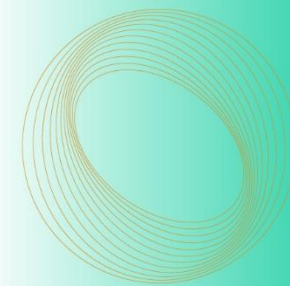




The Business Case Natural Refrigerants

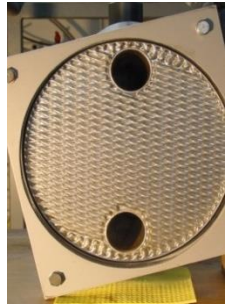


BRUSSELS

29 Sept. 2026



ATMO.org



NatRefs all the Way! Lessons Learned and How They Apply to Mobile AC / HP and Transport Refrigeration

Prof. Stefan Elbel

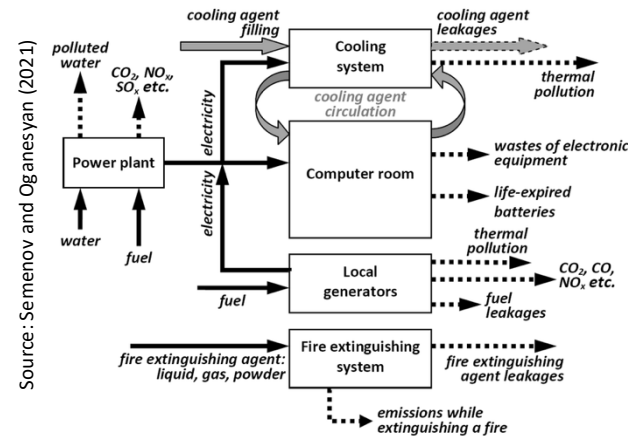
ATMOsphere MAC Summit x TU Berlin

September 29, 2026

Can we still Afford to Fight Global Warming?

Yes, we can. And we have to!

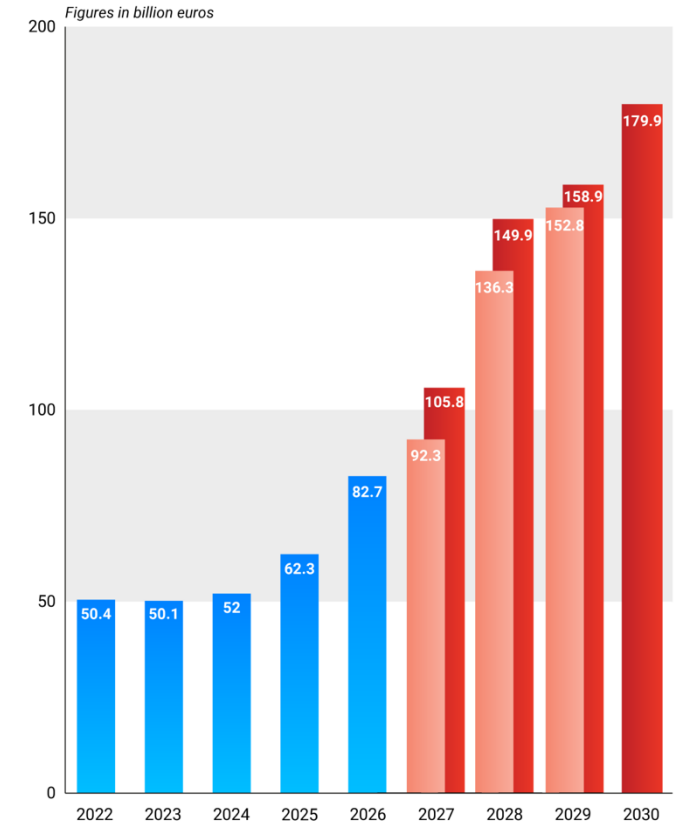
- Safety and (political) stability concerns are used to justify lower priorities for environmental problems
 - Payback for investing in low-GWP tech now will be past our lifetimes
- Data centers are taking away attention
 - IEA emissions estimate: 300 – 500 Mt CO₂/yr from data centers by 2035 (tied to electricity consumption)
 - Road Transport in 2024: 6000 Mt CO₂/yr (2/3 cars, 1/3 trucks)



Defense spending to rise even more sharply

German defense budget in the government's draft budget and financial plan for the federal budget

● Defense spending ● Previous financial planning ● New financial planning



www.Table.media

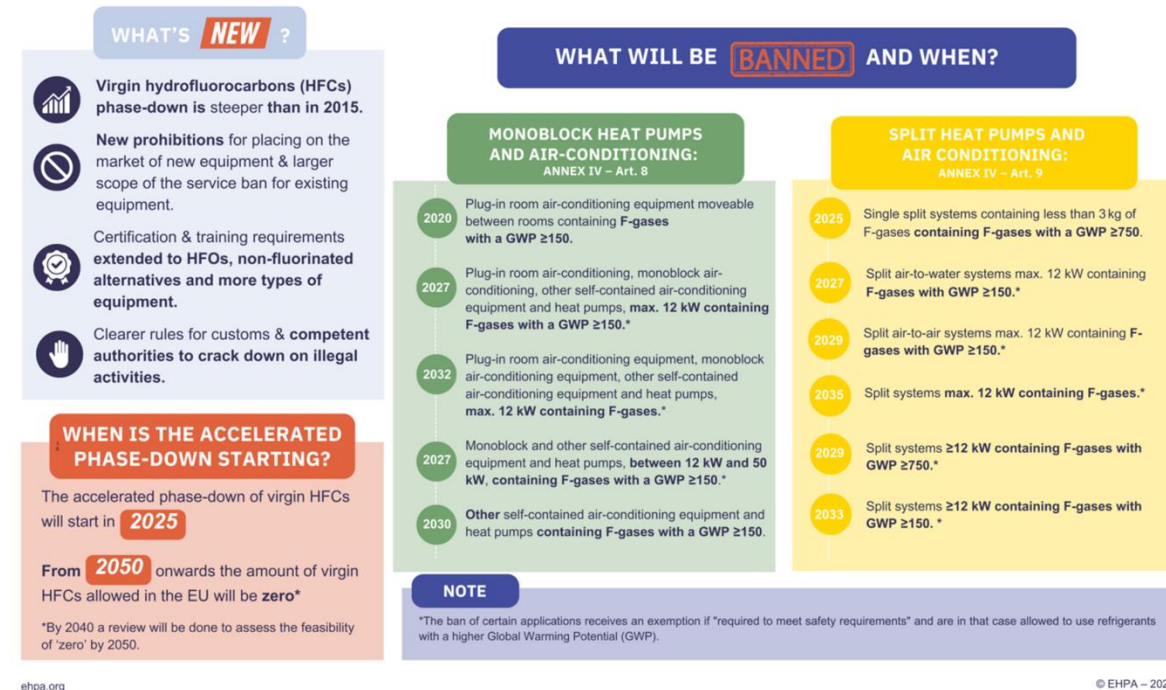
Source: BMF (Budgeted amounts for Section 14, excluding special funds)

The Good News:

Mobile AC / HP & Transport is on the Right Track



- Electric Vehicles have brought new attention to HVAC&R
- We have been developing 2 strong contenders for many years
 - Increasing number of sectors have “competition” between two great fluids R290 and R744
 - EV Thermal Management, Trains, Buses, Mobile (Commercial) Refrigeration, ...
- PFAS & F-Gas bans (or the fear of them coming) will do the rest



Properties of a Good Refrigerant

- Environmentally friendly (ODP, GWP, PFAS)
- Large phase change enthalpy (Δh_{fg}) and large volumetric capacity for small refrigerant flow rates and compressor sizes
- Manageable pressures, with low side pressure above atmospheric pressure (to avoid leak of air into system)
- Manageable flammability (low refrigerant charge system or non-flammable refrigerant)
- Non-corrosive, non-toxic
- Chemically stable
- Compatible with compressor oils

ASHRAE Standards 15 and 34 contain threshold values for toxicity levels and flame propagation velocities that define the different classes

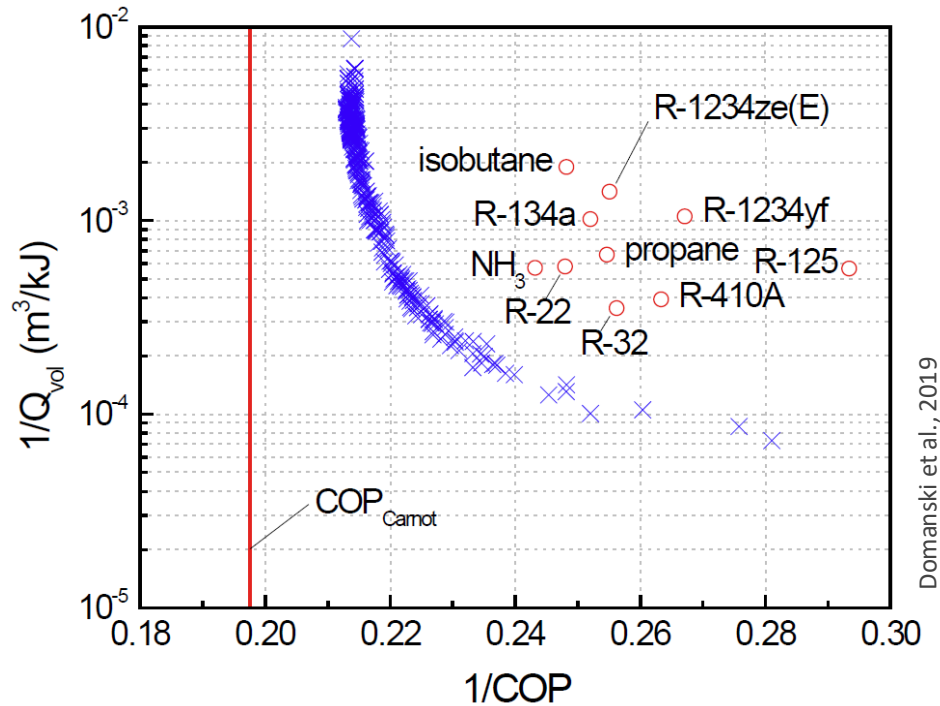


Increasing Number Increasing Flammability ↑	High Flammability	A3 (e.g. R290, R600a)	B3
	Low Flammability	A2 (e.g. R152a)	B2
		A2L (e.g. R1234yf)	B2L (e.g. R717)
	No Flame Propagation	A1 (e.g. R134a, R410A, R744)	B1
		Low Toxicity	High Toxicity

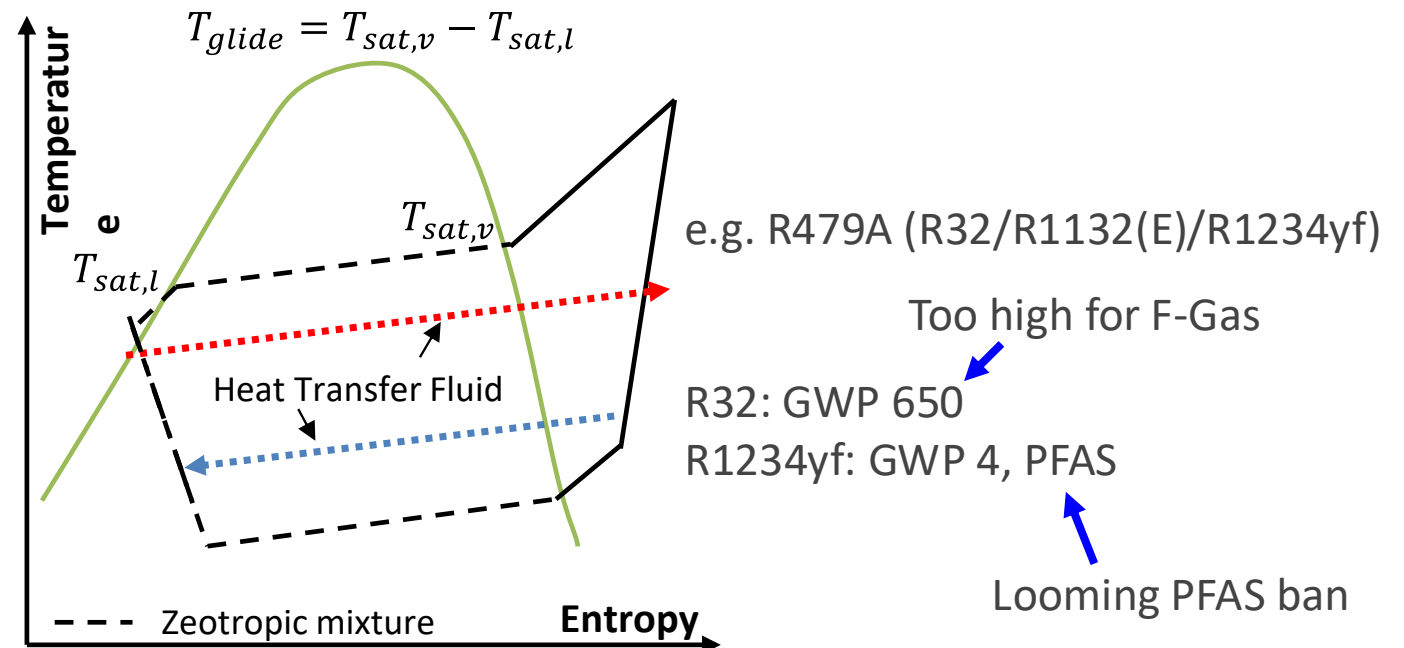
→
Increasing Letter
Increasing Toxicity

- Commercially available at reasonable cost (patents!)
- Suitable thermophysical properties
 - Thermodynamic properties: specific heat, density, vapor pressures, Δh_{fg} , etc.
 - Transport properties: viscosity, thermal conductivity, surface tension, etc.

Don't Wait for the Miracle Fluid... It Doesn't Exist



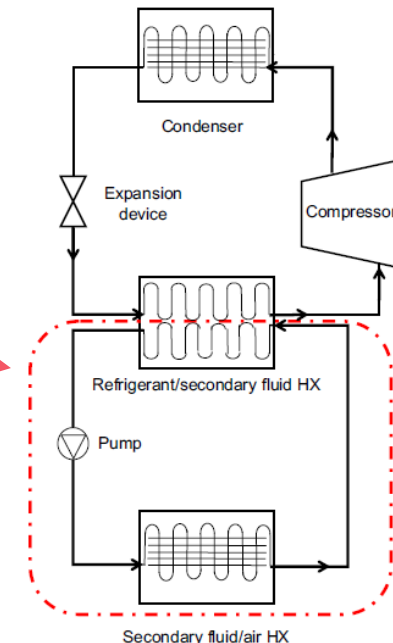
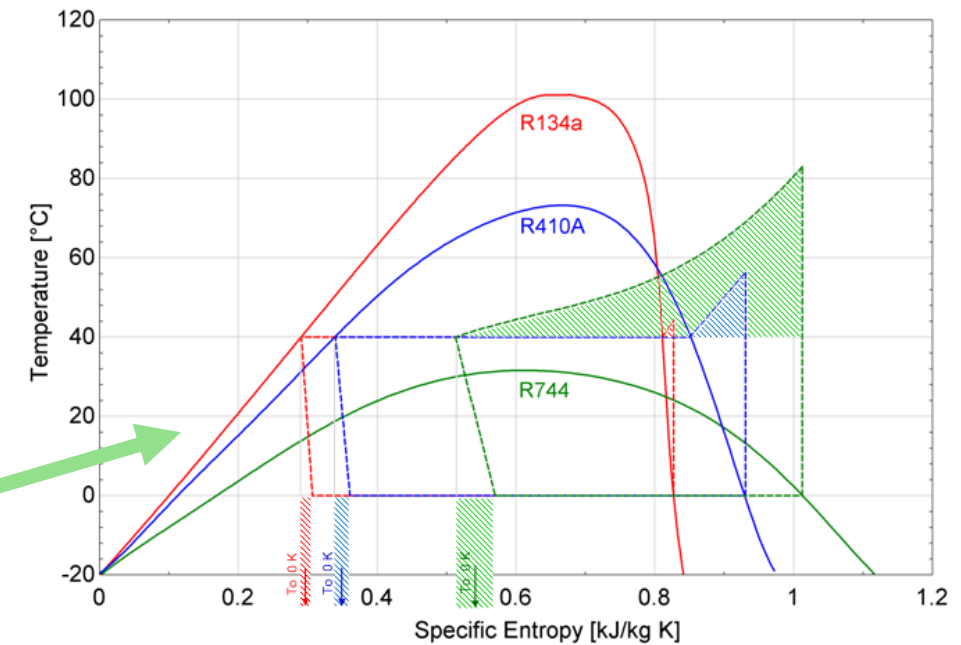
- Can blends save us?
 - Most synthetic low-GWP blends are zeotropic
 - Theoretically better HX performance (Lorenz cycle)
 - Leakage / maintenance issues



Let's work with what we have!

Let's Look at Stationary for a Moment

- NH_3 has always been around – but CO_2 is starting to replace it
 - Will remain in expert systems (industrial refrigeration)
- Water: niche applications, compressor and vacuum are difficult
 - Very attractive for high-temp heat pumps
- Air: low temperature blast freezers and aircraft air conditioning
- **CO_2** : non-toxic, non-flammable but lower COP
 - Safe but costlier system (transcritical cycle, IHX, ejector, ...)
 - **Good for large installations** where leaks are less of a problem
- **HC (R290, R600a, R1270, ...)**: great efficiency, but flammable
 - Conventional technology, but charge limits between 150g – 500g (indoor)
 - **Good for small, hermetic installations** (household refrigerator)
 - Secondary loop architecture (electric vehicles, monobloc heat pumps)
 - How much flammability risk can we tolerate?



How small is “small” and how large is “large”?

Long Path to Successful Implementation of CO₂ Air Conditioning in Cars



R744 lab. prototype system (left) and BMW 520 CFC-12 system (right)

1989: First CO₂ systems at University labs



...the greenhouse gas effect of the car AC system can be cut by a third when applying carbon dioxide as a refrigerant

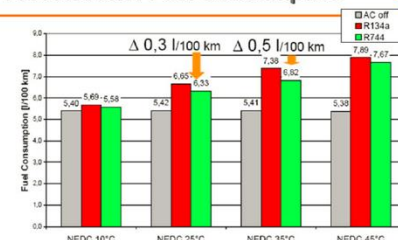
1998: OEMs start equipping cars with CO₂ AC for wind tunnel and field testing

2008: Financial Crisis, OEMs quickly convert to R1234yf

2006: Numerous Asian and European OEMs and suppliers work on 2nd generation CO₂ with much improved performance

Fuel consumption of a Toyota Yaris (MY 2006) with different mobile AC systems when driving a NEDC at various ambient temperatures

Test Results: Fuel Consumption

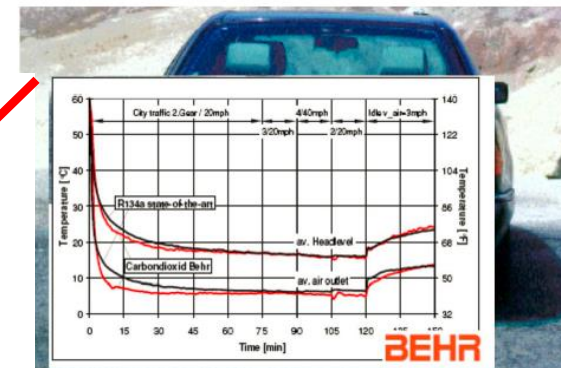


- ⇒ Significant, absolute fuel reduction of 0,3 and 0,5 l/100 km at ambient temperature of 25°C and 35°C for R744
- ⇒ Add on fuel reduction of 25 % at 25°C and 35°C of R744 in comparison to R134a



- Engine 3 cylinders, 1,0 l, 51 kW
- Test vehicle with 15.000 km
- TXV system
- Compressor with external control valve (90 cc)

VDA Alternate Refrigerant Winter Meeting 2007, Saalfelden, Austria.



BEHR- Prototype Vehicle with CO₂ – Cycle, Death Valley 1998

Long Path to Successful Implementation of CO₂ Air Conditioning in Cars



CO₂ car operated by German UBA between 2009 and 2017, accumulates more than 165,000 km



Source: www.uba.de

2009: CO₂ vehicles for long term fleet tests under real conditions



2017: First mass produced car with CO₂ AC systems after some flammability issues with R1234yf



2019: all internal combustion engine cars in EU, USA, Japan back to R1234yf



2020: Electric Vehicle changes everything; R1234yf is not good for low temp heat pump



VW CO₂ Heat Pump



Source: www.volkswagen.de

1.5M vehicles on the road!

2024 - ...: CO₂ and propane seem to be preferred options for EVs going forward

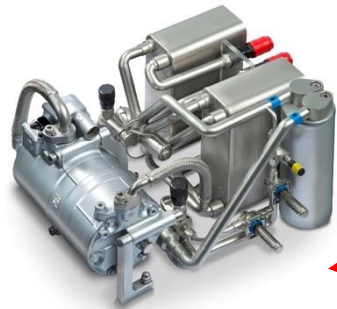
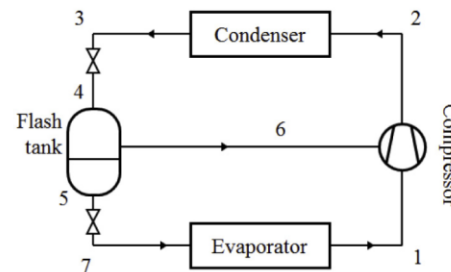
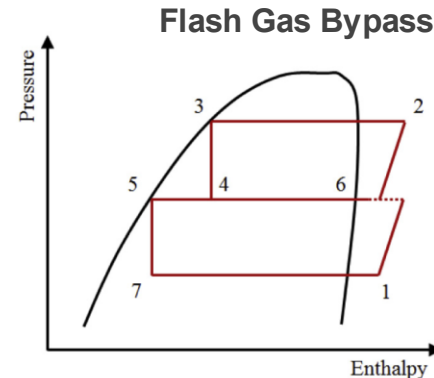
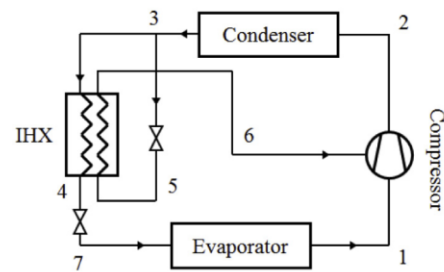
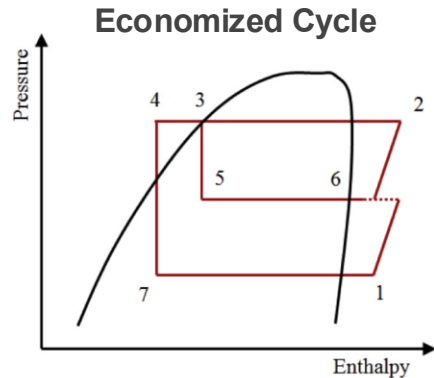


Image: Rheinmetall



Performance Improvements

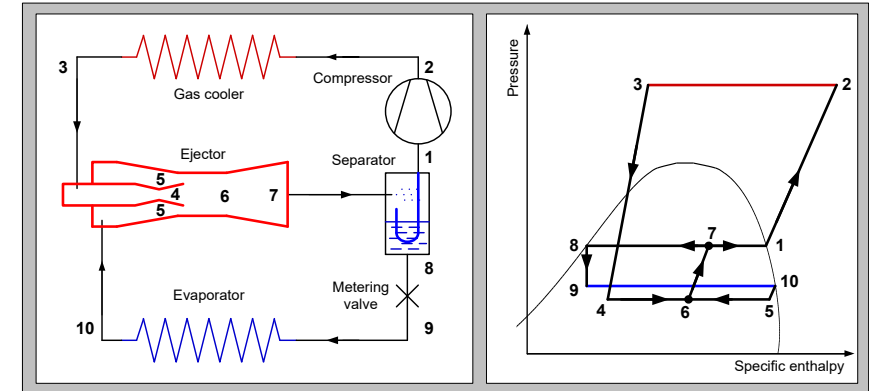


Kim et al., 2017

- Vapor injection is good for HP (discharge temperature)
- Also helps with COP at elevated ambient temperatures
- Liquid injection: not for COP improvement

Ejector cycle COP improvements

- 15 - 30 % with CO₂
- 10 - 15 % with R290, R32, etc.
- ~ 5 % with R1234yf, R600a



Improvement mechanisms of ejector cycle:

- Reduced compressor work (ejector provides pressure lift)
- Higher compressor efficiency (lower pressure ratio) and discharge temperature
- Improved evaporator distribution

Foliaco and Gullo Discover Vehicles (2026) 2:10
https://doi.org/10.1007/s44465-026-00014-3

Discover Vehicles

REVIEW **Open Access**

Advances and challenges of R744 based thermal management systems in electric vehicles

Blanca Foliaco^{1*} and Paride Gullo¹



Managing R290 Safety

- Interesting approaches
 - Adsorb R290 leak
 - Reduce chance of reaching LFL by smart use of ventilation fans (indoor and outdoor)

Sorption-based Safety for R290 Concept

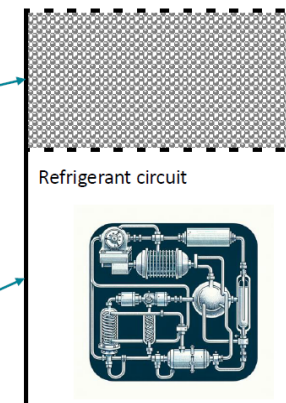
Fraunhofer ISE & Vaillant

6 years joint R&D

Activated Carbon Filter adsorbs R290 in case of leakage



© Carbotech



Tight (enough) housing all R290 components inside

First implementation in 2025 Ground-source heat pump



© Vaillant GmbH

Garage Concentration Testing

Three refrigerant charge amounts

600g, 300g, and 150 g

Three refrigerant leakage scenarios

Fast – severed line – discharge ~ 20 seconds

Medium – large crack leak (e.g. vibration) Discharge times of 1000-2700 seconds

Slow – corrosion leak - Discharge times of 7,000-25,000 seconds

Four garage air exchange rates

Garage door sealed – no intentional air flow

Low – 0.75 Air changes per day

Medium – 5 Air changes per day

Fast – 15 Air changes per day

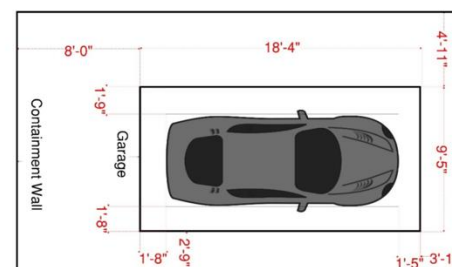
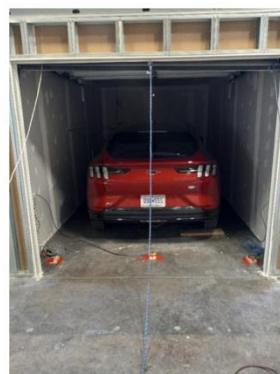
OHX Fan Operation

Not operating – louvers closed

Operation for discharge time plus 1 hour

• Louvers open

• Louvers closed



Number of Sensors:

- RH1-PH5 - Tripoint Sensors
- ST-514 - Flame Heat Sensors
- F15-F28 - Sensation Sensors



8

©Fraunhofer ISE public

Risk Assessment

Consensus among some OEs is starting to be established

Some OEs feel the increased hazard level is manageable and within normal vehicle operation,

Other OEs are continuing to look at other solutions

Garage Concentration Testing is a risk that needs mitigation

Collision scenarios generate clouds above LFL – is an expected result

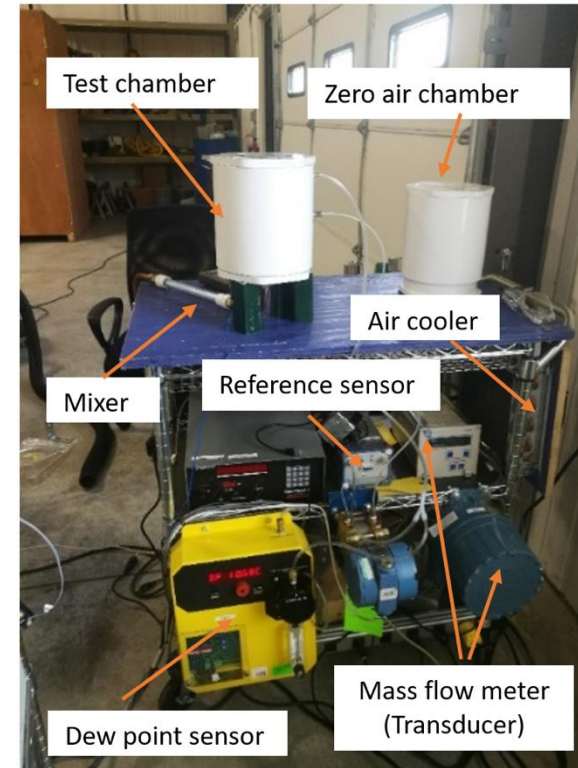
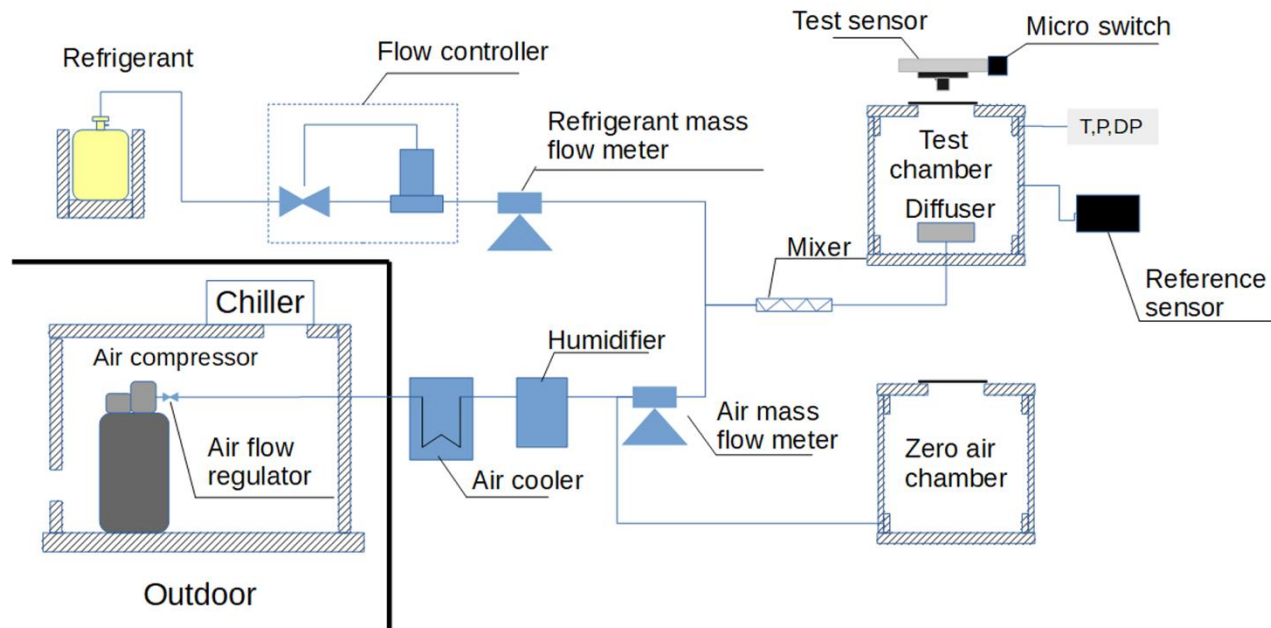
Characterization of Refrigerant Leak Detectors



AHRI #9014 investigated different sensor types:

- Micro Machined Membrane (MMM)
- Non-Dispersive Infra-Red (NDIR)
- Thermal Conductivity (TC)
- Metal Oxide Semiconductor (MOS)
- Speed of Sound (SS)

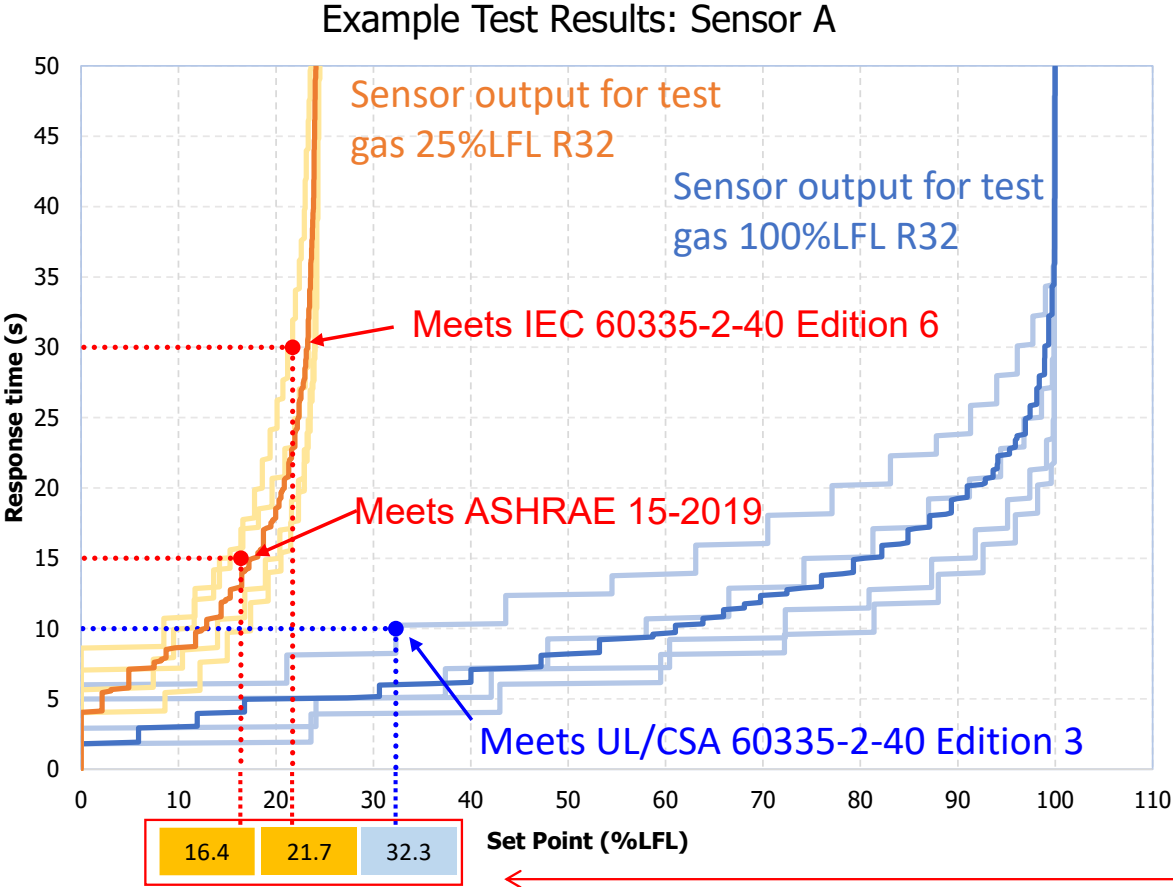
- A “push-through” method has been selected to assess sensor step-change response times
- A test facility has been designed and built



- The main features of this test facility are:

- The test gas concentration can be accurately controlled
- The concentration can be monitored by two independent measurement methods
- Produces nearly ideal step-change, i.e. no error caused by gas diffusion, mixing and transport as with some other methods

Different Standards have Different Requirements

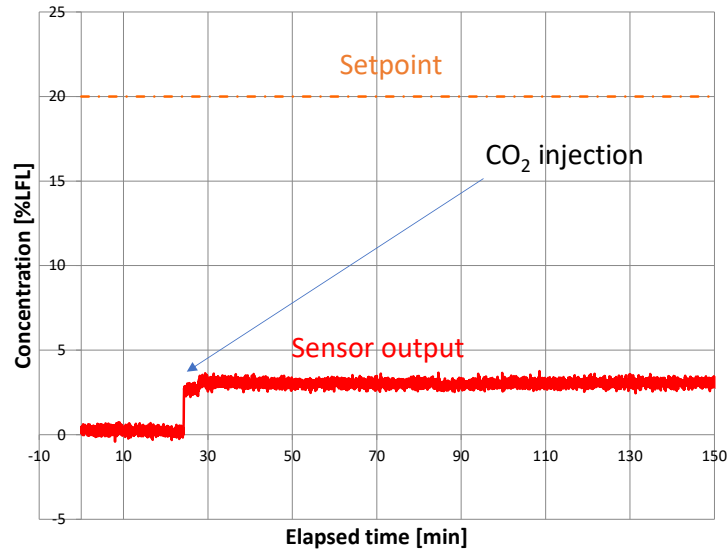


Standard	Test gas concentration	Response time requirement	Maximum allowable setpoint (%LFL)
ASHRAE 15-2019	≤25%LFL	≤15s	16.4
IEC 60335-2-40 ED6	≤25%LFL	≤30s	21.7
UL/CSA 60335-2-40 ED3	≤100%LFL	≤10s	32.3

Proper selection of appropriate sensor setpoint becomes non-trivial



Model Dynamic Behavior



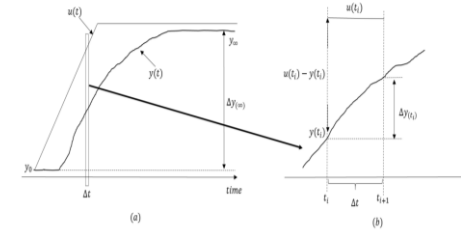
- Time delay θ and the time constant τ can be obtained from the step-change test
- By knowing the actual gas concentration profile, equations (2) and (3) can predict the actual sensor response curve for realistic time-varying concentration profiles

Determined by step-change test

	Sensor		Time delay θ	Time constant τ
A	Micro Machined Membrane	Sample 1	4.4	4.7
		Sample 2	6.3	6.6
		Average	5.4	5.6
B	NDIR	Sample 1	1.4	18.1
		Sample 2	2.4	18.3
		Average	1.9	18.2
C	Thermal Conductivity	Sample 1	0.0	0.1
		Sample 2	0.0	0.1
		Average	0.0	0.1
D	NDIR	Sample 1	0.2	17.2
		Sample 2	0.0	10.2
		Average	0.1	13.7



Dynamic response model

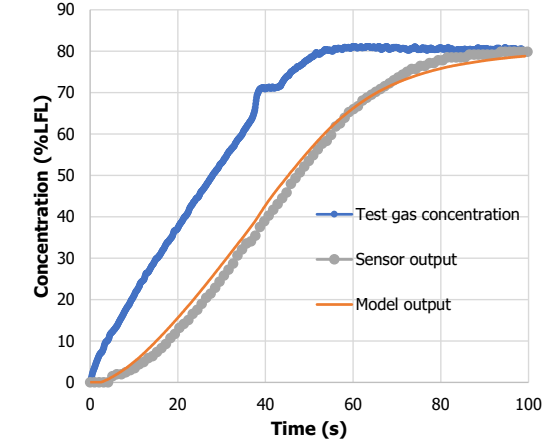


$$\Delta y(t_i) = [u(t_i) - y(t_i)](1 - e^{-\frac{\Delta t}{\tau}}) \quad (2)$$

$$y(t_i) = \begin{cases} y_0, & t_i \leq \theta \\ y_0 + \sum_{t=\theta}^{t_i} \Delta y(t), & t_i > \theta \end{cases} \quad (3)$$



Predicted result for actual response



A. Fluid resistance and poisoning test

JRA 4068T-2016	10.3 Miscellaneous gas resistance test
	10.8 Durability test (gas resistance test and sensor durability test)
UL 60335-2-40 ED3	LL.5DV Selectivity test and poisoning test
IEC 60079-29-1	5.4.4.5 Long-term stability *UL 60335-2-40 LL.4DV requires 100% refrigerant as the test gas for long-term test
	5.4.16 High gas concentration operation above the measuring range

B. Extreme storage condition test

JRA 4068T-2016	None
UL 60335-2-40 ED3	LL.1DV General (refer to IEC60079-29-1)
IEC 60079-29-1	5.4.2 Unpowered storage (-25±3°C and 60±2°C for 24hours)

C. Operation condition test

JRA 4068T-2016	10.4 Temperature test
	10.9 Condensation resistance test
	10.6 Power source voltage fluctuation test
UL 60335-2-40 ED3	LL.1DV General (refer to IEC60079-29-1)

Accurate calculation of sensor response for time-varying concentrations

IEC 60079-29-1	5.4.6 Temperature	5.4.9 Air velocity
	5.4.7 Pressure (±0.5kPa)	5.4.10 Orientation
	5.4.8 Humidity of test	5.4.18 Power supply variations

D. Vibration and impact

JRA 4068T-2016	None
UL 60335-2-40 ED3	LL.1DV General (refer to IEC60079-29-1)
IEC 60079-29-1	5.4.12 Vibration
	5.4.13 Drop test for portable and transportable equipment

E. Repeatability test

JRA 4068T-2016	10.7 Stability test
UL 60335-2-40 ED3	LL.1DV General (refer to IEC60079-29-1)
IEC 60079-29-1	5.4.4.2 Short-term stability

Sensor Harshness Tests

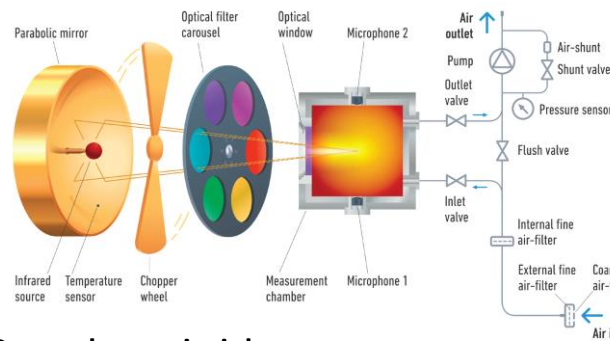
cts
Creative Thermal Solutions, Inc.

Flammable Refrigerants Require Accurate Leak Rate Measurements



- Refrigerant emissions from entire systems or single components
- Resolution of 0.5 g/year
- Single component refrigerants and blends
- Using very accurate IR-photo-acoustic measurement principle

PHOTOACOUSTIC SPECTROSCOPY (PAS)



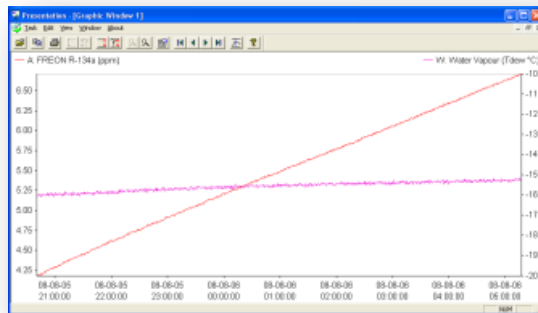
Gas analyzer principle

Component leak facility



System leak facility

Emissions testing according to SAE J2763 and EC 706



Exciting New Systems and Components



Source: Spheros

R290 Bus AC & HP



Source: Transcold

R744 Reefer



R290 Reefer Proof-of-Concept

Source: GMCC



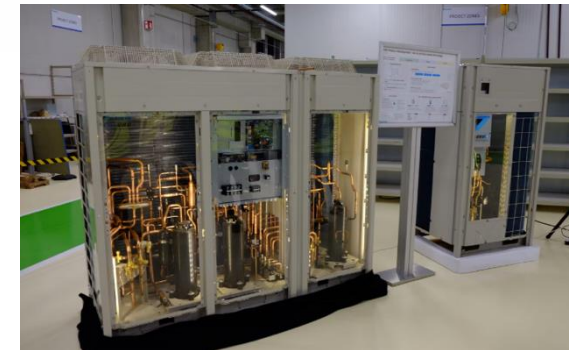
R290 Horizontal-mount Compressor



Source: Daikin



R744 VRF (large DX)



More Exciting New Systems and Components



SCHAEFFLER



Integrated R290 Cooling System



MAHLE

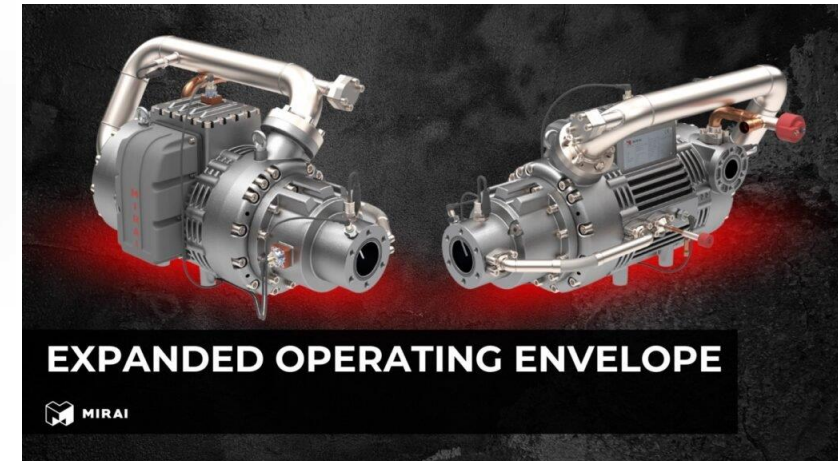


Energy Recovery Module HeatX Range+

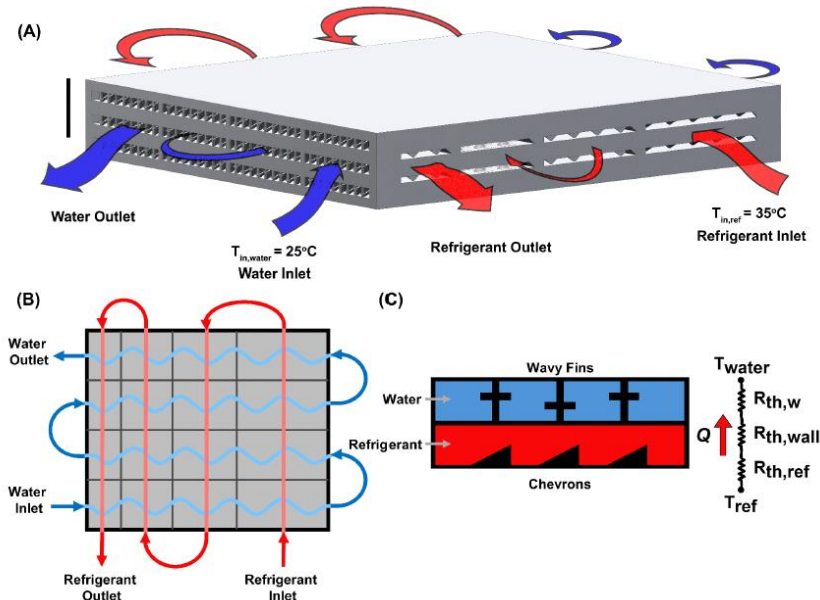
ebm papst



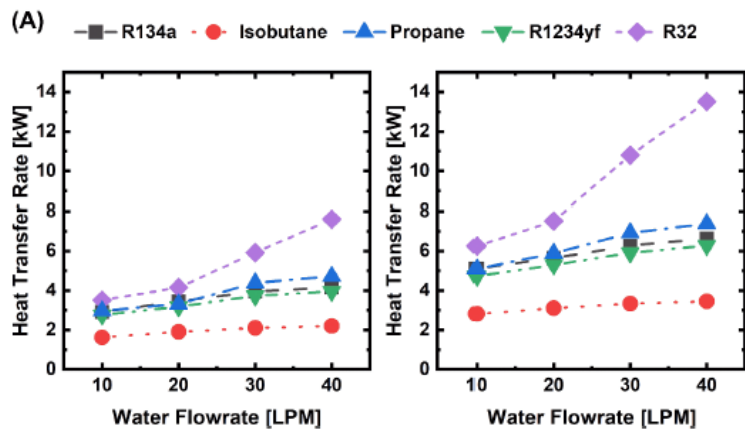
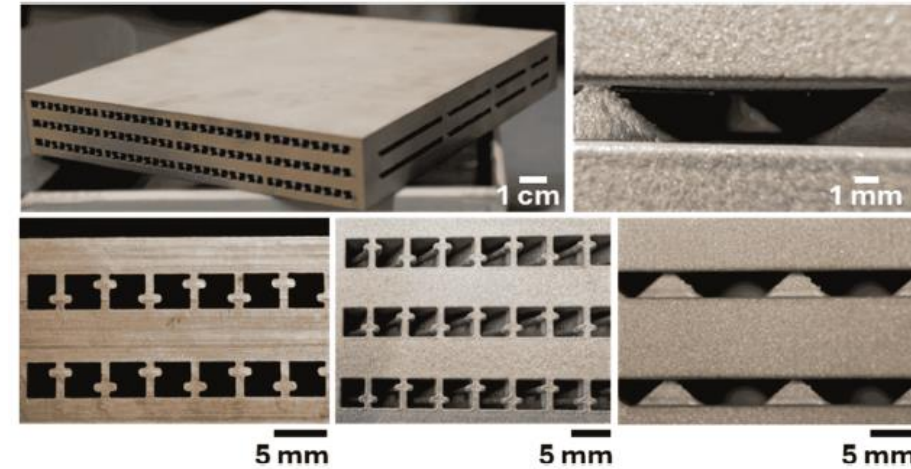
Oil-free R290 Turbo Compressor



Compact 3D-Printed Water Cooled Condenser

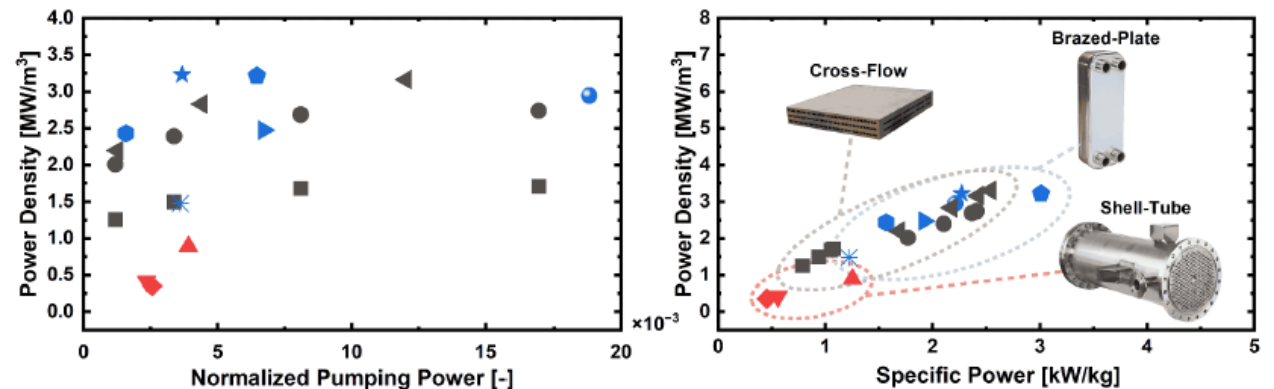


Zaki et al., 2025

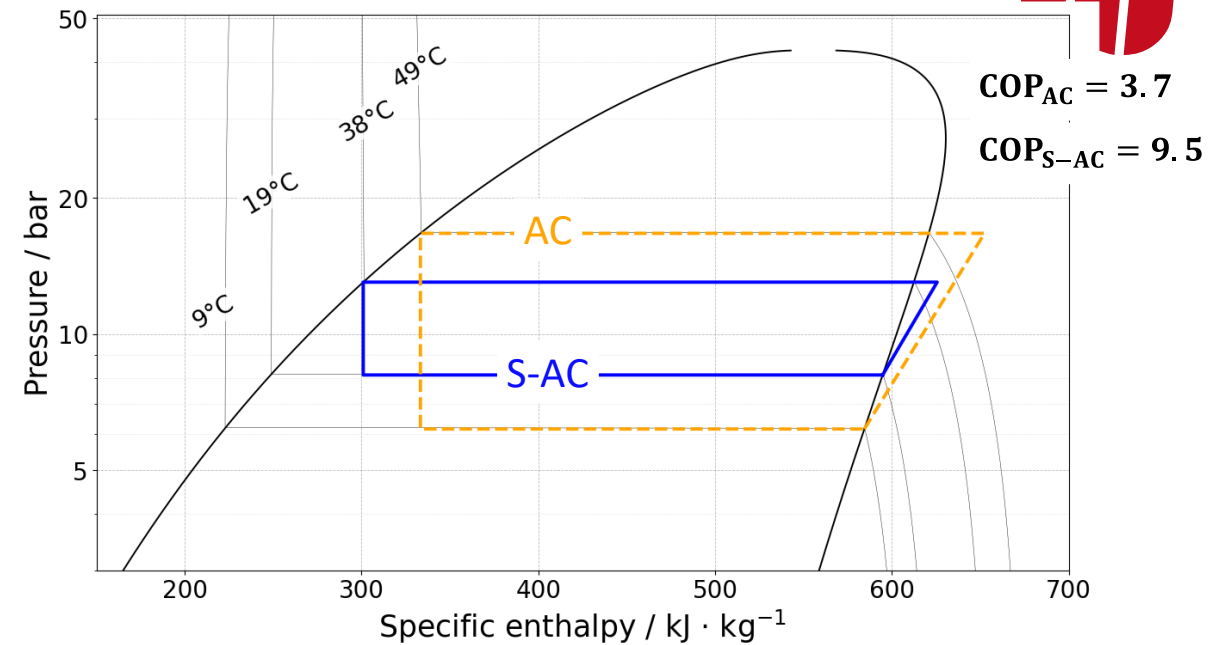
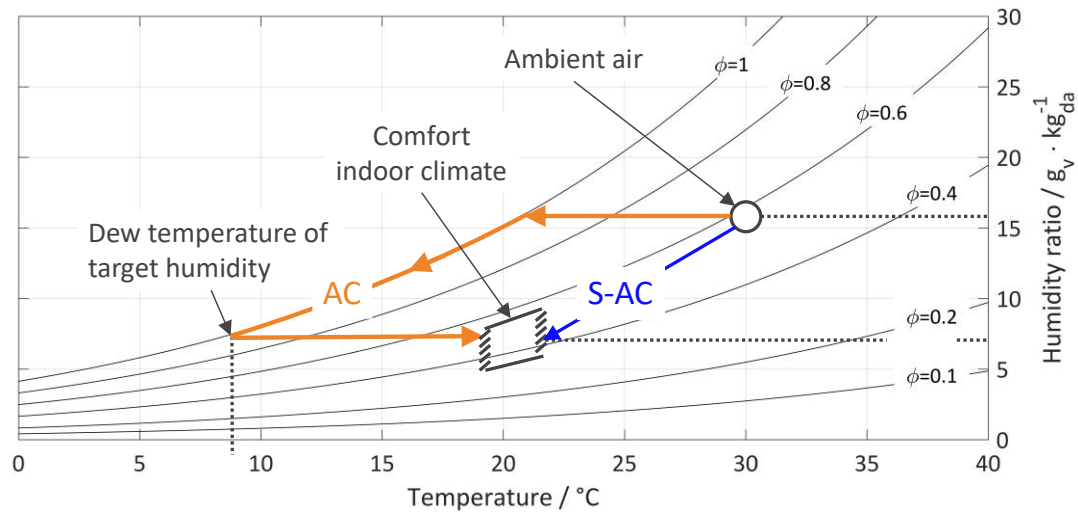


Legend for the plots:

- This Work
- This Work Thin-walled
- ◀ This Work Compact
- ▼ Bitzer Shell-tube 1
- ▲ Bitzer Shell-tube 2
- ◆ Bitzer Shell-tube 3
- ▶ SWEP BPHX 1
- ◀ SWEP BPHX 2
- ★ SWEP BPHX 3
- ◀ Danfoss BPHX 1
- Danfoss BPHX 2
- ✱ Danfoss BPHX 3

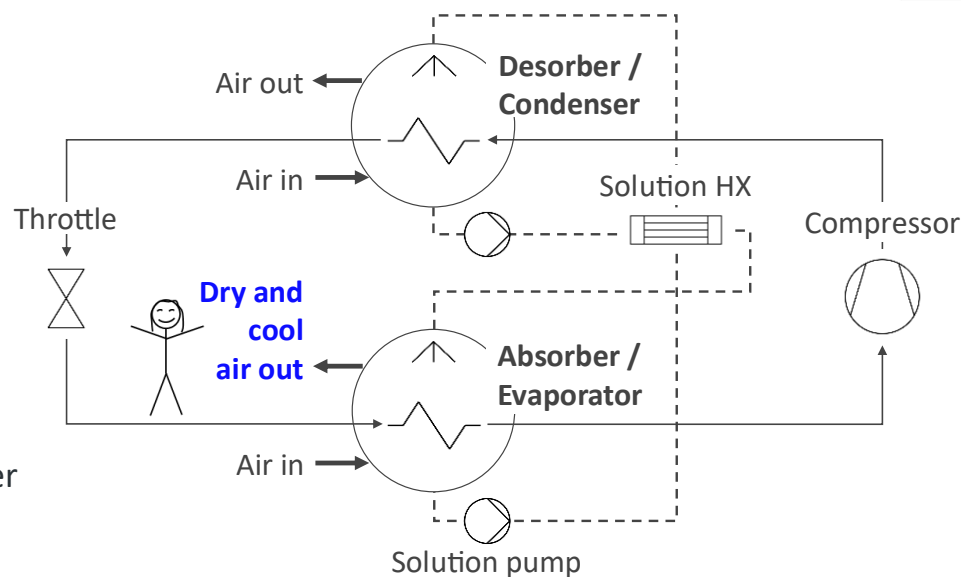


Hybrid Air Conditioning With Absorptive Dehumidification



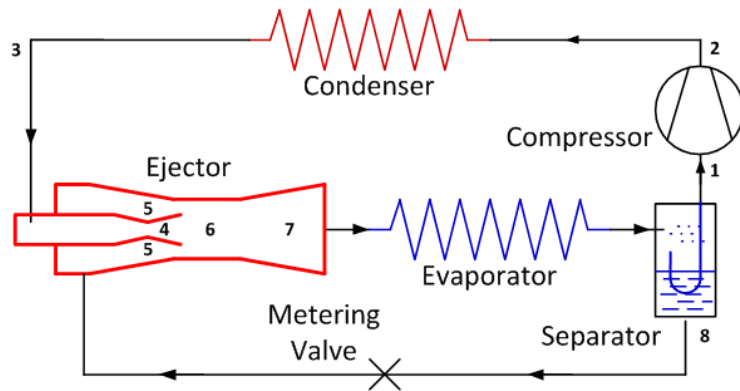
System Design

- **Ionic liquid** as non-corrosive hygroscopic desiccant
- **Propane R290** as natural Refrigerant
- Heat and mass transfer occur **simultaneously**



Dramatically improved COP because evaporator can operate above dew point of air (and still dehumidify)

Benefits of Liquid Overfeed with Ejector



NH₃ outlet

- Eliminate refrigerant dryout
- Reduce distribution problems

Side view of
NH₃ BPHX



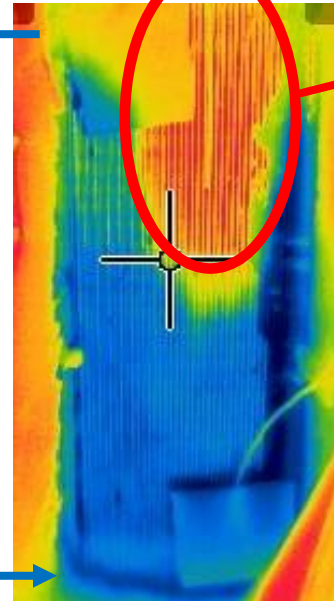
NH₃ inlet

Low-quality: boiling dominated and
low-to-moderate HTC



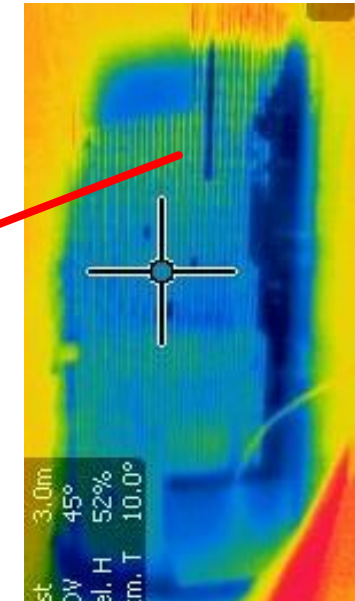
High quality: high velocity but little or no liquid on
walls ("dryout") makes for very low HTC

Moderate quality: Increased amount of vapor leads to higher velocity; combination of
boiling and convective heat transfer leads to very high HTC



Significant superheated area in
DX mode (low ΔT and HTC)

No superheated region,
constant refrigerant
temperature throughout (much
better HTC and high ΔT)



Conditions:

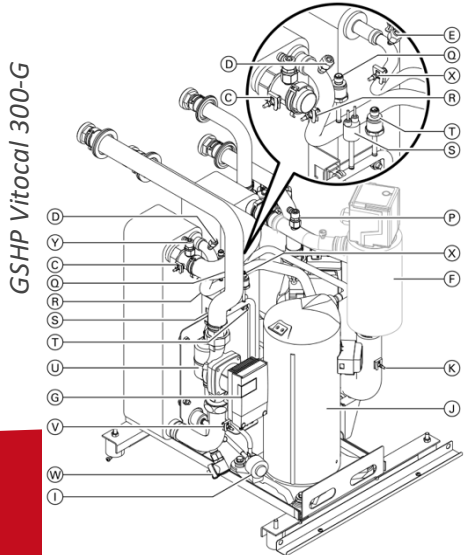
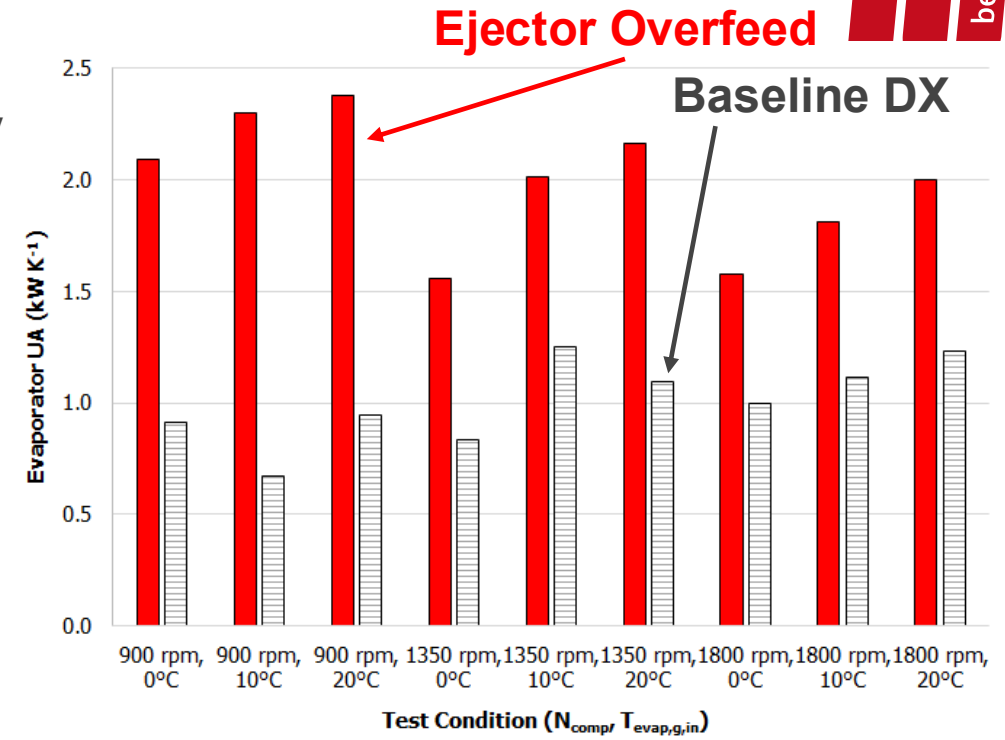
35°C condensing temp
1350 min⁻¹ compressor speed
10°C heat source temp

DX Cycle
 $T_{\text{evap}} = 2^\circ\text{C}$
 $\Delta T_{\text{SH}} = 9^\circ\text{C}$

Ejec Overfeed
 $T_{\text{evap}} = 7^\circ\text{C}$
 $x_{\text{evap,out}} = 0.78$

Cycles compared at multiple compressor speeds and heat source temps, representing a factor of 3x variation in capacity

- Evaporator overall heat transfer coefficient (UA) increased between 60 and 200%
- **2 - 6°C rise in evaporation temp with overfeed**
- Highest improvement at low capacity (most superheat in DX)
- Capacity improved by 3 – 28%
- COP increased simultaneously by up to 28%



Expand concept proven to work with NH_3 to R290 , while simultaneously reducing refrigerant charge

Conclusions



- There is no application that could not be done with natural refrigerants
 - R744: great fluid, but transcritical cycle needs help
 - R290: great fluid, but safety needs to be addressed
- Technology is being developed in all directions
- Prediction: R744 and R290 will coexist for different applications
 - There is space for NH_3 applications as well

Thank you!

elbel@tu-berlin.de