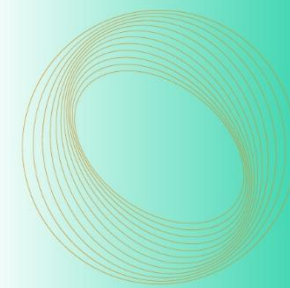




The Business Case Natural Refrigerants



BRUSSELS

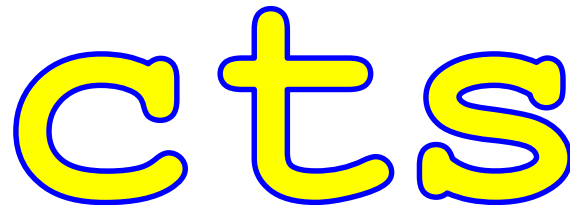
29 Sept. 2026

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Key Considerations to Maximize Performance in Natural Refrigerant Mobile Systems via Design and Experimental Evaluation

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CTS R&D History and Capabilities

- 20+ years of R&D often focused on natural refrigerants
- Capacity from 3 kW to **2.5 MW**
- **46 test chambers**; sizes up to L 20m x W 7m x H 6m
- Temperature control **-40°C to 70°C**; humidity control dry to 100%
- Highest measurement accuracy through unique approach using **3 independent energy balances**



Natural refrigerants R&D topics:

R744

- **ICE and EV heat pump and A/C systems**
- **High speed rail**
- Mobile container and shipboard refrigeration
- Mobile environmental conditioning systems
- Bottle cooler / Coke machines
- Residential water heater heat pumps and HVAC
- Commercial water heating and space conditioning
- Refrigerators
- Supermarket refrigeration
- Walk in coolers

10,000m² of specialized laboratory space

R290

- **EV HP and A/C systems dual secondary loop**
- Medical refrigeration
- Bottle cooler / Coke machines
- Residential HVAC
- Juice machines
- And the list goes on...



Key Areas of Focus for Natural Refrigerants Under Consideration for BEVs

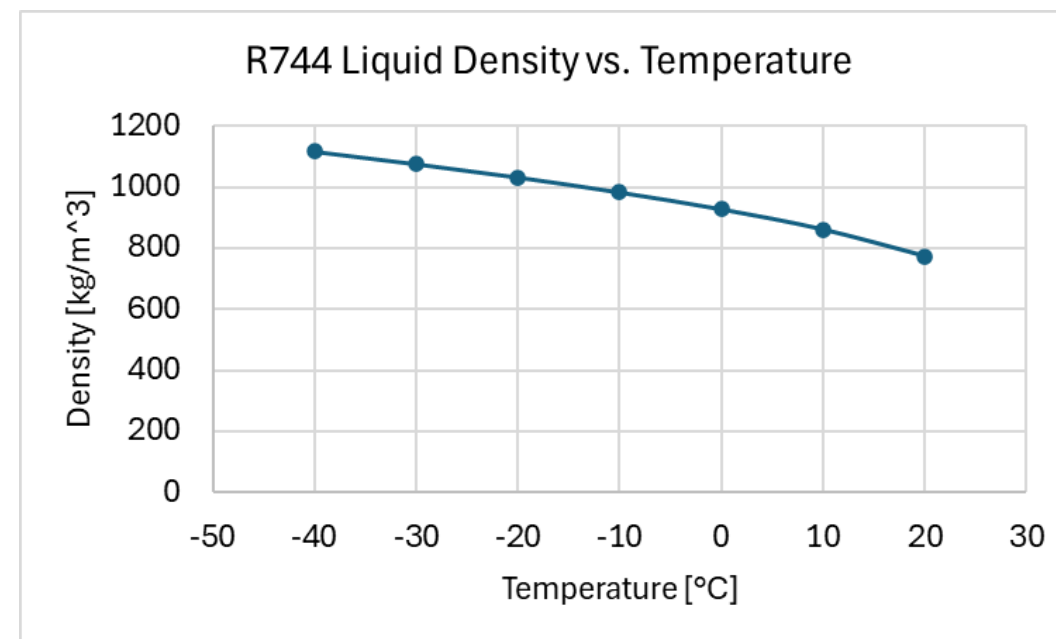
Refrigerant	Vapor Density at 0°C [kg/m³]	Liquid Density at 0°C [kg/m³]	Density Ratio [-]
R134a	14.4	1295	89.9
R1234yf	17.7	1177	66.5
R290	10.4	529	50.9
R744	97.7	927	9.5

R744

- Vapor density very high → Small compressor displacement
- Ratio of liquid to vapor density in accumulator is very low leading to additional **R&D needed for separation and accumulation**
- Liquid density is high at low refrigerant temperatures potentially leading to **oil return issues** in the accumulator at low temp heating conditions
- Transcritical operation adds need / opportunity for **high side pressure control** to maximize capacity and/or COP

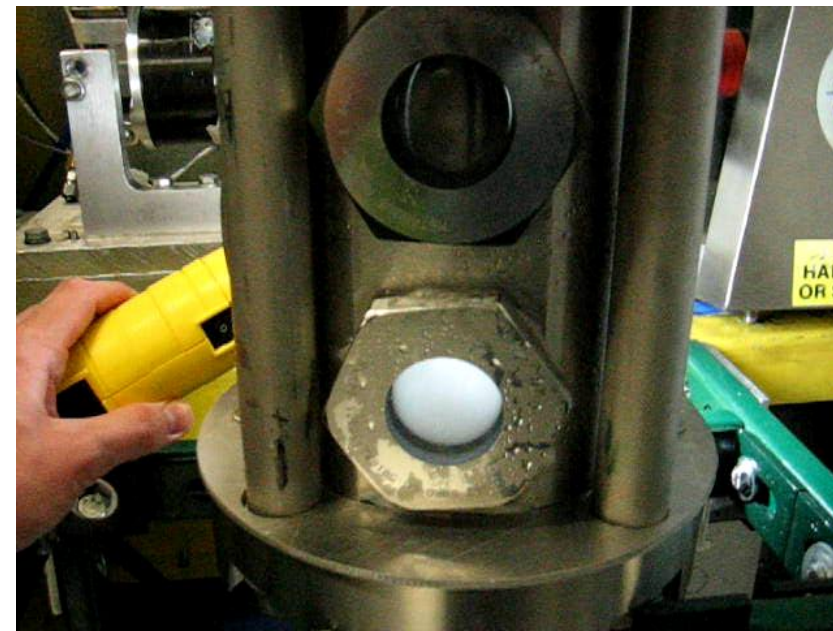
R290

- Vapor density very low → Large compressor displacement though Δh is high
- Flammability drives the need for **charge minimization**
- High solubility in oil will lead to high refrigerant charge in the case of large oil sumps
- **Distribution in secondary plate HXs** plays a large role in performance

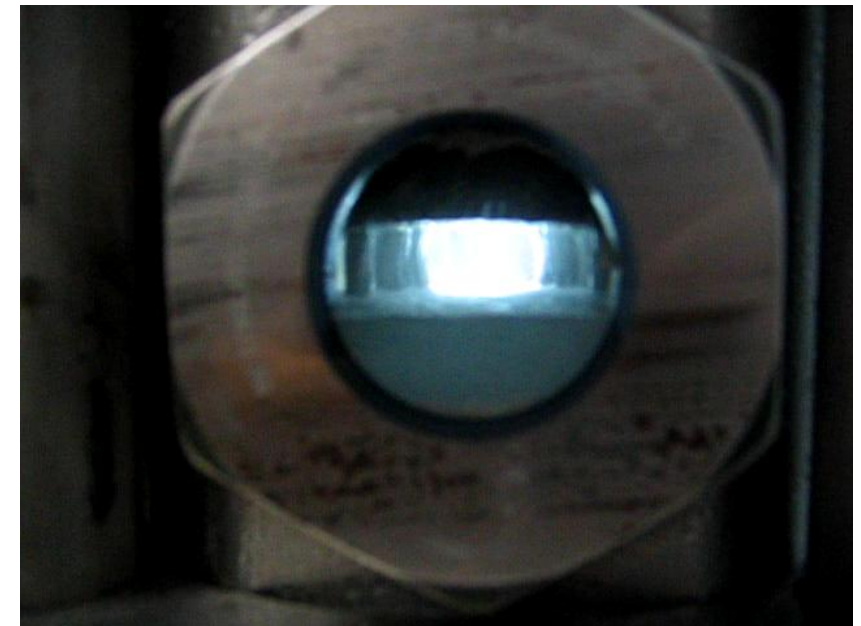
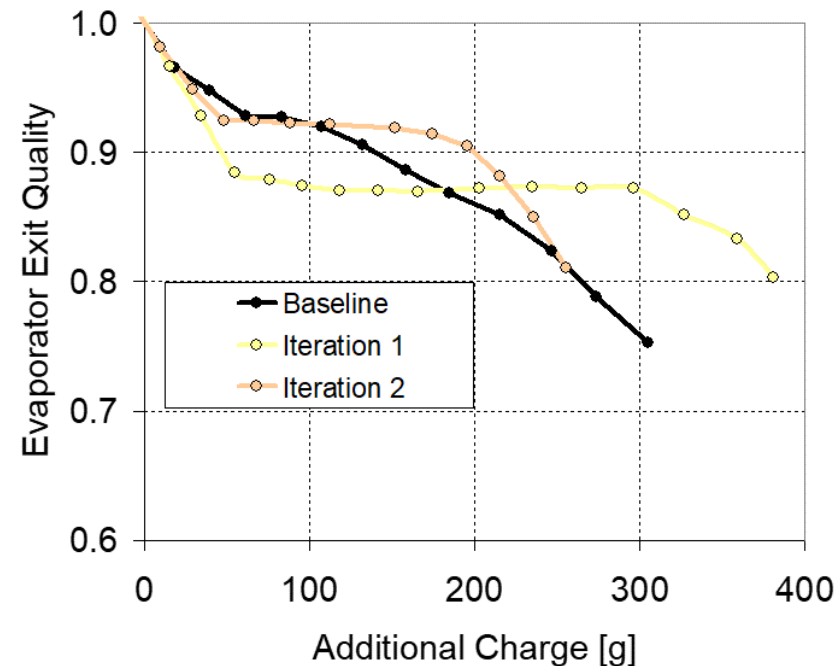
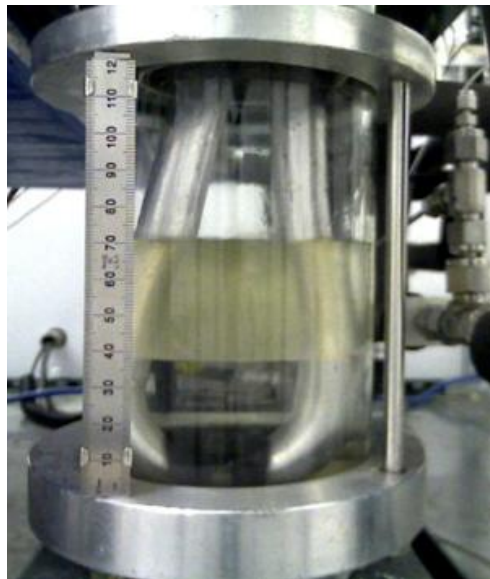


Accumulator Design Considerations and Visualization with R744

R744 presents additional challenges to achieve good separation and accumulation of liquid in accumulator such as very low liquid/vapor density ratio

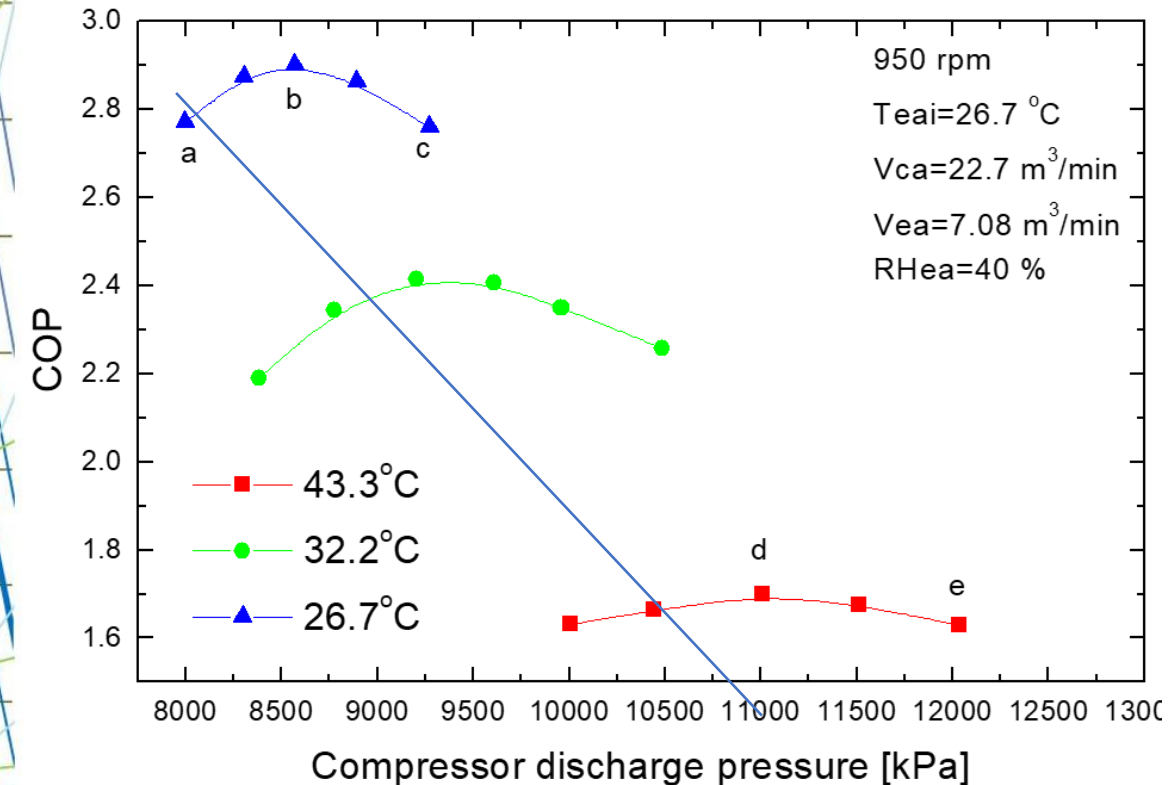
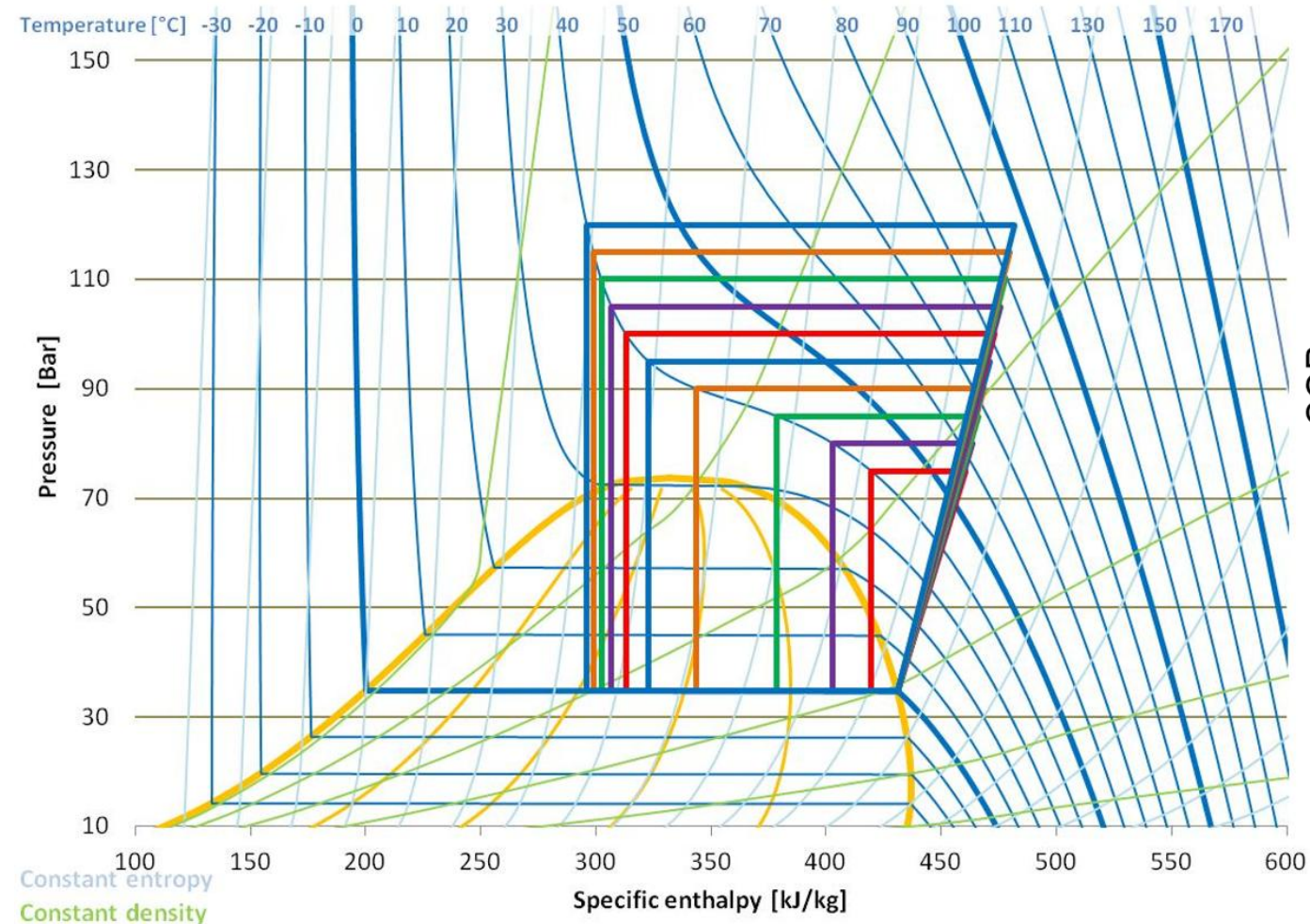


Baseline: high turbulence and poor separation



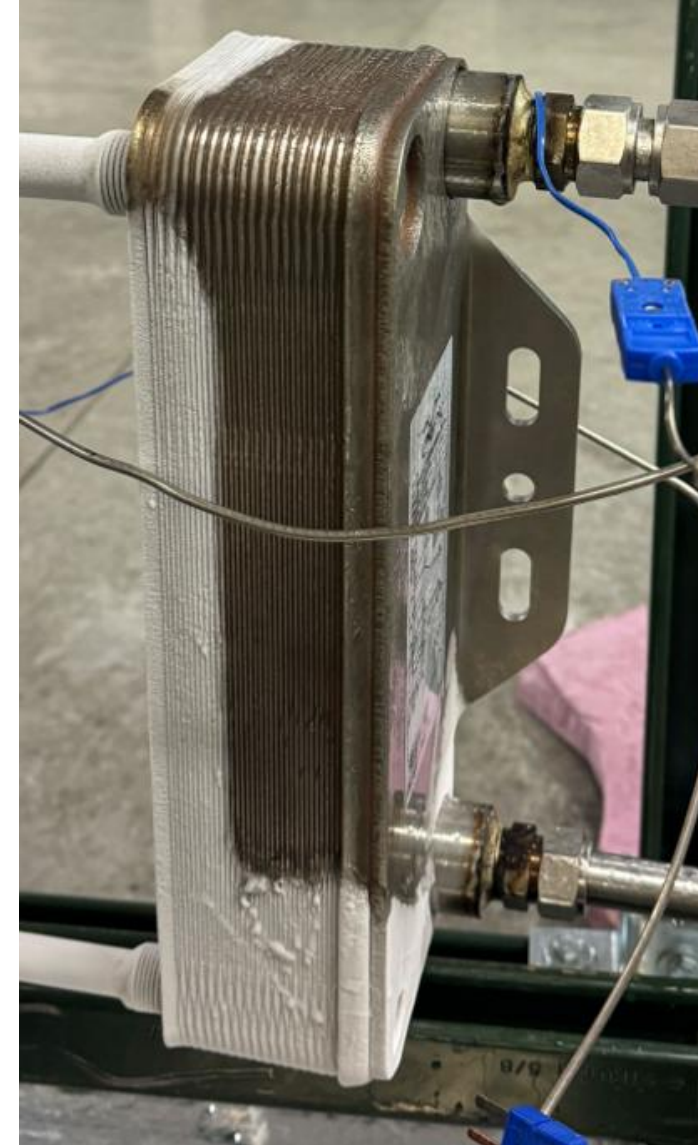
Iteration 2: improved design with good separation

High Side Pressure Optimization for R744 Systems

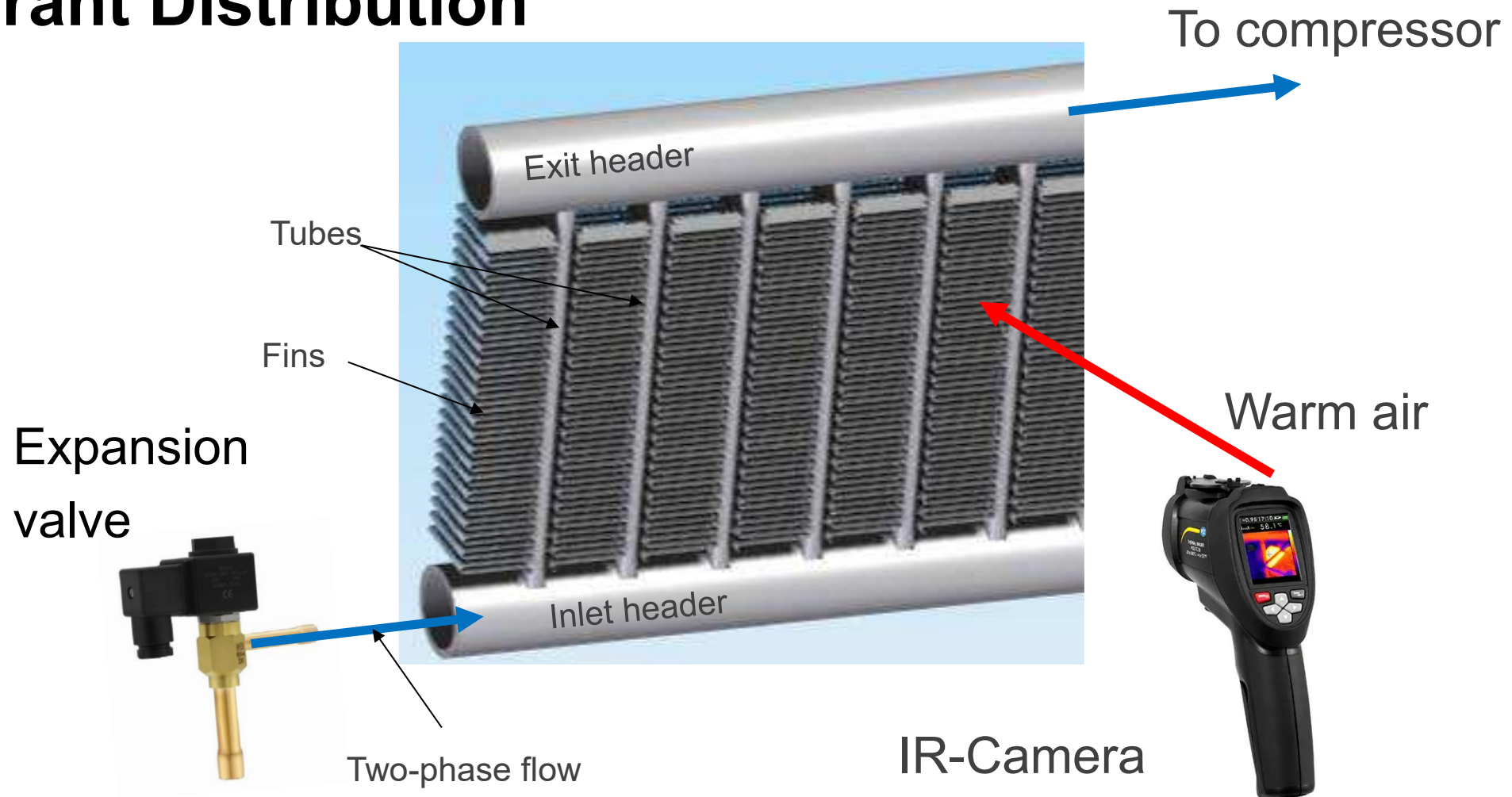


R290 Distribution Challenges in BPHXs

- Well-performing BPHXs designed for conventional refrigerants exhibit poor distribution with R290
- Very different refrigerant velocities and densities relative to conventional refrigerants cause maldistribution
- BPHX bypasses most liquid refrigerant through $\frac{1}{4}$ of the plates (indicated by frost pattern)
- Despite closing expansion device, no proper superheat control; capacity low due to underutilization of heat transfer area

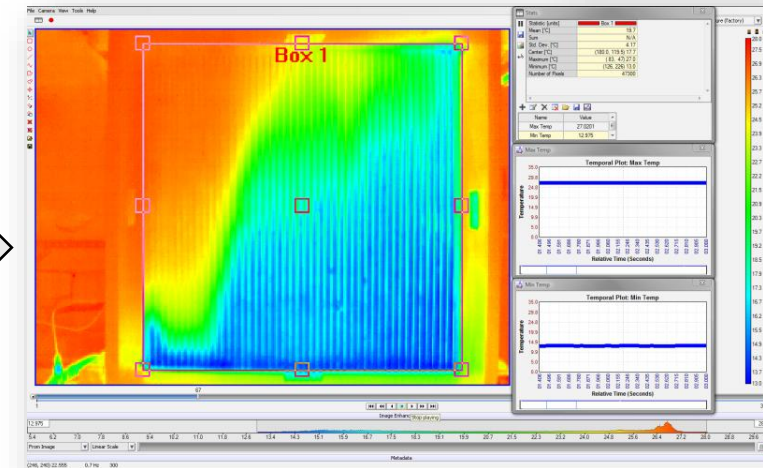
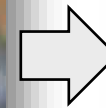
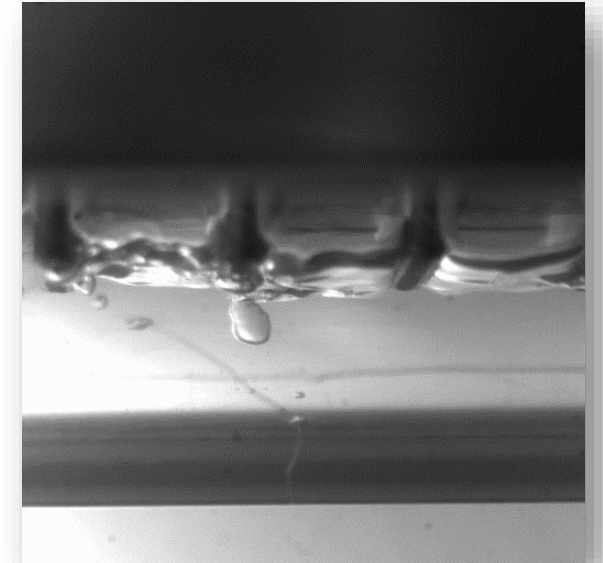


Setup to Explore Two-Phase Refrigerant Distribution



Header Distribution Visualization and Improvement in Evaporators

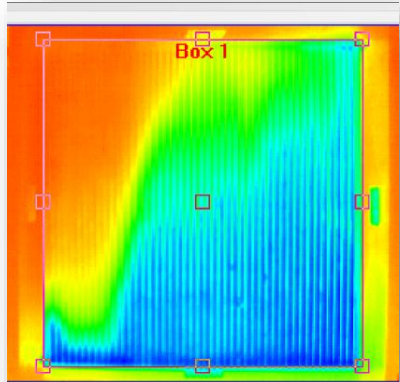
- ❑ Liquid inertia causes pooling to the far side of the heat exchanger and good liquid feeding (right side of HX)
- ❑ Vapor feeds initial tubes, is quickly superheated, and poorly utilizes HX area (left side of HX)
- ❑ Even in the case of pure liquid, reverse vapor flow impacts stability



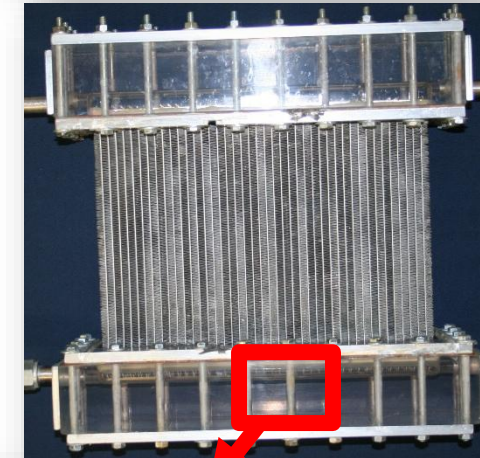
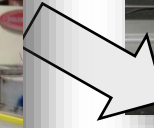
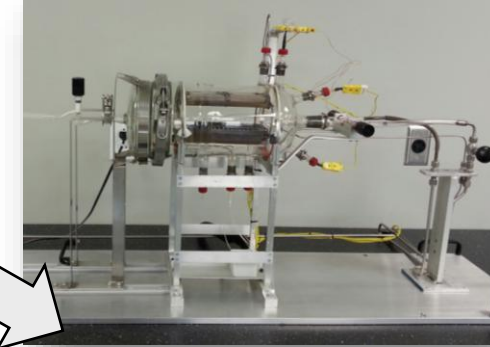
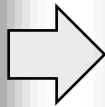
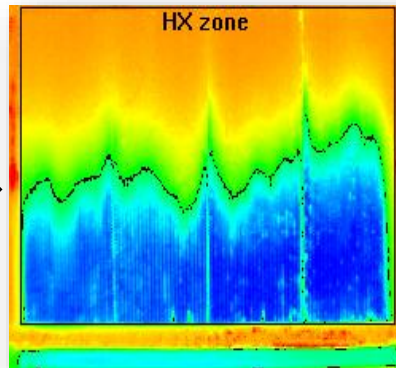
Prototype HX Fabrication and Visualization

Evaporator inlet header visualization for custom vehicle evaporator with distribution improvement mechanisms

Baseline



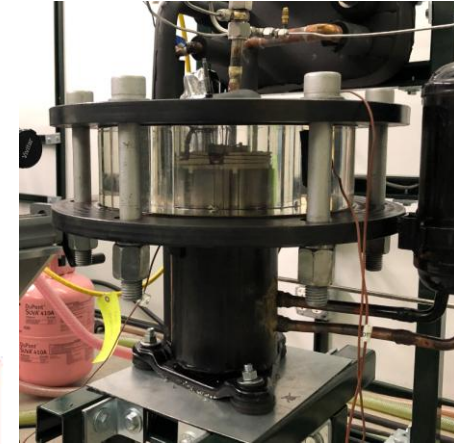
Improved HX



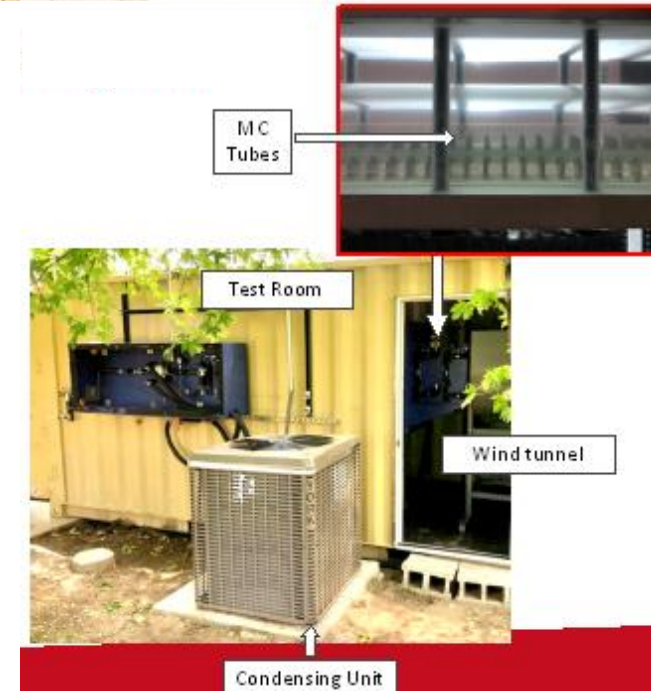
Custom Designed R290 Remote Flow Visualization Facility

Safety approaches for R290 visualization testing:

- Fully remote operation
- Class 1 Div 2 electrical equipment
- Deflagration panels
- Gas sensing
- Ventilation / emergency ventilation
- Elimination of electrical heating
- Charge minimization

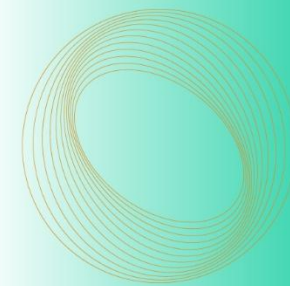


Safety Wiring and Flammable Gas Detection	Special Equipment	Ventilation





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Thank you
for listening
Any questions?



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