

Evaluation of Refrigerants for Different Applications

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Assessment Criteria for Refrigerants

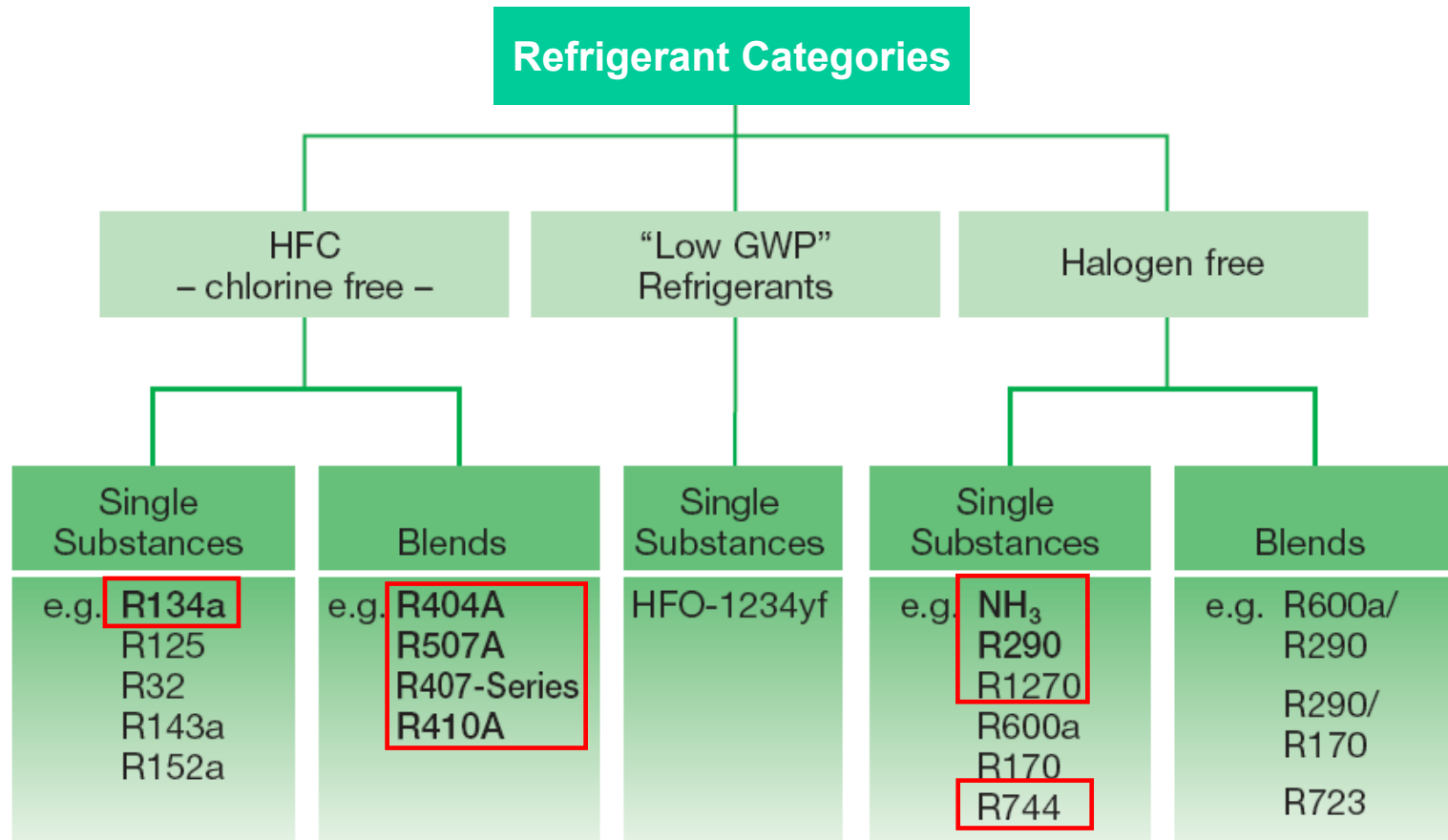
Energy Efficiency
Emissions
Safety

System Costs
Life Cycle Cost
Reliability

NH₃ **HFC**
? ? ?
CO₂ **HC**
HFO-1234yf



General Survey of Actual Refrigerants



Following evaluation is focused on:

- Stationary systems – commercial and industrial applications
- Presently used or considered HFC and halogen free refrigerants

The “Ideal“ Refrigerant

- ❑ High (thermodynamic) energy efficiency / COP
 - High enthalpy of evaporation / low mass flow
 - High critical temperature
 - Low vapor density in relation to pressure level
 - ➔ Low temperature loss with pressure drop
 - Favorable heat transfer coefficients
- ❑ High volumetric cooling capacity
 - Low flow volume, small cross sections
- ❑ Moderate pressure levels
- ❑ No or low temperature glide
- ❑ Low global warming potential (GWP)
- ❑ Low toxicity, not flammable / explosive
- ❑ Good material compatibility

Impact
80-90%

Impact
10-20%

TEWI

Properties of Refrigerants for MT & LT Applications

Refrigerant	Relative Efficiency [%]		Relative Volumetric Cooling CAP [%]		Pressure Levels [%]	GWP [100 a]	Safety Group	Material Compatibility
	MT ①	LT ①	MT ①	LT ①				
HCFC Refrigerant (Reference) ⇒ ozone depleting (subject to phase-out)								
R22	100	100	100	100	100	1500	A1	✓
HFC Refrigerants								
R134a	102	N/A	62	N/A	67	1300	A1	✓
R404A (R507A)	95	105	102	112	118	3260 (3300)	A1	✓
R410A	95	94	140	145	150	1725	A1	✓
Halogen Free Refrigerants								
R1270 (R290)	99	104	107	115	107	3	A3	✓
NH₃	105	102	108	95	103	0	B2	☹ Cu
CO₂ ②	85 ③	100	470	720	500 (trans-critical)	1	A1	☺ Elastom.

① R22, HFC, HC, NH₃: EN12900 references

② CO₂: MT (trans-crit.): SST -7 / tgc 35°C / 86bar
LT (sub-crit.): SST -32 / SDT -5°C

③ Equal efficiency @ low ambient temperatures
- similar seasonal efficiency in moderate climates

④ EN378 and ASHRAE 34
A3: flammable/explosive, B2: toxic

Properties of Refrigerants for HT Applications

Refrigerant	Relative Efficiency [%] HT ①	Relative Volumetric Cooling CAP [%] HT ①	Pressure Levels [%] ①	GWP [100 a]	Safety Group ③	Material Compatibility
HCFC Refrigerant (Reference) ⇒ ozone depleting (subject to phase-out)						
R22	100	100	100	1500	A1	✓
HFC Refrigerants						
R134a	101	64	68	1300	A1	✓
R407C	97	95	102	1520	A1	✓
R410A	94	140	157	1720	A1	✓
Halogen Free Refrigerants						
R290 (R1270)	100	84	88	3	A3	✓
NH₃	104	115	105	0	B2	☹ Cu
CO₂ ②	80	410	510 (trans-critical)	1	A1	☹ Elastom.

① R22, HFC, HC, NH₃: EN12900 reference

② CO₂: HT (trans-crit.): SST +7 / tgc 40°C / 100 bar

③ EN378 and ASHRAE 34

A3: flammable/explosive, B2: toxic

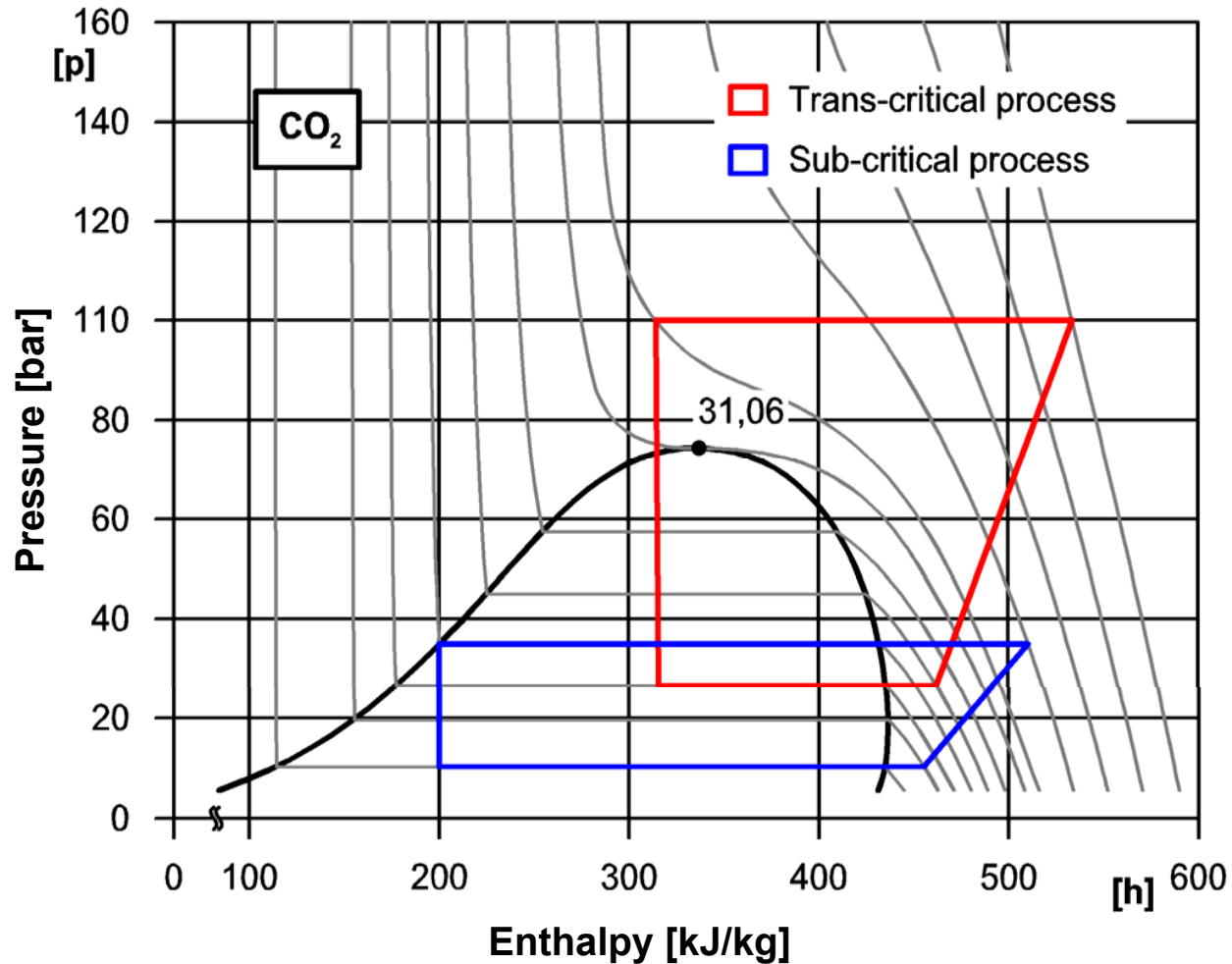
Comparative Assessment of (Major) HFCs

	Strength	Weakness
R134a	<ul style="list-style-type: none"> ▪ High thermodynamic efficiency in HT/MT, lowest GWP of HFCs <ul style="list-style-type: none"> - low energy cost & TEWI ▪ Low pressure levels <ul style="list-style-type: none"> - screws: very high efficiencies - reduced leakage potential 	<ul style="list-style-type: none"> ▪ Low volumetric cooling capacity <ul style="list-style-type: none"> - larger compr. displacement - larger pipe sizes - negative impact on cost ▪ Limited to HT & MT
R404A (R507A)	<ul style="list-style-type: none"> ▪ High thermodynamic efficiency in MT & LT <ul style="list-style-type: none"> - low energy cost (MT & LT) ▪ Low discharge & oil temp. <ul style="list-style-type: none"> - good for high pressure ratio 	<ul style="list-style-type: none"> ▪ High GWP <ul style="list-style-type: none"> - high TEWI in case of leakage ▪ Reduced efficiency at high condensing temperatures (tc)
R410A	<ul style="list-style-type: none"> ▪ High volumetric cooling cap. <ul style="list-style-type: none"> - small compr. displacement - small pipe sizes - low temp loss (pressure drop) ▪ Favorable heat transfer 	<ul style="list-style-type: none"> ▪ Discharge temp. similar to R22 <ul style="list-style-type: none"> - limited application (esp. LT) ▪ High pressure levels <ul style="list-style-type: none"> - increased leakage potential (preferably factory-built units)

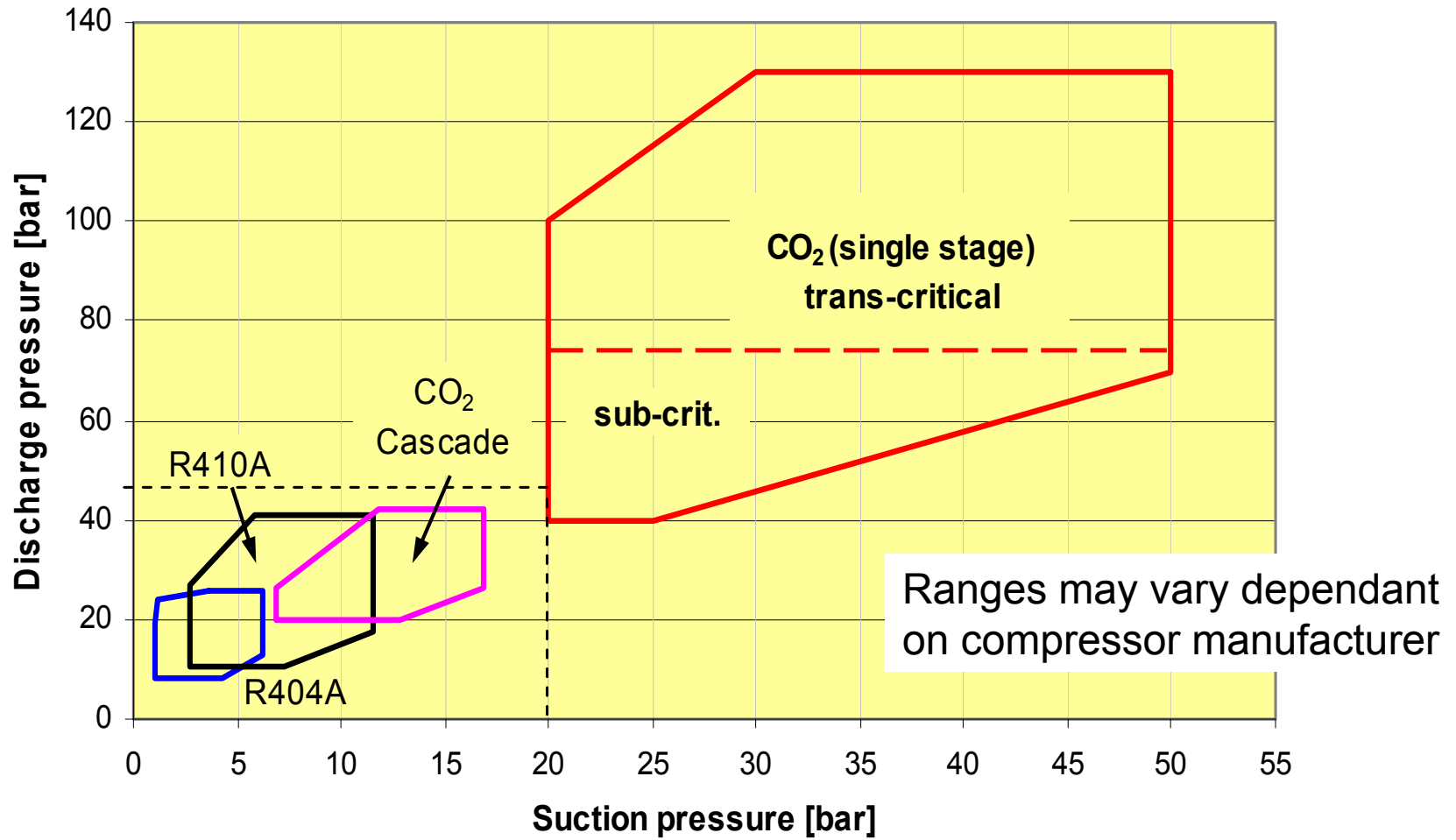
Comparative Assessment of NH₃ and HCs

	Strength	Weakness
NH₃ (R717)	<ul style="list-style-type: none"> ▪ Ideal in thermodynamics, high energy efficiency ▪ Very low mass flow ▪ No GWP ▪ Applicable for HT, MT & LT <ul style="list-style-type: none"> - properties favorable for industrial applications 	<ul style="list-style-type: none"> ▪ Toxic (and mildly flammable) <ul style="list-style-type: none"> - stringent safety requirements - may require secondary system (possible negative impact on cost and efficiency) ▪ Limited material compatibility <ul style="list-style-type: none"> - mainly open drive compr. ▪ Very high thermal load <ul style="list-style-type: none"> - 2-stage or screws for LT
R290 R1270	<ul style="list-style-type: none"> ▪ High thermodynamic efficiency ▪ Mass flow lower than HFCs ▪ Negligible GWP ▪ Applicable for HT, MT & LT <ul style="list-style-type: none"> - preferably in factory-built low charge systems 	<ul style="list-style-type: none"> ▪ Highly flammable / explosive <ul style="list-style-type: none"> - stringent safety requirements - strong limitations in charge or explosion proof design - may require secondary system ▪ High refrigerant solubility in oil <ul style="list-style-type: none"> - lubrication issues

CO₂ (R744) – A General Solution?



Design Criteria for CO₂ Compressors (Systems) – Example for Pressure Ranges – CO₂ vs. HFCs



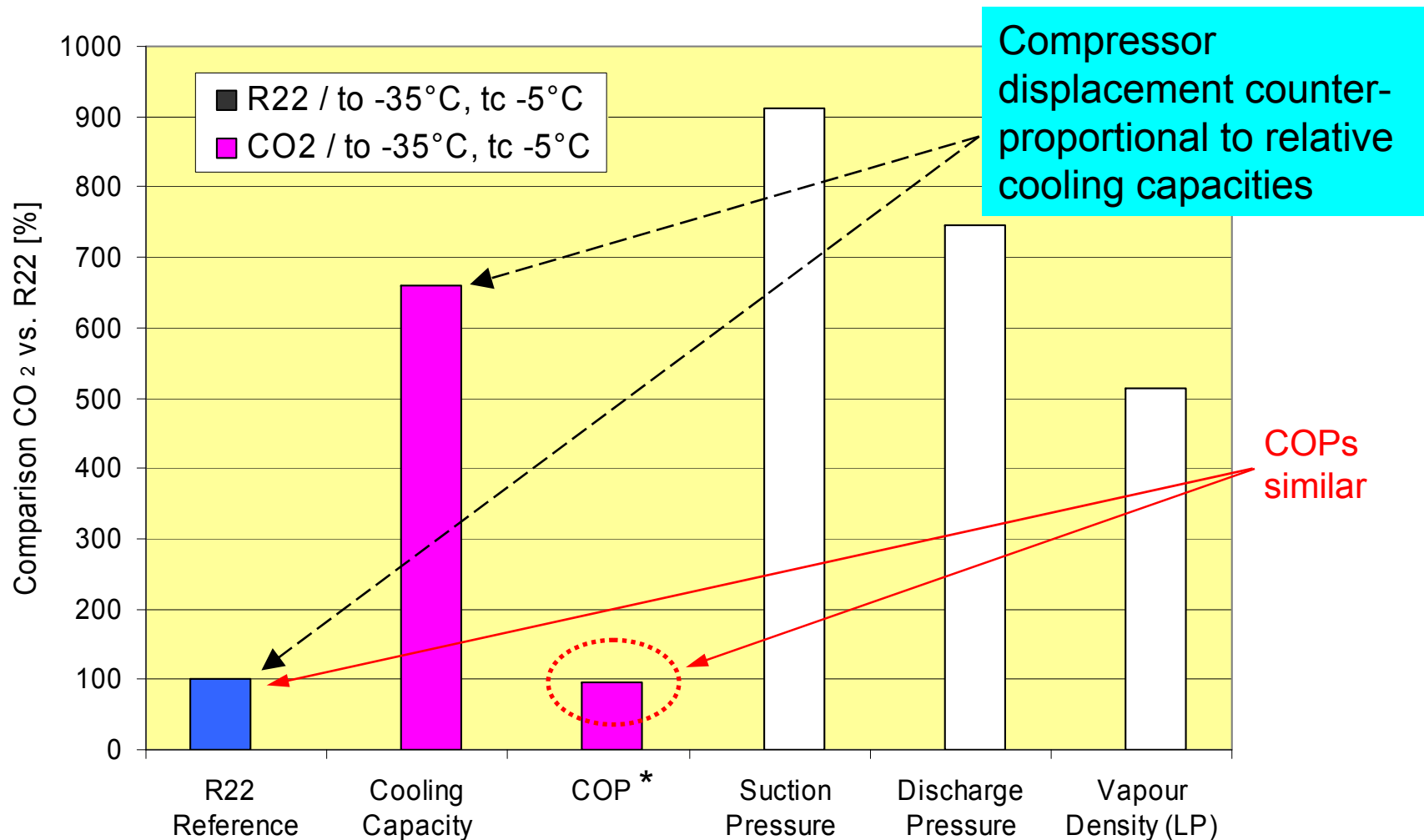
Challenges for the Application of CO₂

Example: Compressor Design Criteria

General issues

- ❑ Compressor design criteria and requirements depend very much on application conditions
 - Sub-critical operation
 - ➔ e.g. low temperature cascade system
 - Trans-critical operation
 - ➔ HT, MT, LT (2-stage) systems, heat pumps
- ❑ Properties of CO₂ require very demanding compressor (system) techniques regarding:
 - Material strength ⇒ safety, cost
 - Reliability ⇒ mechanical load, thermal load, lubrication issues
 - Efficiency ⇒ challenge in trans-critical operation with high heat sink temperature

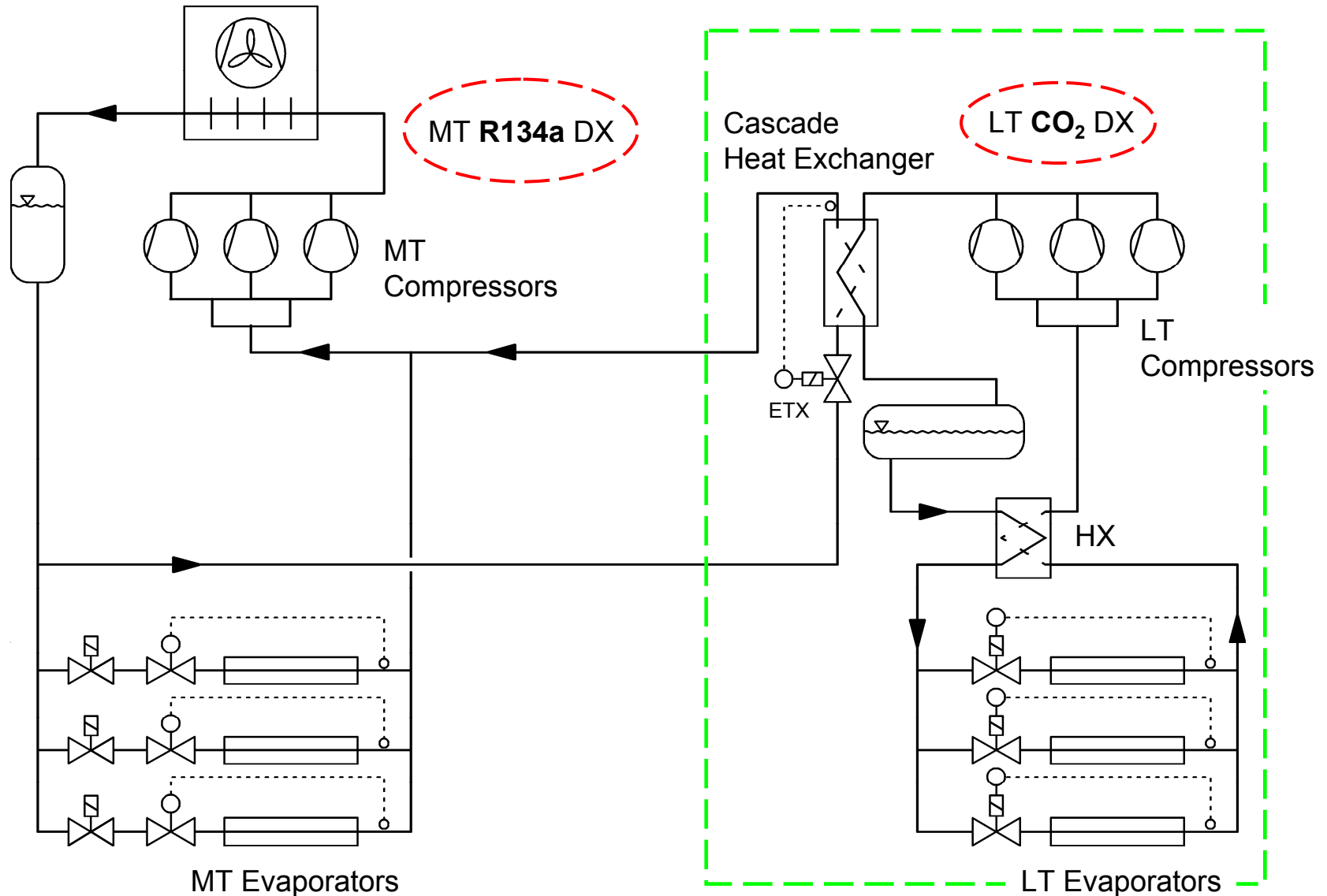
Compressor Performance & Efficiency – Low Temp CO₂ (sub-critical) vs. R22



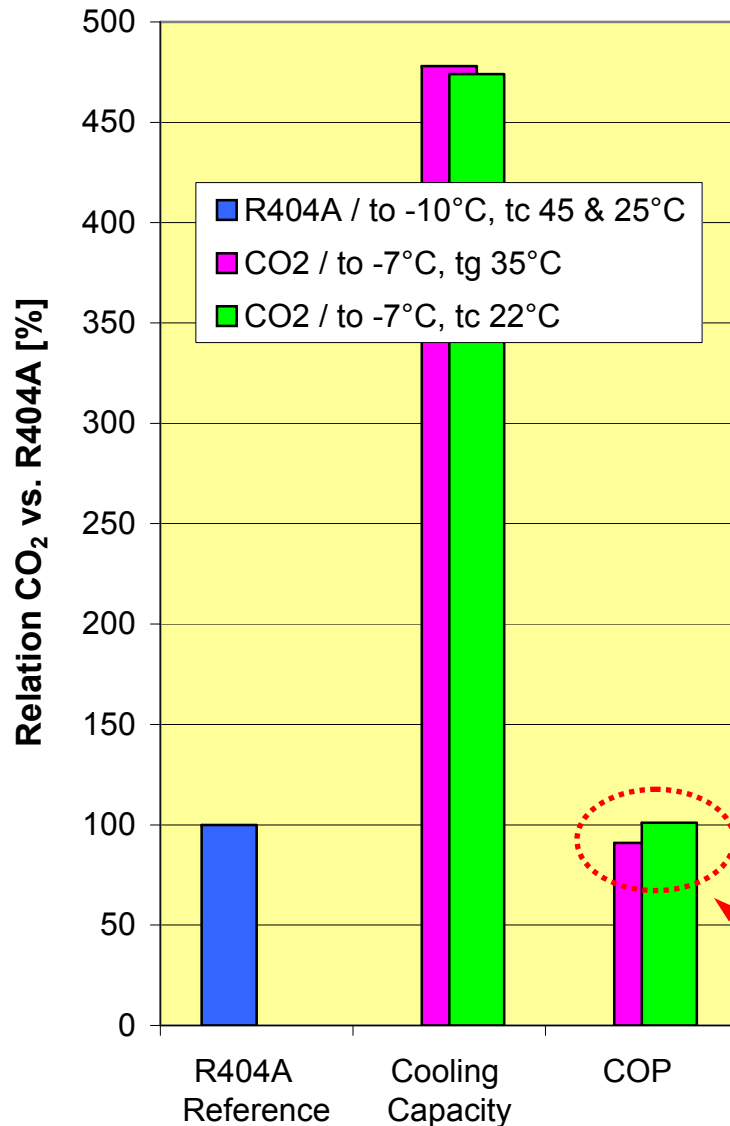
* Industrial compressors ⇒ COP with CO₂ vs. NH₃ equal or better only below -40°C

Example of Hybrid Application – Medium Temp R134a / Low Temp CO₂ Cascade

simplified sketch



Compressor Performance & Efficiency – Medium Temp Conditions (trans-critical) CO₂ vs. R404A



Assumptions:

□ Ambient temp: 32°C / 10°C

□ R404A

t_o -10°C, Δt_{oh} 10 K, t_c 45°C / 25°C,
no liquid subcooling (EN12900)

□ CO₂

t_o -7°C, Δt_{oh} 10 K

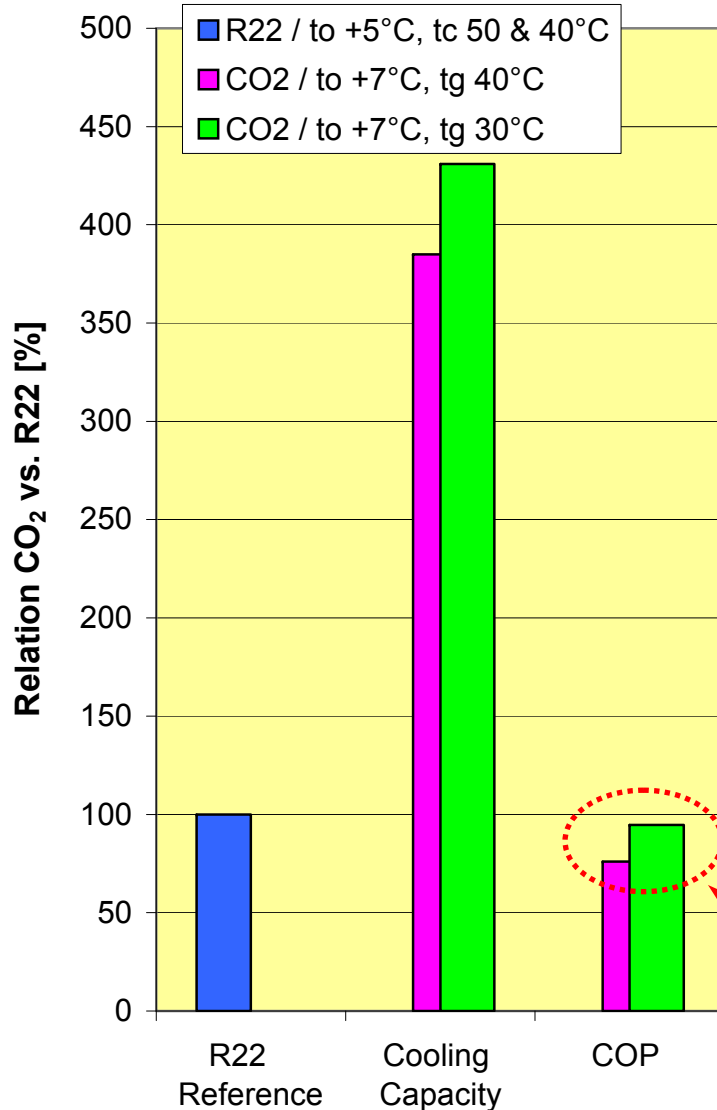
- t_o -7° due to improved heat transfer
- and reduced temperature loss
(reduced influence of pressure drop)

$t_{gas\ out}$ 35°C (32° ambient)

t_c 22°C (10° ambient)

COPs similar under moderate conditions

Compressor Performance & Efficiency – A/C Conditions (trans-critical) CO₂ vs. R22



Assumptions:

□ Ambient temp: 35°C / 25°C

□ R22

t_o +5°C, Δt_{oh} 10 K, t_c 50°C / 40°C,
no liquid subcooling (EN12900)

□ CO₂

t_o +7°C, Δt_{oh} 10 K, internal HX

- +7° due to improved heat transfer

- and reduced temperature loss

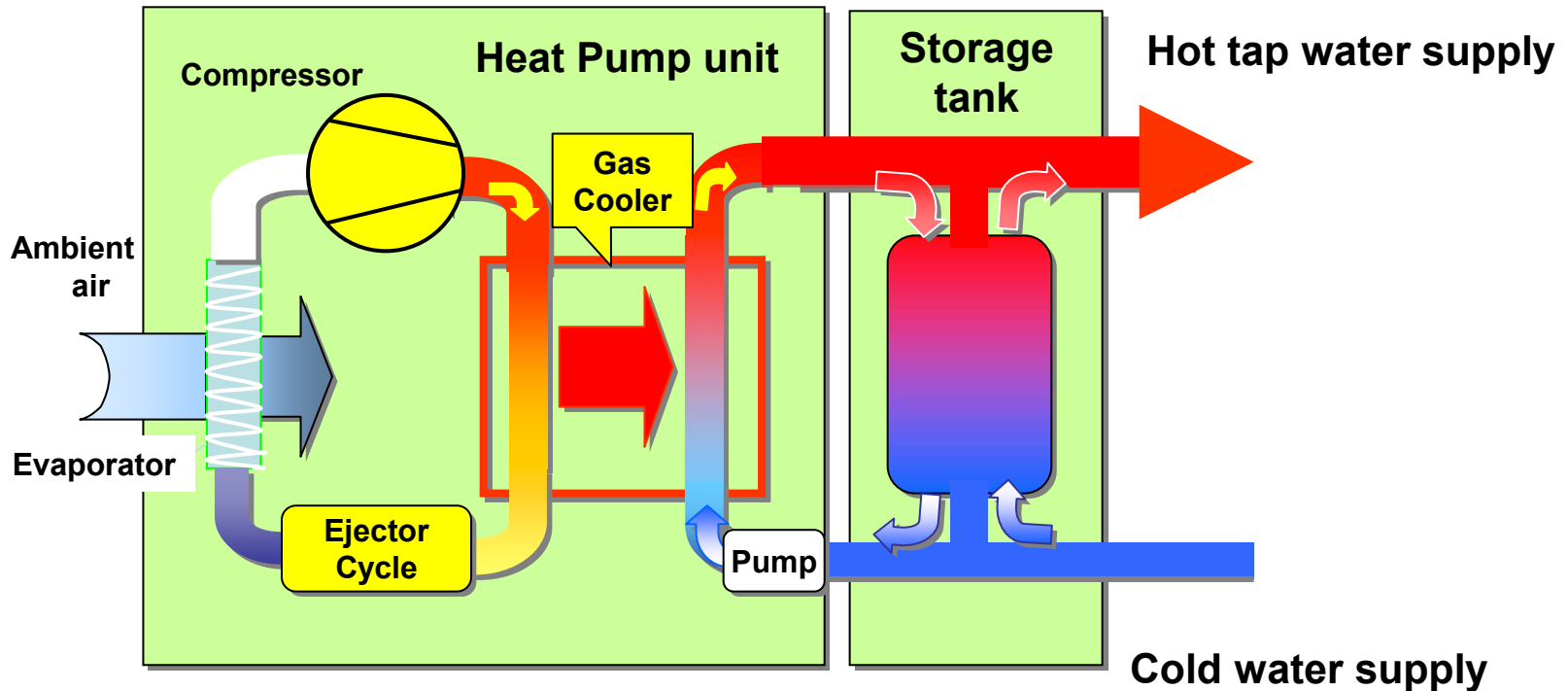
(reduced influence of pressure drop)

$t_{gas\ out}$ 40°C (35° ambient)

$t_{gas\ out}$ 30°C (25° ambient)

Lower despite of CO₂ system optimization

Compressor Performance & Efficiency – Sanitary Water Heat Pump (trans-critical) CO₂ vs. R134a



Comparison CO₂ vs. R134a – water inlet 17° / water outlet 65°C

- CO₂: $t_o + 7^\circ\text{C}$ / p_{HP} 100 bar / t_{gas} 25°C
- R134a: $t_o + 5^\circ\text{C}$ / t_c 68°C / liq. Subc. 10 K / internal HX

$$\Rightarrow \text{COP}_{\text{HP}}^* = 4.24 \text{ (+ 32\%)}$$

$$\Rightarrow \text{COP}_{\text{HP}}^* = 3.22$$

* Compressor efficiency 65%

Conclusion on the Application of CO₂

- ❑ Sub-critical systems (e.g. low temp cascade)
 - Are on a high development stage with favorable efficiencies
 - Hybrid solutions HFC (MT) / CO₂ (LT) increasingly applied
 - ➔ High efficiencies, low TEWI & Eco-Efficiency @ reasonable cost
- ❑ Trans-critical systems
 - Demanding technology with specific challenges regarding
 - ➔ Material strength, reliability, efficiency and cost
 - Efficiencies are about equal to other solutions in MT & LT systems at moderate climate conditions ⇨ e.g. supermarket systems
 - Efficiencies are lower where gas cooler outlet temperature is high and no "after cooling" can be realized ⇨ e.g. stationary A/C
 - Efficiencies can be higher where low gas cooler outlet temperatures can be maintained ⇨ e.g. sanitary water heat pumps

CO₂ technology is no general solution for the substitution of HFCs

- ❑ **No single refrigerant ideal for all applications – Issues:**
 - Volumetric cooling capacity, pressure levels, application ranges
 - Efficiency, TEWI (COP & GWP), system costs
 - Safety classification & requirements material compatibility

Major Characteristics / preferred applications

HFCs ⇒ Favorable in general properties, tailored options, but high GWP
– Containment! Reduced charge, permanent joints

HCs ⇒ Favorable thermodynamics, low GWP, but flammable / explosive
– Safety! Preferably low charge factory-built units

Major Characteristics / preferred applications (cont'd)

- NH_3 \Rightarrow Ideal in thermodynamics, no GWP, but toxic
- Safety! Properties favorable for industrial applications
- \Rightarrow Limited material compatibility, thermal load extremely high
- Requires special compressor and system technology
-
- CO_2 \Rightarrow Favorable environmental & safety properties, but very high pressures & lower efficiencies with high ambient temperatures
- Opportunity for specific applications (with particular benefits in combination with heating)
 - Hybrid solutions as an efficient option, ideal as secondary fluid