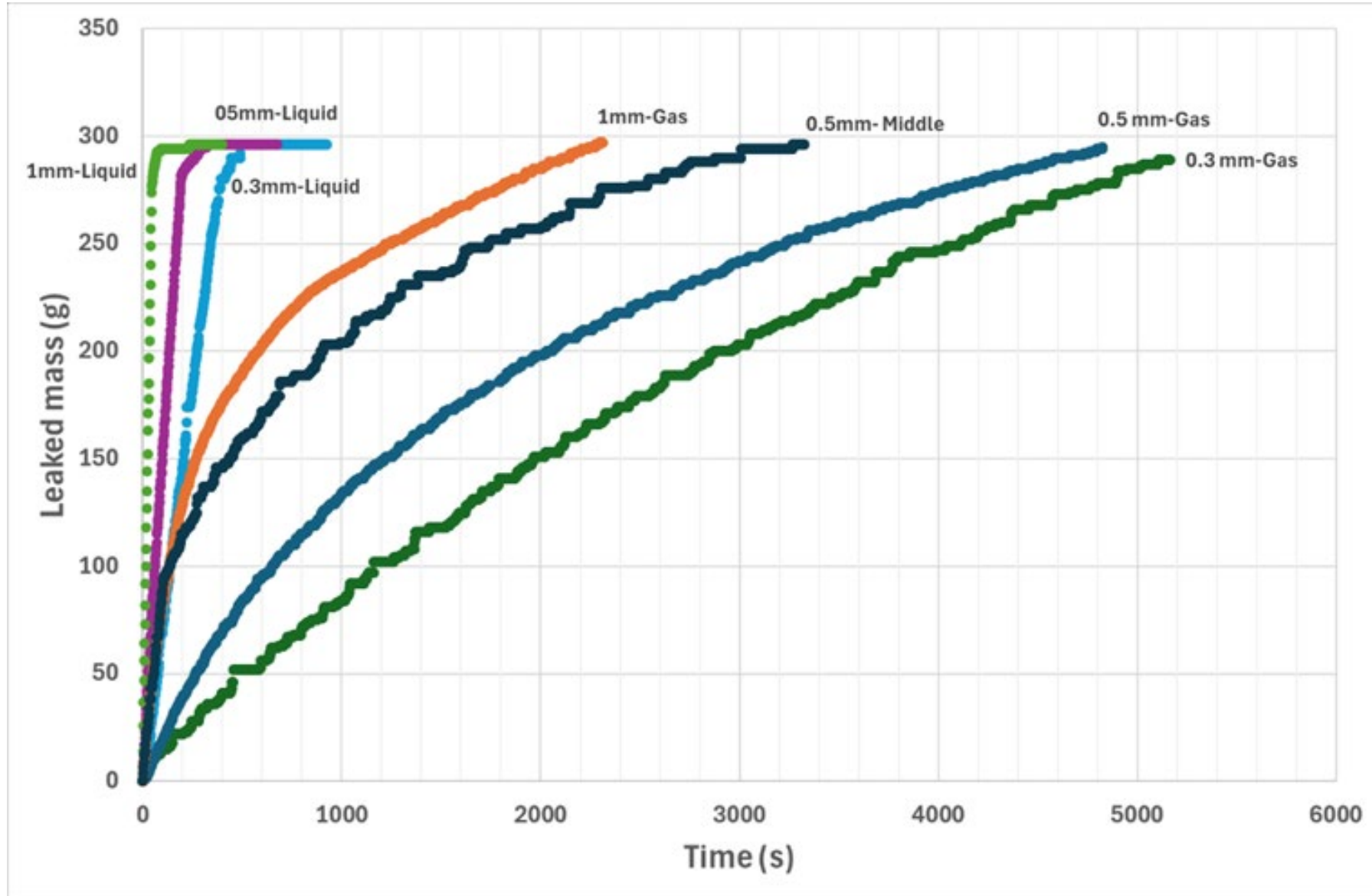
All cases approach ~1 bar as the system empties and equalizes with atmosphere.



Liquid leakage rate strongly depends on hole diameter.

Smaller holes sustain higher pressure for a longer time, while larger holes lead to rapid depressurization.

Cumulative Leaked Mass



Theoretical Leakage Rate

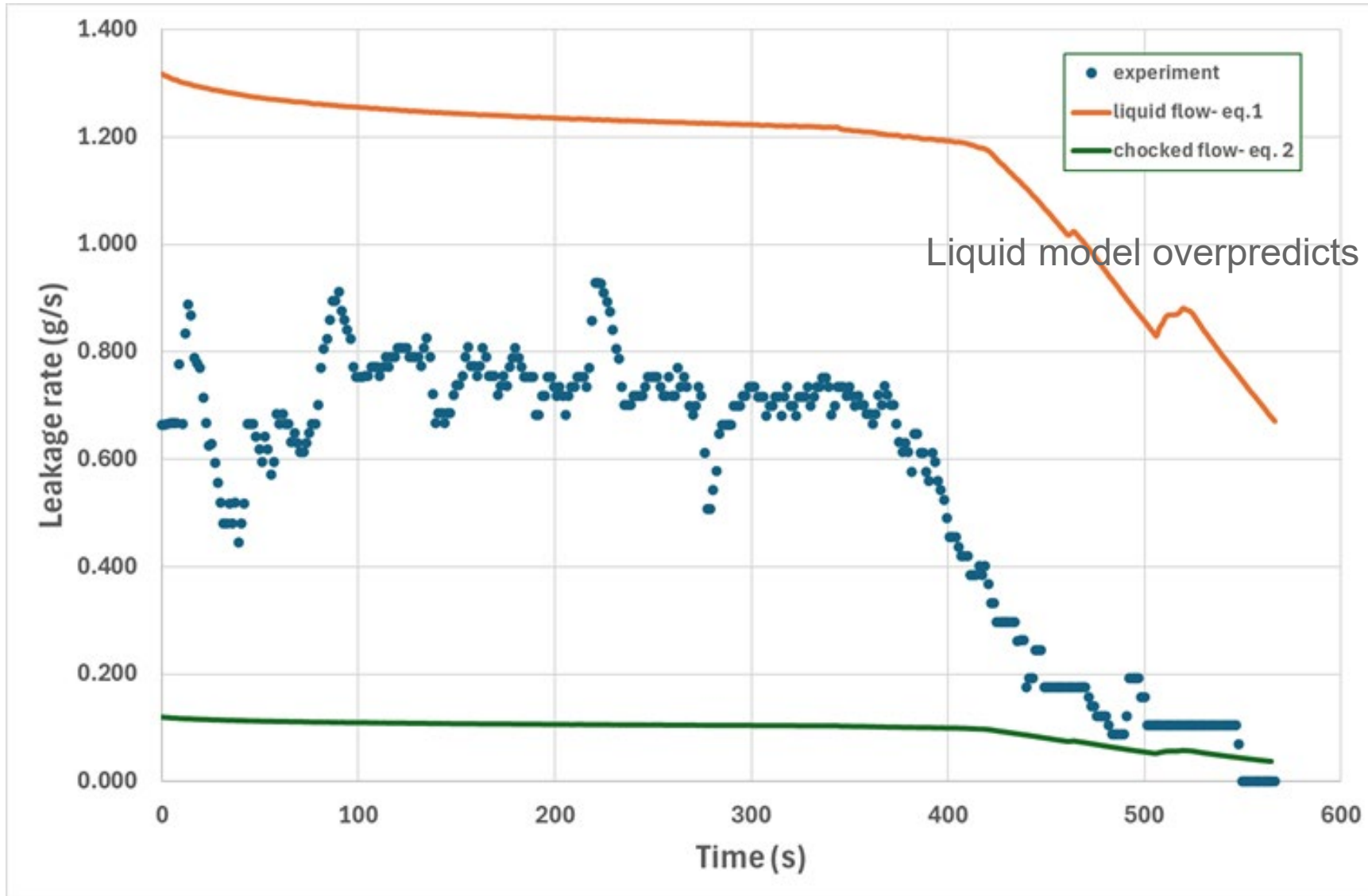
$$1) \quad \dot{m}_l = C_d A_0 \sqrt{2 \rho_\ell (p_0 - p_{atm})}$$

standard incompressible orifice equation

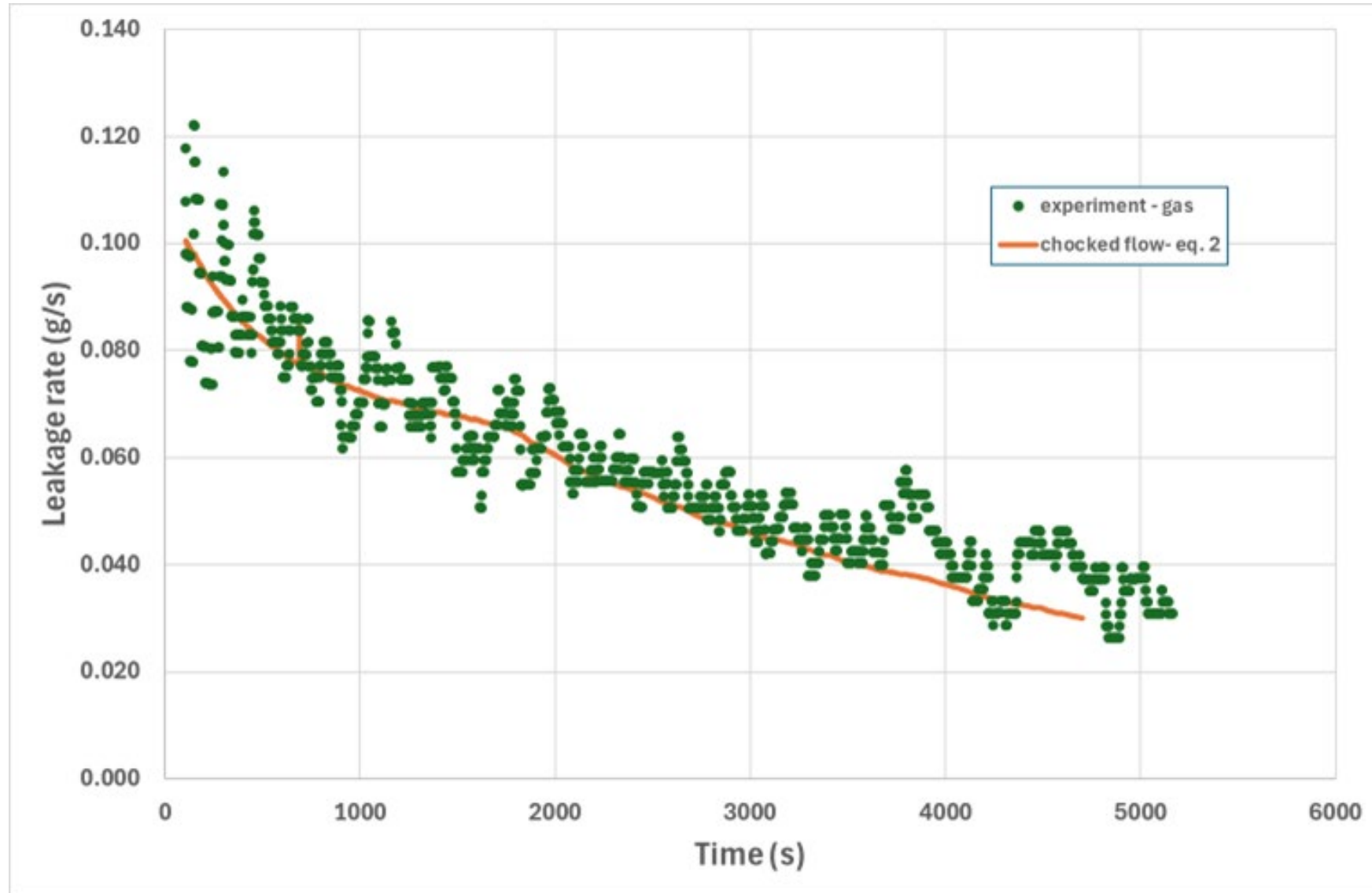
$$2) \quad \dot{m}_g = 0.06 C_d A_0 \sqrt{k \rho_0 (p_0 - p_{atm}) \left(\frac{2}{k+1} \right)^{\frac{k+1}{k-1}}}$$

standard choked-flow equation

Liquid-Phase Leakage Rate Comparison (0.3 mm)

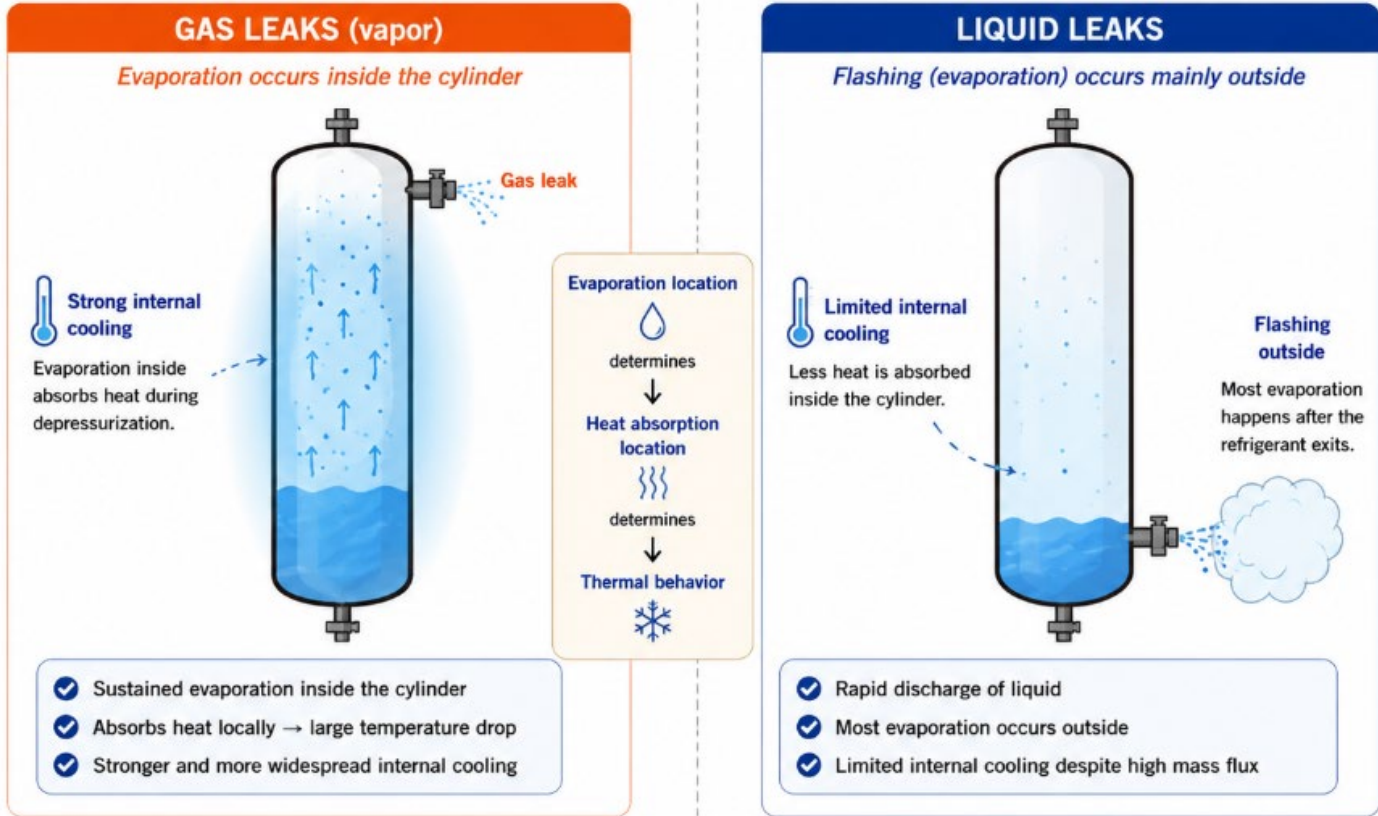


Gas-Phase Leakage Rate Comparison (0.3 mm)



Key Thermal Insight

Cooling behavior is governed by the location of evaporation



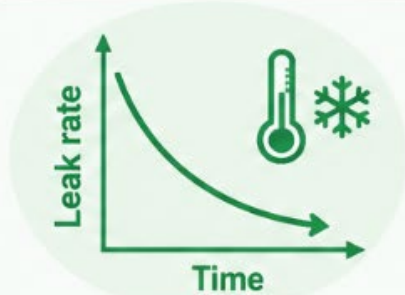
Gas leaks cause stronger internal cooling because evaporation occurs inside the cylinder during depressurization.
Liquid leaks discharge rapidly, but evaporation mainly occurs outside, resulting in limited internal cooling.

Conclusions



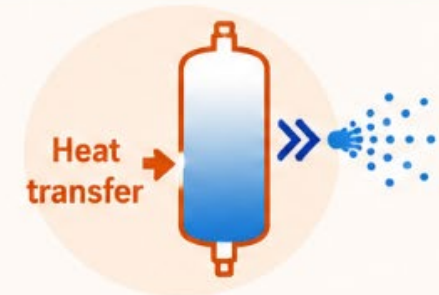
1. Liquid leaks much higher than gas

Liquid leaks produce mass release rates several orders of magnitude higher than gas leaks.



2. Leak rate decreases due to cooling and pressure decay

Evaporation-induced cooling lowers pressure and temperature, resulting in a continuous reduction of the leakage rate over time.



3. Leakage strongly coupled to heat transfer

Leakage behavior is governed by heat transfer and phase change processes, making thermal effects a key factor in release prediction.



Thank you...

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