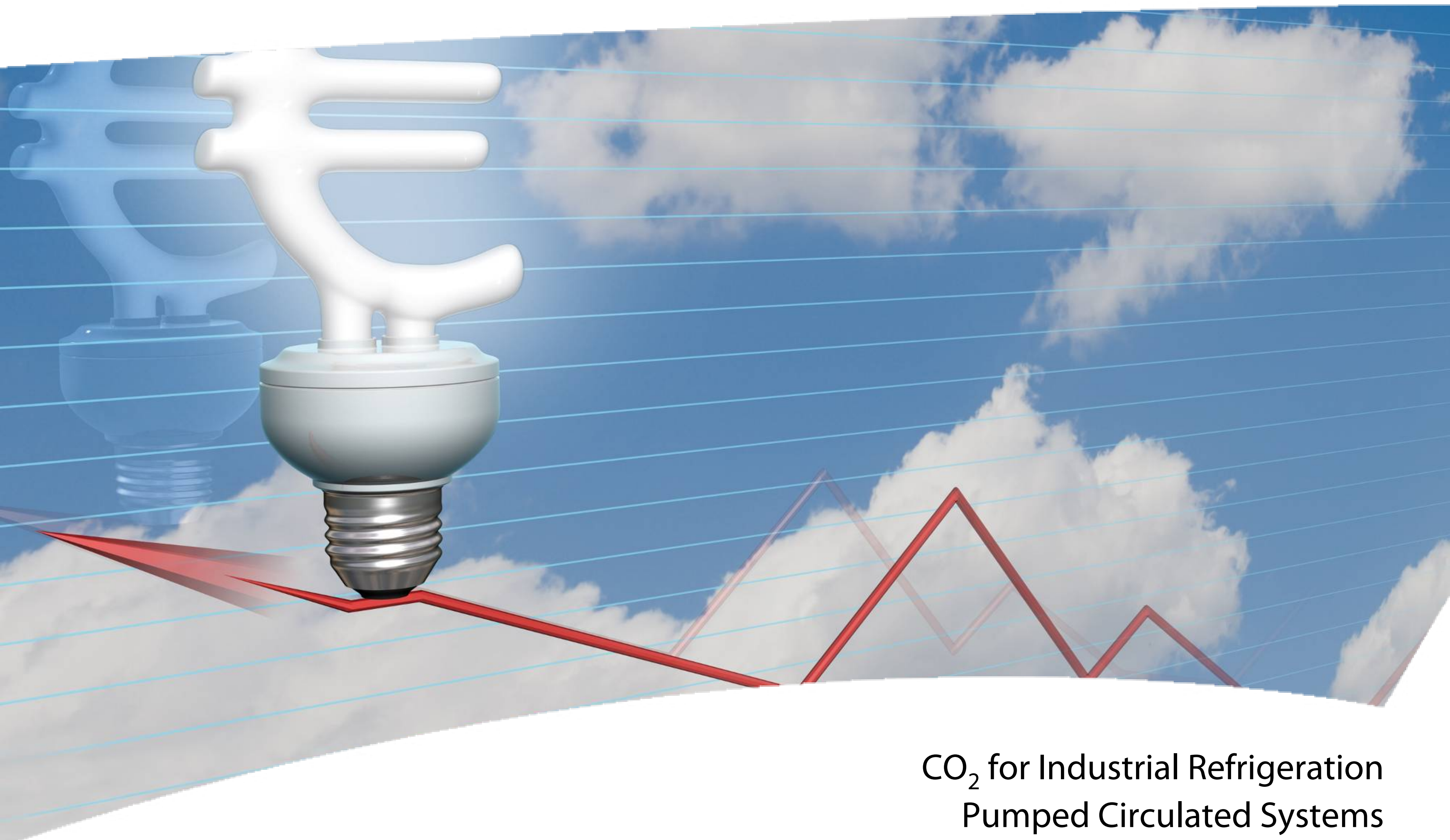


CO_2 for Industrial Refrigeration
Pumped Circulated Systems

REFRIGERATION AND AIR CONDITIONING

Content:

1. Background and drivers
2. CO_2 vs. water based brines: summary
3. CO_2 properties as brines
4. Calculation example
    1. Energy reduction potential
    2. Savings potential
5. Features of the CO_2 secondary systems
    1. System layout
    2. Pump control
    3. Temperature control
    4. Stand still pressure control
    5. Defrost
6. Case stories
7. Danfoss products

1. Chillers' drivers

- Charge reduction
  - Environment (HFC – global warming)
  - Safety (ammonia and hydrocarbons, toxicity and flammability)

- Typical charge reduction in a chiller:

Standard system	> 2000 kg
Chiller with evaporative condenser and flooded shell&tube HE	< 500 kg
Chiller with evaporative condenser and flooded PHE	< 200 kg
Chiller with PHE condenser and flooded evaporator	50-100 kg
Chiller with PHE condenser and DX evaporator	< 20 kg

- **But an unavoidable consequence is increased energy consumption!**

2. CO_2 vs. water based brines – summary

- Energy savings with CO2 systems
  - higher evaporating temperature due to lower temperature difference in the PHE and evaporators
  - much smaller pumps
  - smaller heat in-flow via insulation due to smaller pipes
  - better heat exchange
- As a consequence, a significant carbon footprint reduction of the installation
- CO2 systems are more economical: both lifetime and first cost
- Installation is simple
- Smaller pipes – easier installation, especially when copper is used.
- No issues with food safety or good damage in case of leaks
- No freezing issues
- No oil in evaporators

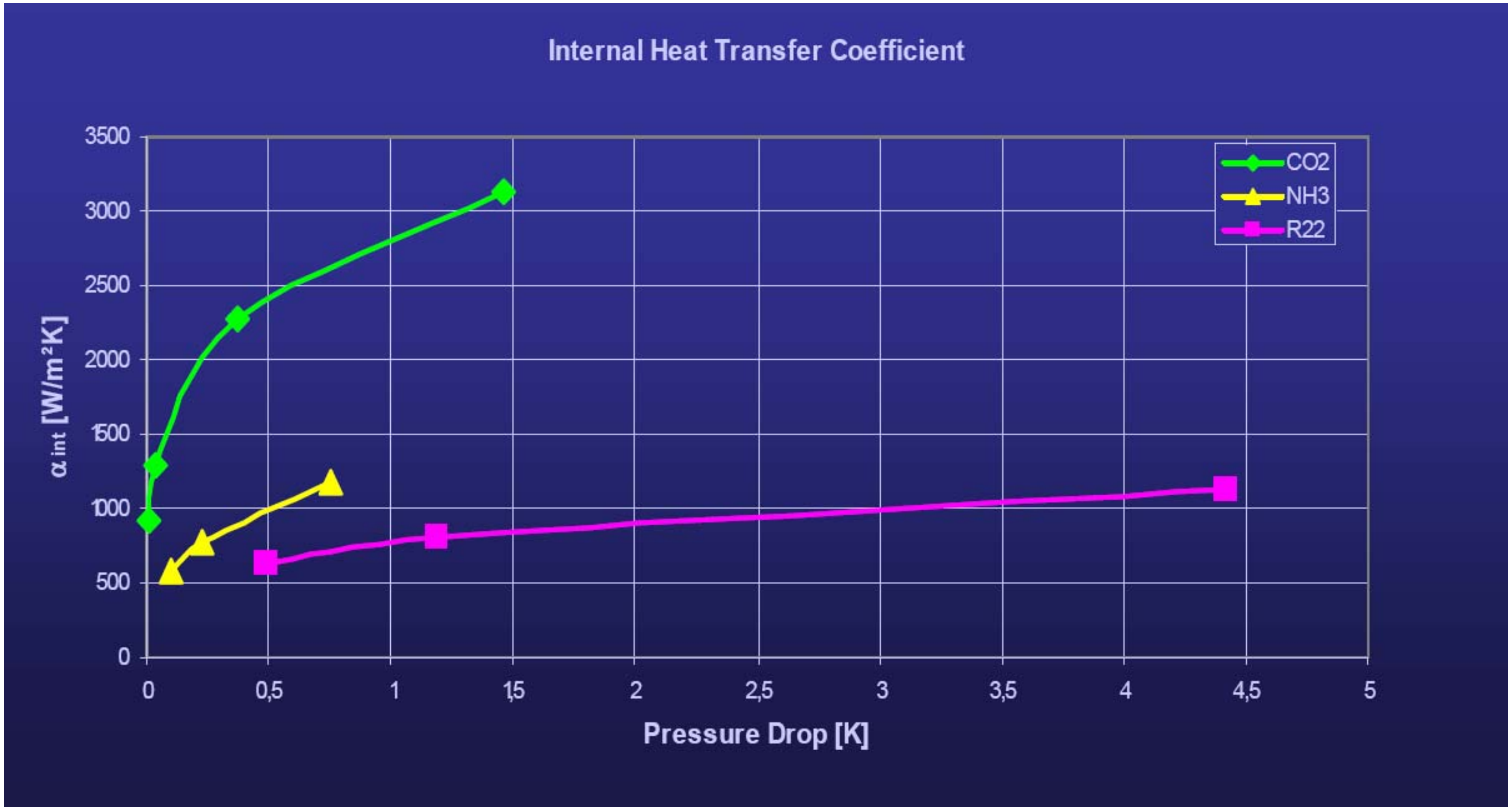
2. CO_2 properties as brine

- ODP = 0 (Ozone depletion potential)
- GWP = 1 (Global warming potential)
- Not flammable
- Not toxic (EN 378)
- Low viscosity
  - small pumps
- High volumetric cooling capacity
  - small pipes
- Moderate pressures
  - 40-45 bar for most of the pump circulated systems

Substance	Critical temperature and pressure
CO_2	**31°C** / 73,8 bar
Propane	96,7 °C / 42,4 bar
Water	374 °C / 22 bar
Ammonia	132 °C / 113 bar

Substance	Triple point
CO_2	**-56,6°C** / 5,18 bar
Propane	-188 °C / 0,3 mPa
Water	0 °C / 0,006 bar
Ammonia	-77,6 °C / 0,06 bar

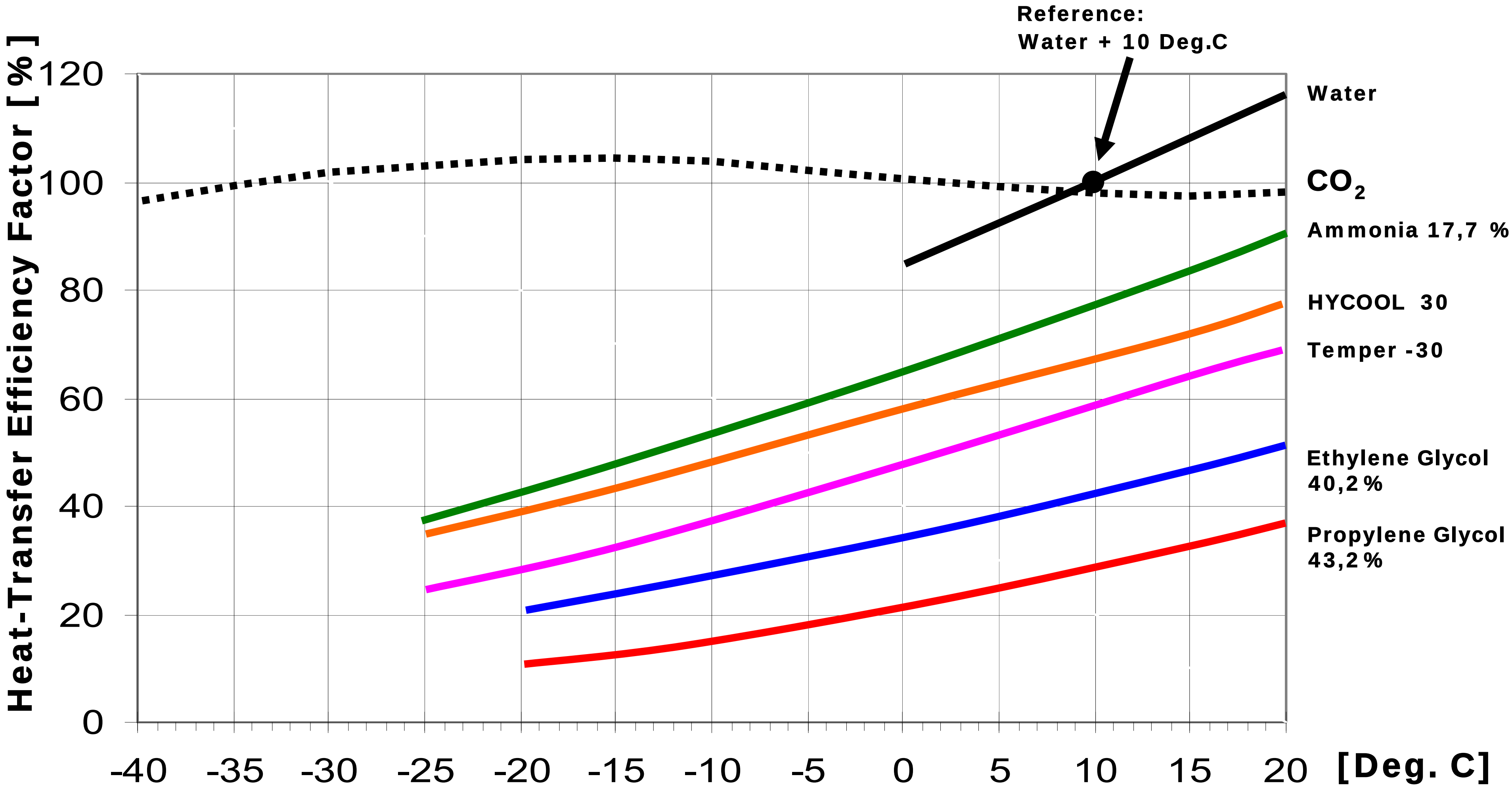
Internal heat transfer coefficient with flooded operation vs. other refrigerants



- Source: Günter

2. CO2 as a brine – lower energy consumption

High Heat-Transfer Efficiency Factor



The Heat-Transfer Efficiency Factor expresses the relation between the heat-transfer coefficient and the cooler temperature.

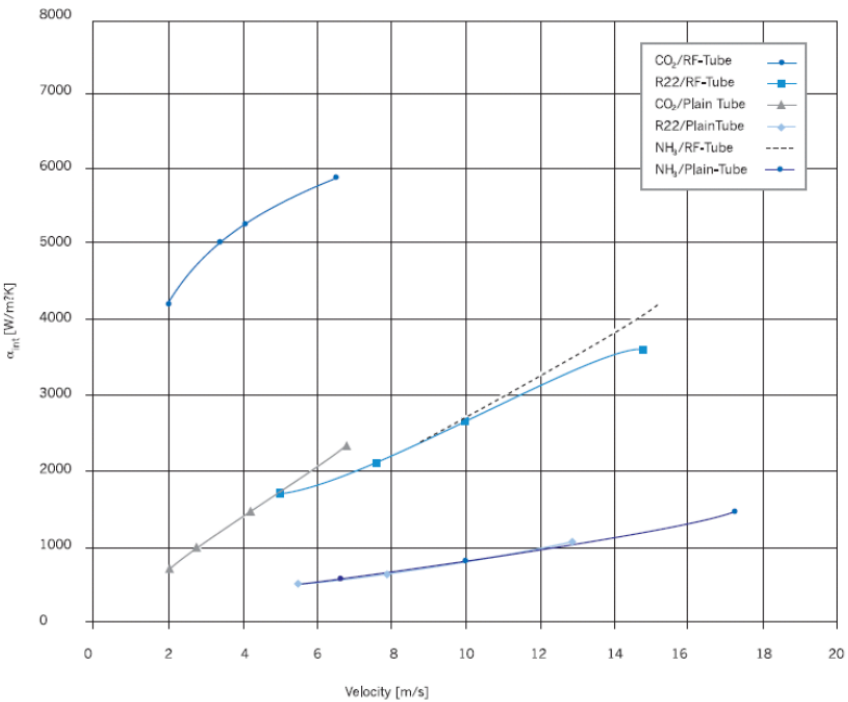
2. CO_2 as a brine – lower energy consumption

- High heat transfer efficiency factor + constant evaporating temperature + better distribution of refrigerant in heat exchangers result in:
  - Lower temperature difference in cascade PHE (1-2 K)
  - Lower temperature difference (2-3 K) in evaporators

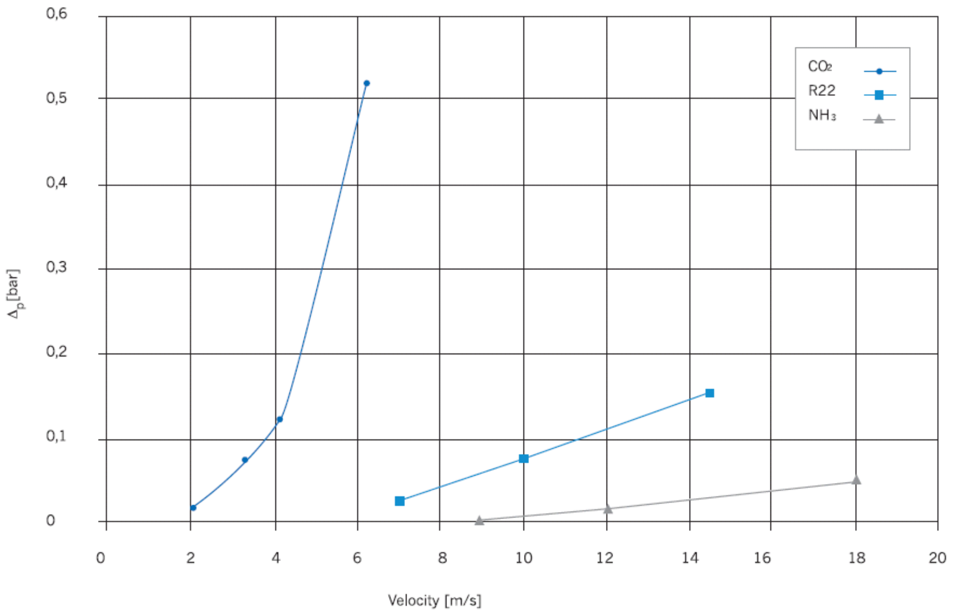
- **Higher suction pressure and lower energy consumption of the chiller**

2. CO2 as a brine – lower energy consumption

Low circulation rate (1.1 – 2)



Heat transfer of different refrigerants in relation to velocity.*

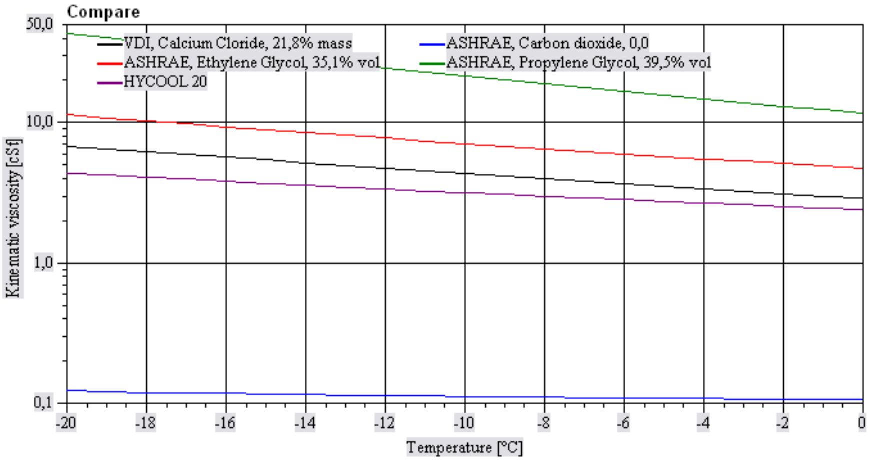


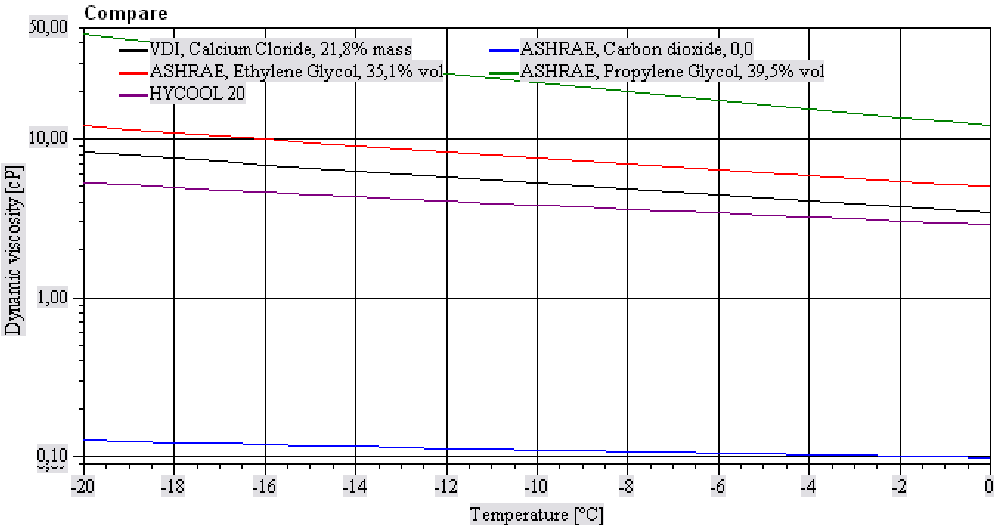
Pressure loss in relation to refrigerant velocity*

*DESIGN CRITERIA FOR CO2 EVAPORATORS, Roland Handschuh, Güntner

2. CO2 as a brine – lower energy consumption

Low viscosity





2. CO_2 as a brine – lower energy consumption

Pumps: Low circulation rate (1.1 – 2*), low viscosity

	Power, kW	
	-10^0C	-20^0C
CO2	**0,97**	**0,85**
CaCl2	**13,34**	**14,22**
Hycool	**16,02**	**16,15**
Ethylene Glycol	**15,87**	**18,8**
Propylene Glycol	**14,03**	**16,68**

- Calculated power consumption by pumps in case of ca. 500 kW capacity

Example: CO_2 circulation rates for different evaporator types

- Air-coolers
  - CO_2 – 1.1 to 2
  - NH_3 – 3 to 10
- Plate freezers
  - CO_2 – 4-5
  - NH_3 – 10 to 20

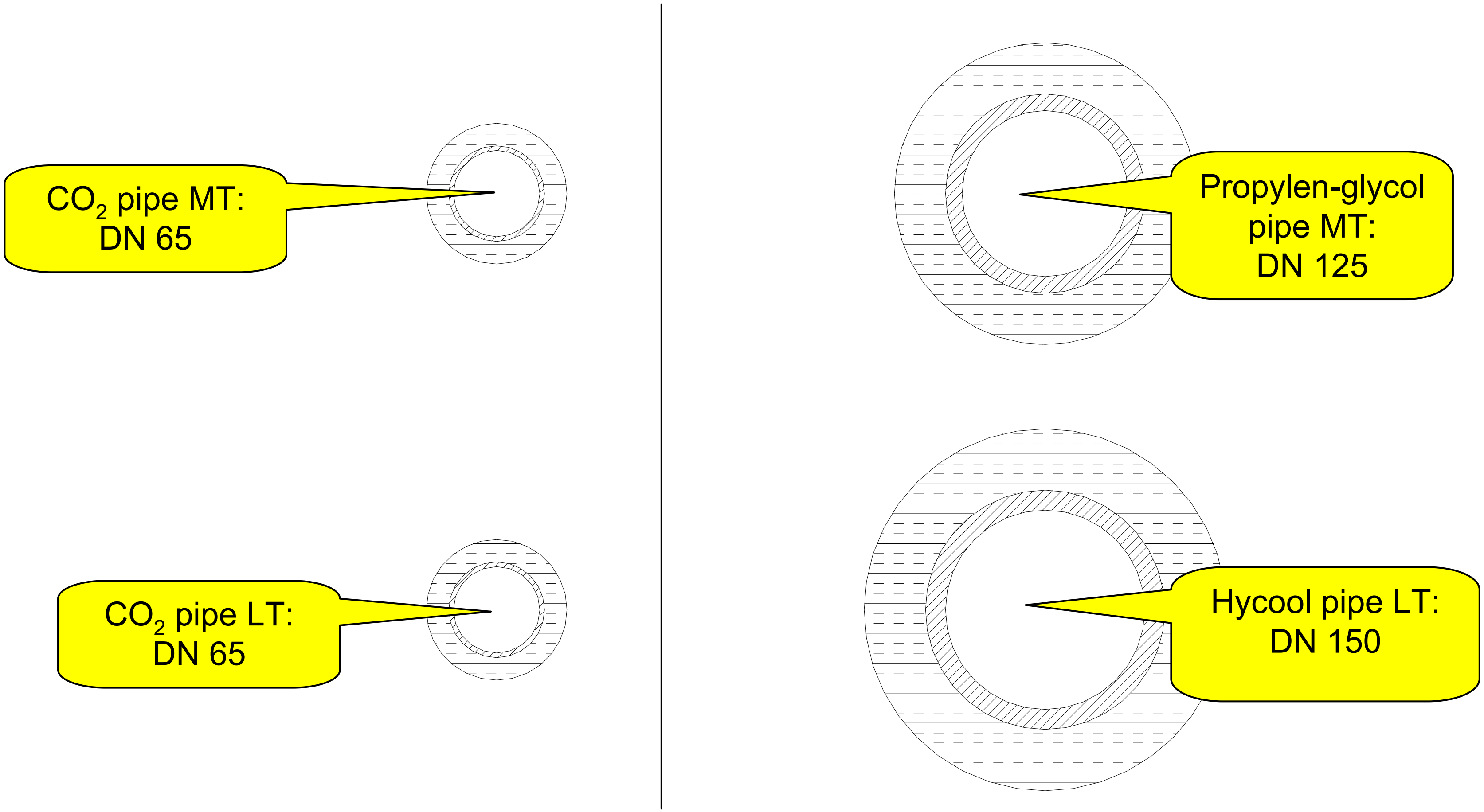
2. CO_2 as a brine – lower energy consumption

- Low circulation rate 1.1 - 2
- Low viscosity
- Low massflow

- **Low energy consumption by pumps**

2. CO_2 as a brine – Lower energy consumption

Pipe size and insulation reduction – lower heat gains



- Heat gain only due to smaller piping could mean more than 5% of the total energy savings (dependent on the ambient conditions)**

*Steel and stainless steel pipes could also be used

2. CO_2 as a brine – lower energy consumption

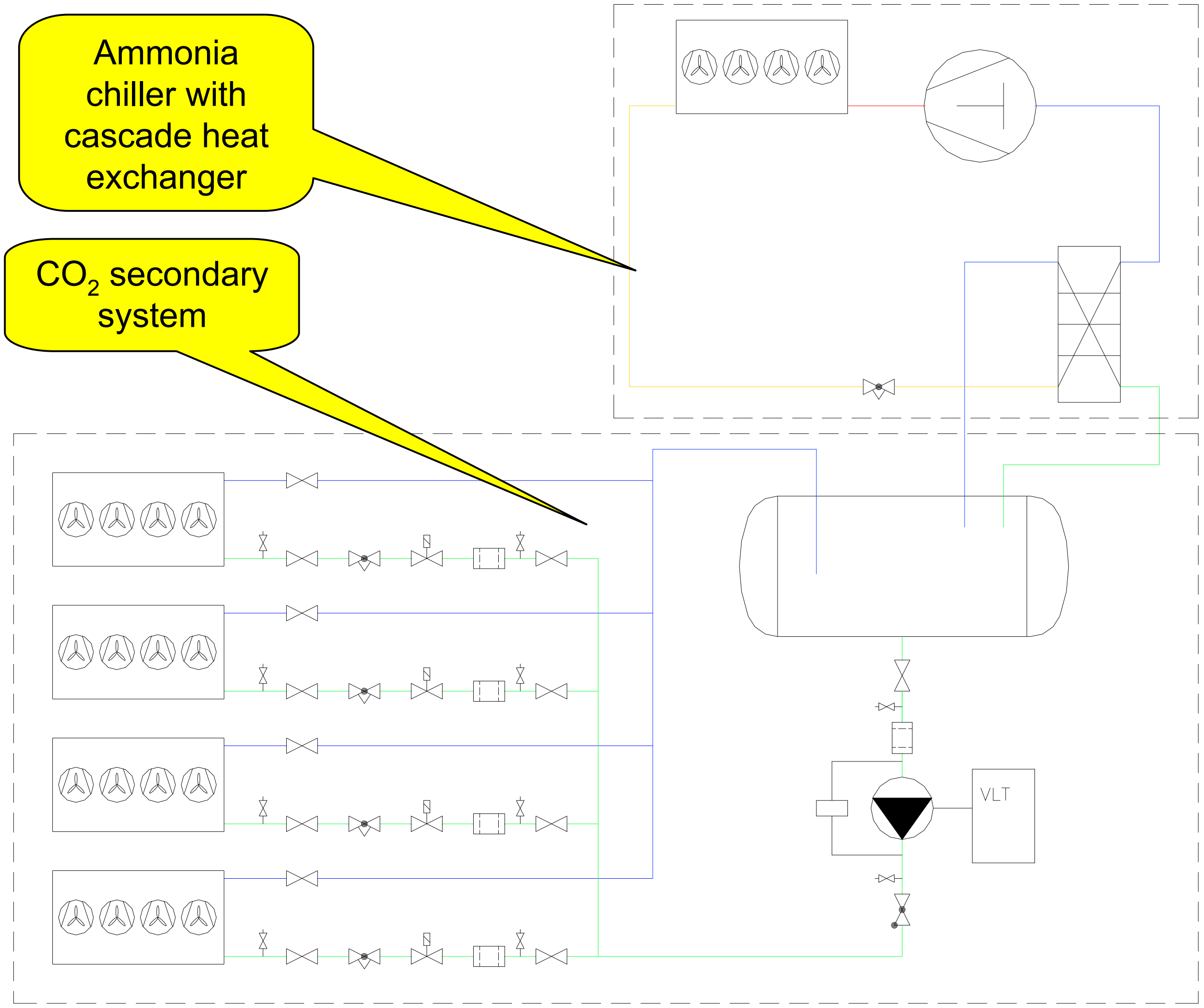
- Smaller discharge pipes
- Smaller return pipes

- **Heat gain only due to smaller piping could mean more than 5% of the total energy savings (dependent on the ambient conditions)***

*Carbon Dioxide In North American Supermarkets, David Hinde

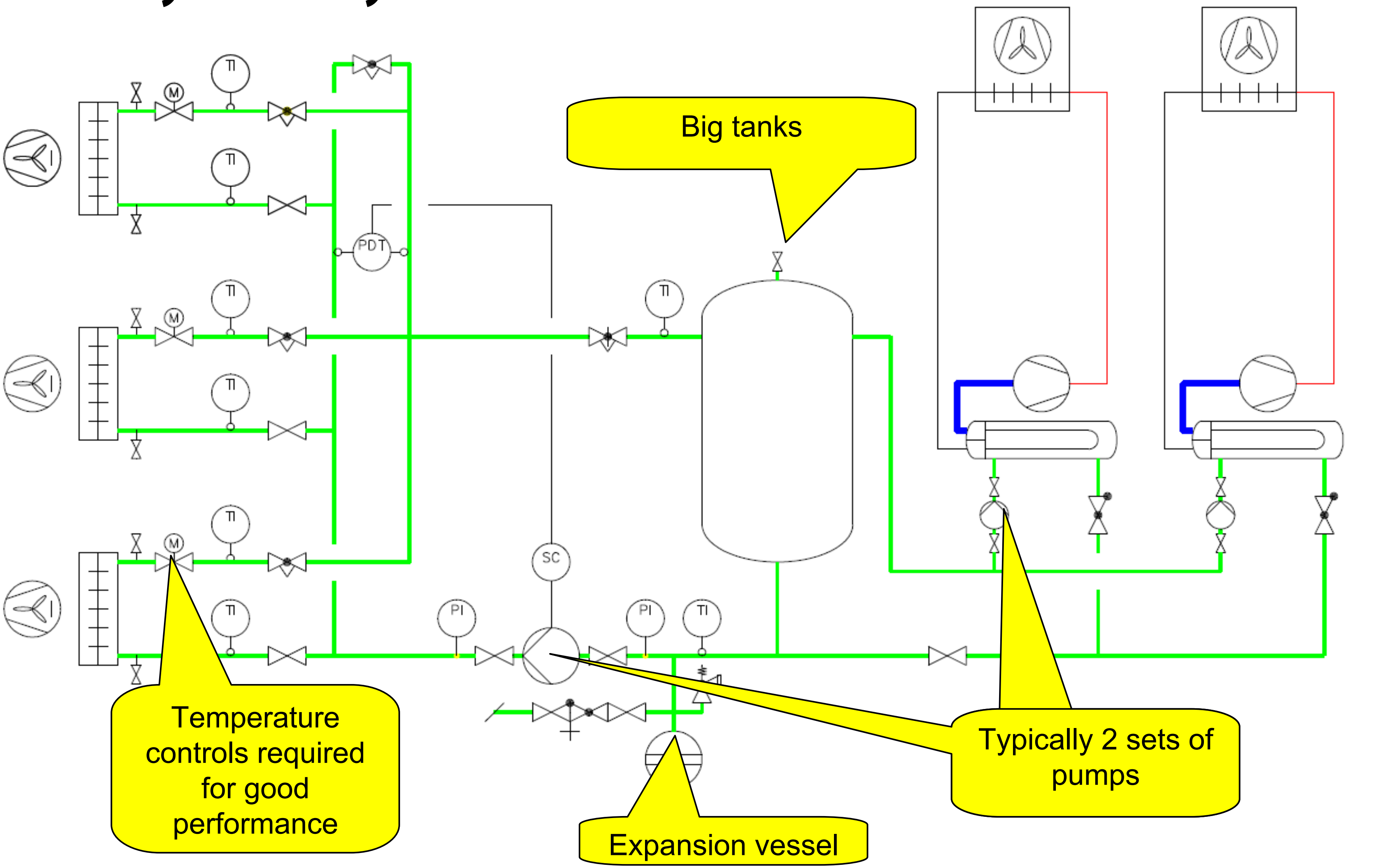
2. CO_2 as a brine – competitive cost

Simple CO_2 pumped diagram



3. CO_2 as a brine – competitive cost

Brine systems layout



2. CO_2 as a brine – competitive cost

- Simple layout
- Less components
- Easier engineering
- Faster start-up
- Less maintenance

- **Competitive system cost**

2. CO_2 as a brine – competitive cost

Smaller components

- Smaller CO2 pipes
  - Less insulation
  - Smaller valves

- Smaller CO2 pumps
  - Smaller frequency drives
  - Reduced number of pumps

- Smaller chiller
  - Due to lower energy consumption

Competitive cost of CO2 systems*

* Detailed analysis of the components is presented in the calculation example

4. Calculation example

- Cold storage facility
  - 500 kW of MT and LT capacity
  - air temperature 0^0C and -20^0C
  - 23 coolers cold rooms/23 coolers in frost rooms
  - pumped operation
  - System layout
    - System 1: NH_3 chiller + CO_2
    - System 2: propylene-glycol MT + Hycool LT

3. Calculation example

Energy consumption

CO2 secondary efficiency calculation tool. Version 3.9

	CO2	Propylene Glycol	Units
Air temperature, t_{air}	0		°C
Cooling power, Q_o	500		kW
Circulation rate, n	1,1		-
Temp. dif. in evap., dt_{evap}	5,0	7,0	K
Temp. dif. in PHE, dt_{PHE}	2,0	3,0	K
Brine temp. dif., $t_{out} - t_{in}$		4,0	K
Evaporating temp., t_o	-7,0	-10,0	°C
Additional heat gains, k_q	5%	7%	%
Additional heat gains, Q_{add}	25	34	kW
Pump power cons., P_{pump}	0,7	11,0	kW
Adjusted cooling power, $Q_{o,ad}$	525,7	543,6	kW
Compr. power cons., P_{comp}	126,5	145,3	kW
Working hours, daily	18,0		h
Total install energy cons.	**127**	**156**	kW
Total daily energy cons.	**2.289**	**2.812**	kW*h
Energy savings	**19%**		%

3. Calculation example

Energy consumption

CO2 secondary efficiency calculation tool. Version 3.9

	CO2	Hycool	Units
Air temperature, t_{air}	-20		°C
Cooling power, Q_o	500		kW
Circulation rate, n	1,1		-
Temp. dif. in evap., dt_{evap}	5,0	7,0	K
Temp. dif. in PHE, dt_{PHE}	2,0	3,0	K
Brine temp. dif., $t_{out} - t_{in}$		4,0	K
Evaporating temp., t_o	-27,0	-30,0	°C
Additional heat gains, k_q	7%	9%	%
Additional heat gains, Q_{add}	35	47	kW
Pump power cons., P_{pump}	0,6	15,6	kW
Adjusted cooling power, $Q_{o,ad}$	535,6	561,3	kW
Compr. power cons., P_{comp}	259,9	302,6	kW
Working hours, daily	18,0		h
Total install energy cons.	**261**	**318**	kW
Total daily energy cons.	**4.690**	**5.728**	kW*h
Energy savings	**18%**		%

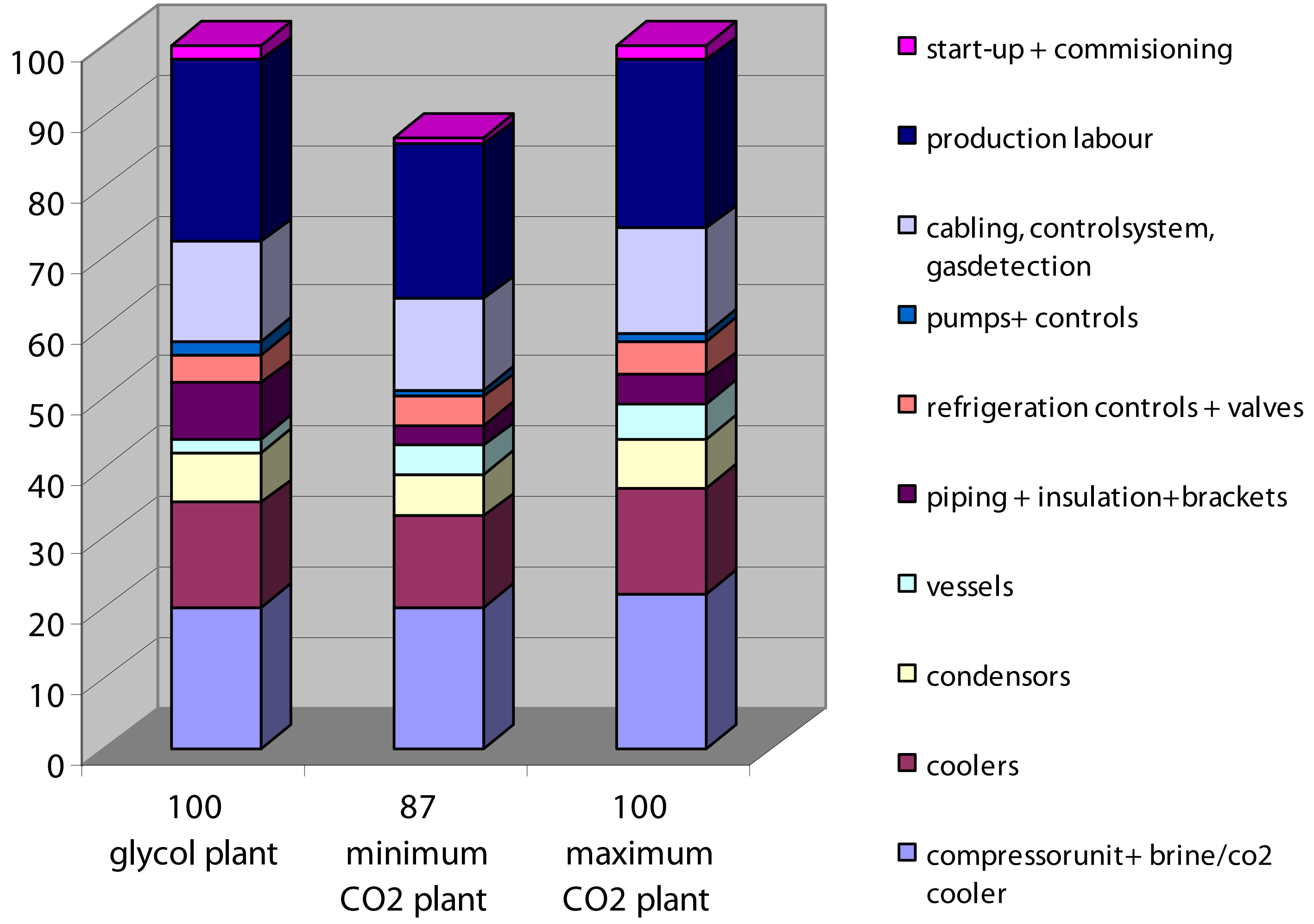
4. Calculation example
First cost

Spread due to the learning curve

	glycol plant	CO2 plant min	CO2 plant max
		minimum	maximum
	100	87	100
compressor unit+ brine/co2 cooler	20	20	22
coolers	15	13	15
condensers	7	6	7
vessels	2	4	5
piping + insulation+brackets	8	3	4
controls + valves	4	4	5
pumps+ controls	2	1	1
cabling, control system, gas detection	14	13	15
production labour	26	22	24
start-up + commissioning	2	1	2

4. Calculation example

First cost



4. Calculation example

First cost NH3/CO2 vs. HFC/glycol cost optimized chiller

	HFC/brine	NH_3/CO_2	
	82	87	
compressor unit+ brine/co2 cooler	10	20	less swept volume for same capacity
coolers	15	13	less surface, no gradient between temp in and out
condensers	4	6	smaller condensor because of less motorpower compressor
vessels	2	4	higher working pressures, so higher design pressures
piping + insulation + brackets	7	3	pipes 1/3 in weight, support construction less heavy, insulation less
refrigeration controls + valves	3	4	higher working pressures, so higher design pressures, dedicated functions
pumps+ controls	2	1	less swept volume for same capacity
cabling, control system, gas detection	14	13	Smaller cables but additional gas detection
production labour	24	22	less piping weight , construction lighter
start-up + commissioning	1	1	only for first plants risk if higher cost because of new technology

Relatively small first cost difference <10%, but in this case the efficiency and running cost difference is even higher!

4. Calculation example

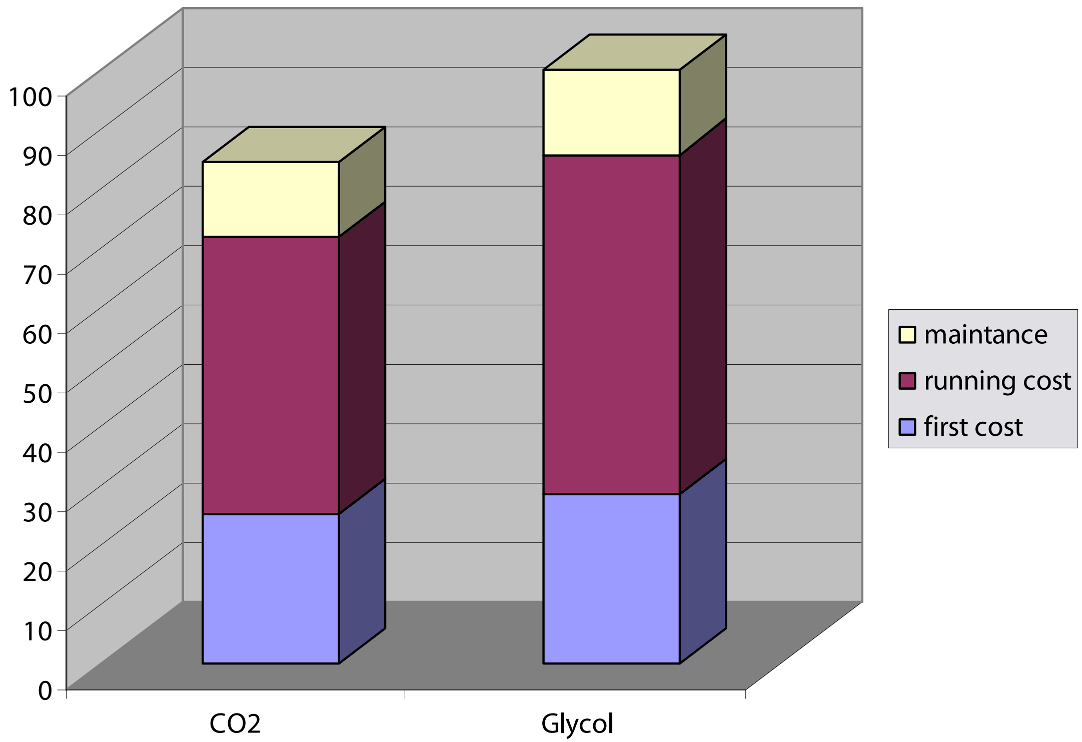
Financial impact - HT

Money calculation			
kW*h price	*0,1*		EURO
Life time of the installation	*15*		years
Discount rate	*10%*		%
First cost	*500.000*	*500.000*	EURO
Energy cost, life time	1.256.033	1.542.621	EURO
Total energy savings	**286.588**		EURO
Annual energy savings	**19.106**		EURO
NPV	**145.322**		EURO

4. Calculation example
Financial impact - MT

Money calculation			
kW*h price	0,1		EURO
Life time of the installation	15		years
Discount rate	10%		%
First cost	500.000	500.000	EURO
Energy cost, life time	2.572.996	3.142.791	EURO
Total energy savings	**569.795**		EURO
Annual energy savings	**37.986**		EURO
NPV	**288.932**		EURO

4. Calculation example
Life time costs



- CO_2 brine systems have at least 15% lower lifetime cost – including installation, energy and maintenance costs
- The system is a future proof, as it is efficient and uses no synthetic refrigerants

4. Calculation example

Carbon footprint

High temperature/ propylene glycol

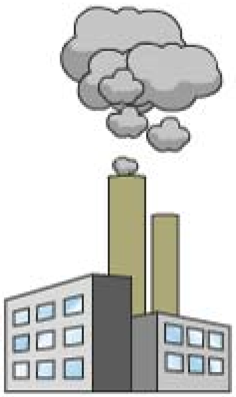
CO2 calculation			
Energy intencity	0,65		kg CO2/kW
CO2 savings	**1.859**		ton
Cars equivalent		14.410.861	km
Trees equivalent		5.484	pcs

Medium temperature/ Hycool

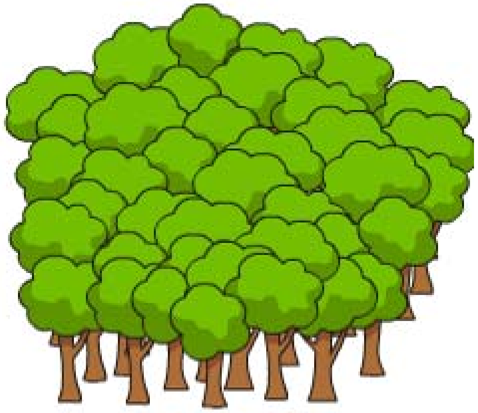
CO2 calculation			
Energy intencity	0,65		kg CO2/kW
CO2 savings	**3.696**		ton
Cars equivalent		28.651.731	km
Trees equivalent		10.903	pcs

4. Calculation example
Carbon footprint

- www.cotoo.com


37,333 tons

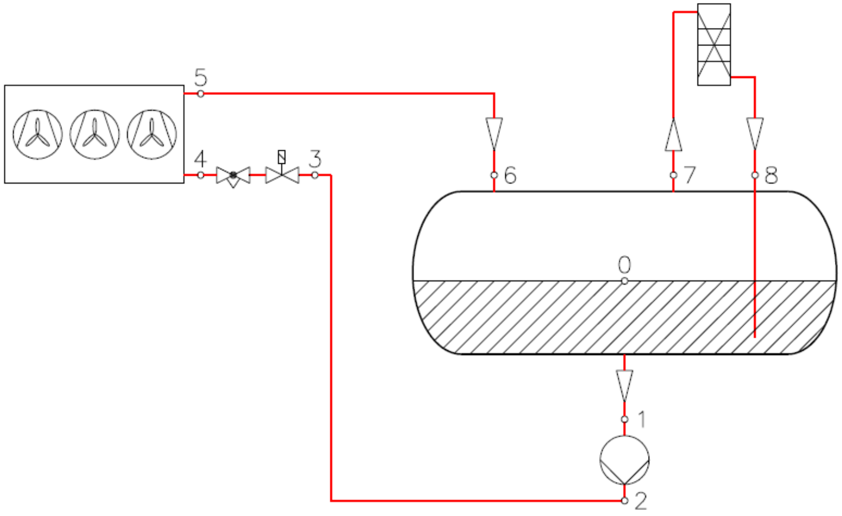

289,403,100 km

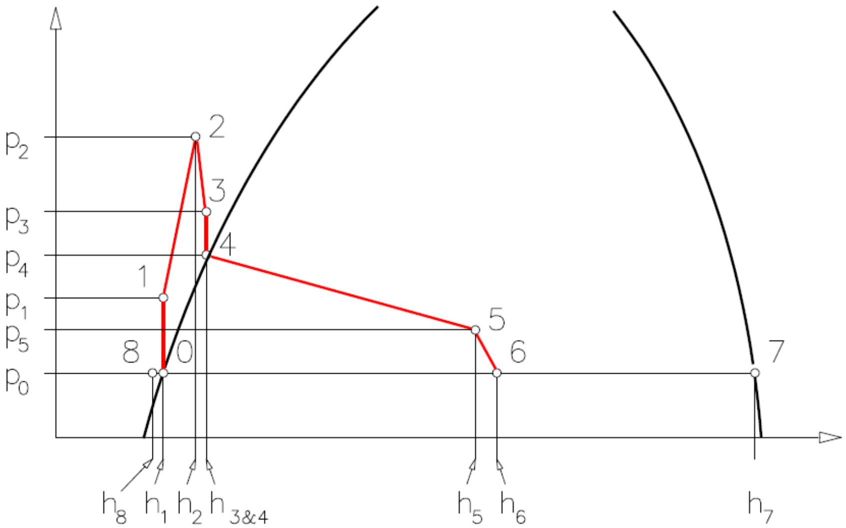

110,127 trees

5. Technical solutions

- CO_2 brine systems are simple, but there are a few aspects that needs to be taken care of:
  - Stand still pressure
  - Cascade heat exchanger control in DX systems
  - Pump control
  - Defrost

5. Technical solutions
process in pumped CO_2 systems





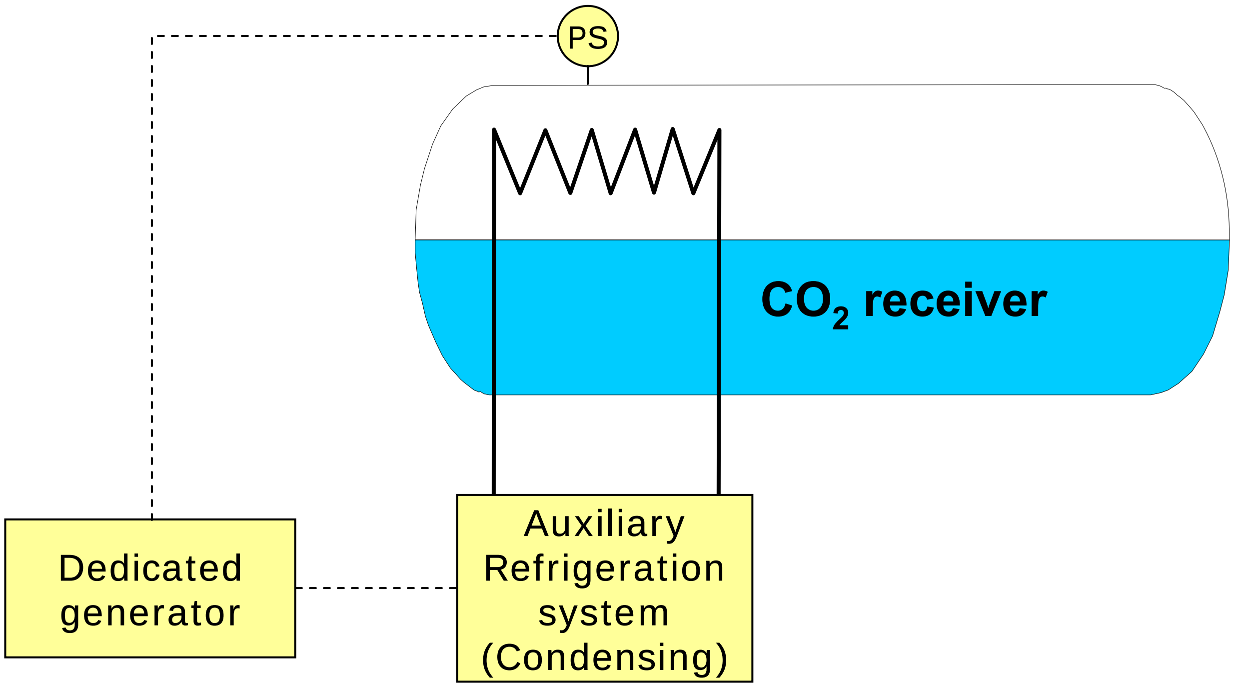
5. Technical solutions

Pressure rating of CO_2 systems

- Typical working pressure between 15 and 35 bar, similar to other refrigerants
- MWP 40-50 bar, depending on defrost
- Stand still pressure could rise up to 85 bar (or even higher) if not taken care of – mitigation is required
- Stand still unit is a simple and cost effective method to address the issue
- Please be careful when using copper piping. MWP of copper pipes could vary a lot depending on the wall thickness

5. Technical solutions

Standstill temperature control

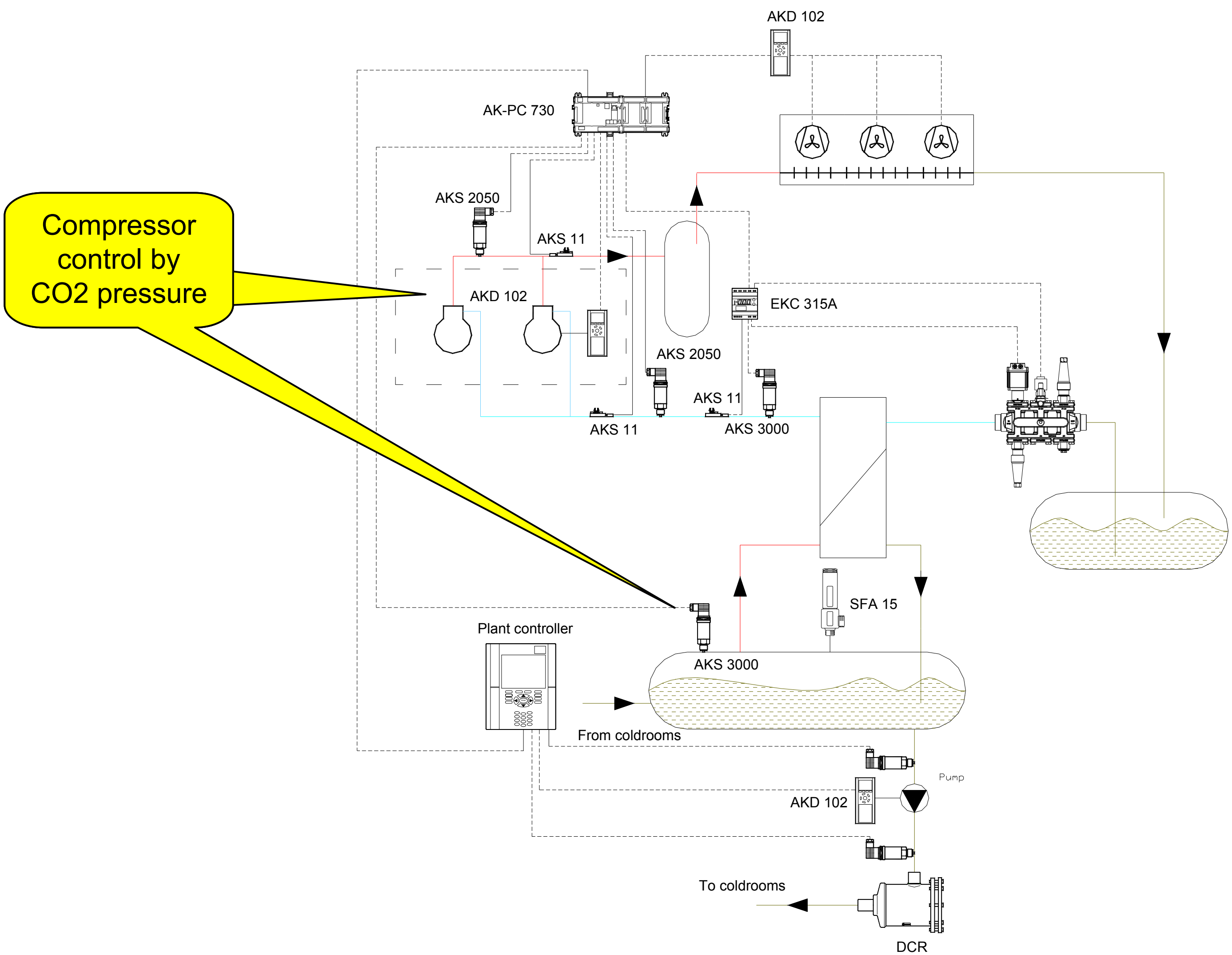


Auxiliary cooling system - in case of power failure

Capacity dependent of system design and ambient temperature (~ 4kW / 1000 kW)

5. Technical solutions

Cascade heat exchanger control



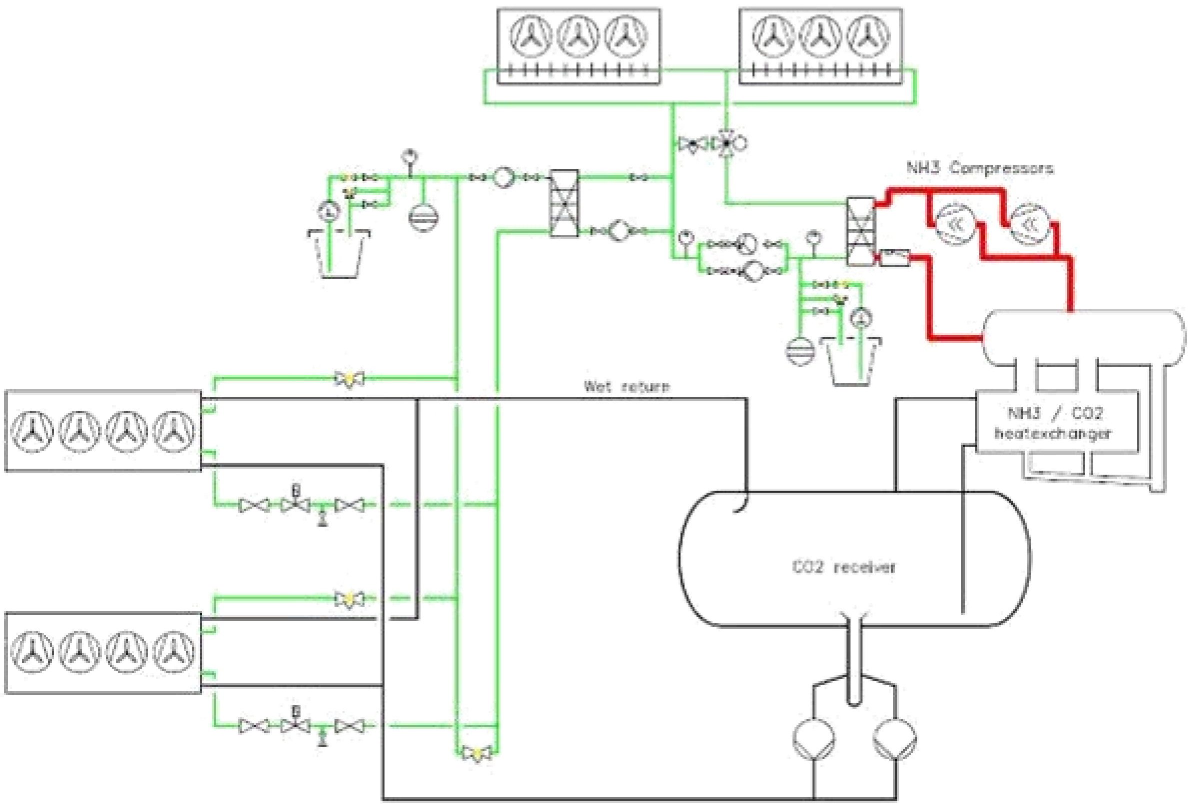
5. Technical solutions
Pump control

- Low circulation rate in CO_2 – 1.1 to 2
- Piping and protection devices are similar to other refrigerants
- Energy consumption of CO_2 pumps is very small, but it is still a good idea to equip them with a frequency converter (especially as it will be a small one):
  - With fixed control devices on evaporators such as REG valves, the flow control and distribution will be much more stable (when pumps are controlled according to the pressure differential, not the head pressure)
  - Still further energy reduction possible. Even a small 2 kW pump running with VLT can save up to 7 MW*h! And that would adds up to the savings from higher evaporating pressure due to more stable operation

5. Technical solutions
Defrost

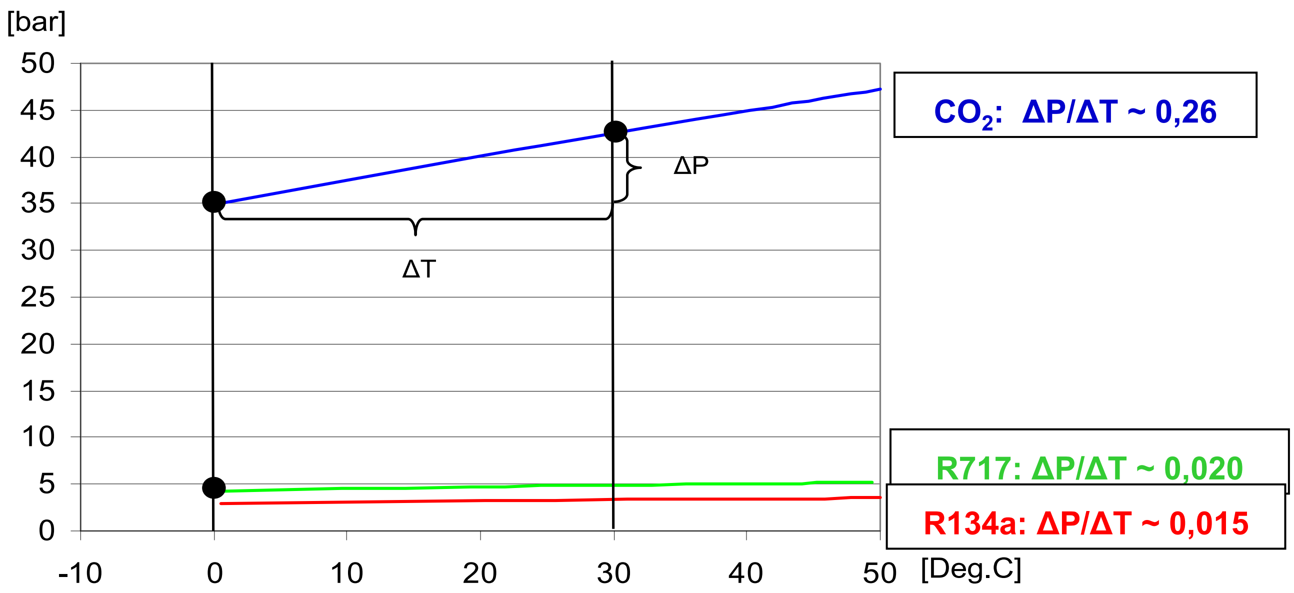
- Most typical defrosts for CO_2 brine systems:
  - Electrical (similar to standard brines)
  - Brine defrost (additional system)
  - Water defrost (drain required)
  - Hot gas defrost (requires additional vessel and HE heated by HP stage)

5. Technical solutions
Defrost – brine (example)



5. Technical solutions
Defrost – considerations

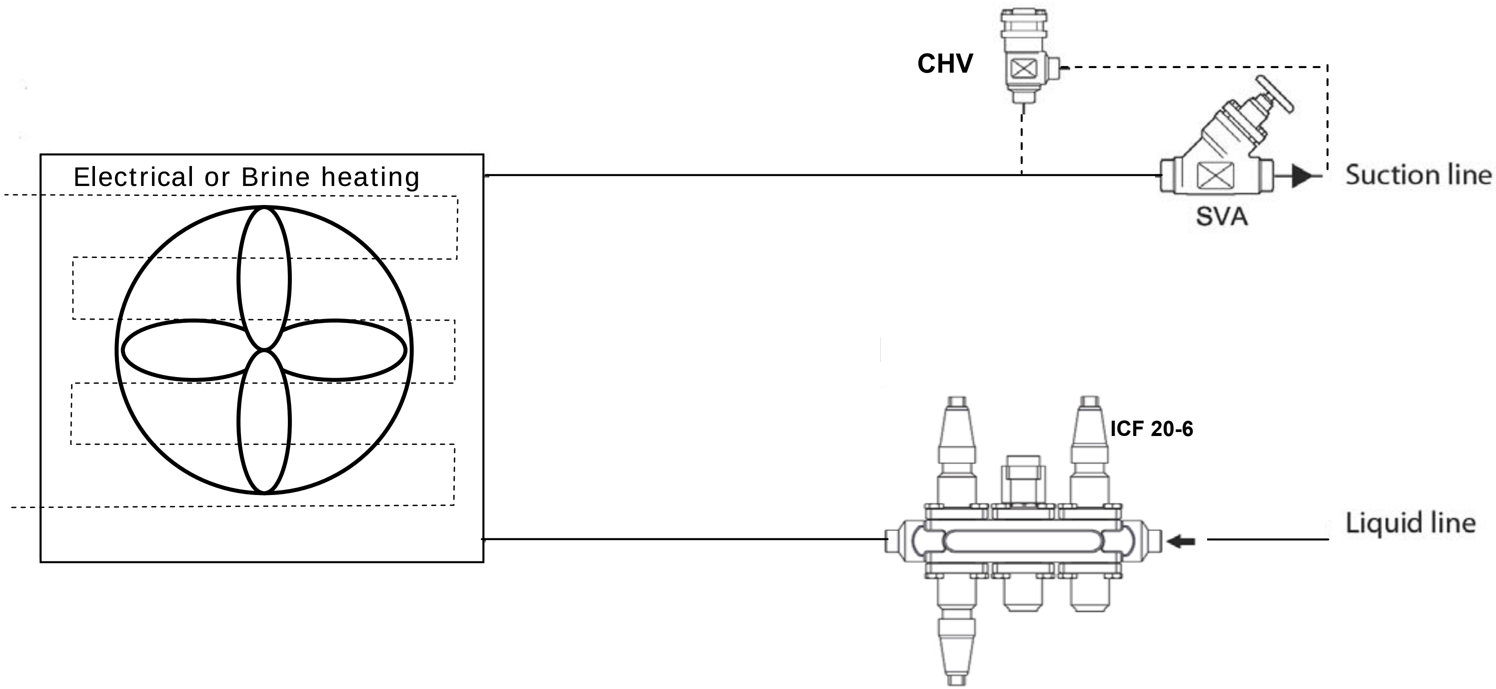
- The pressure rating of the system should correspond to the defrost pressure. It is still possible to have a 40 bar system, but then there must be no liquid CO_2 in evaporators during defrost.



5. Technical solutions

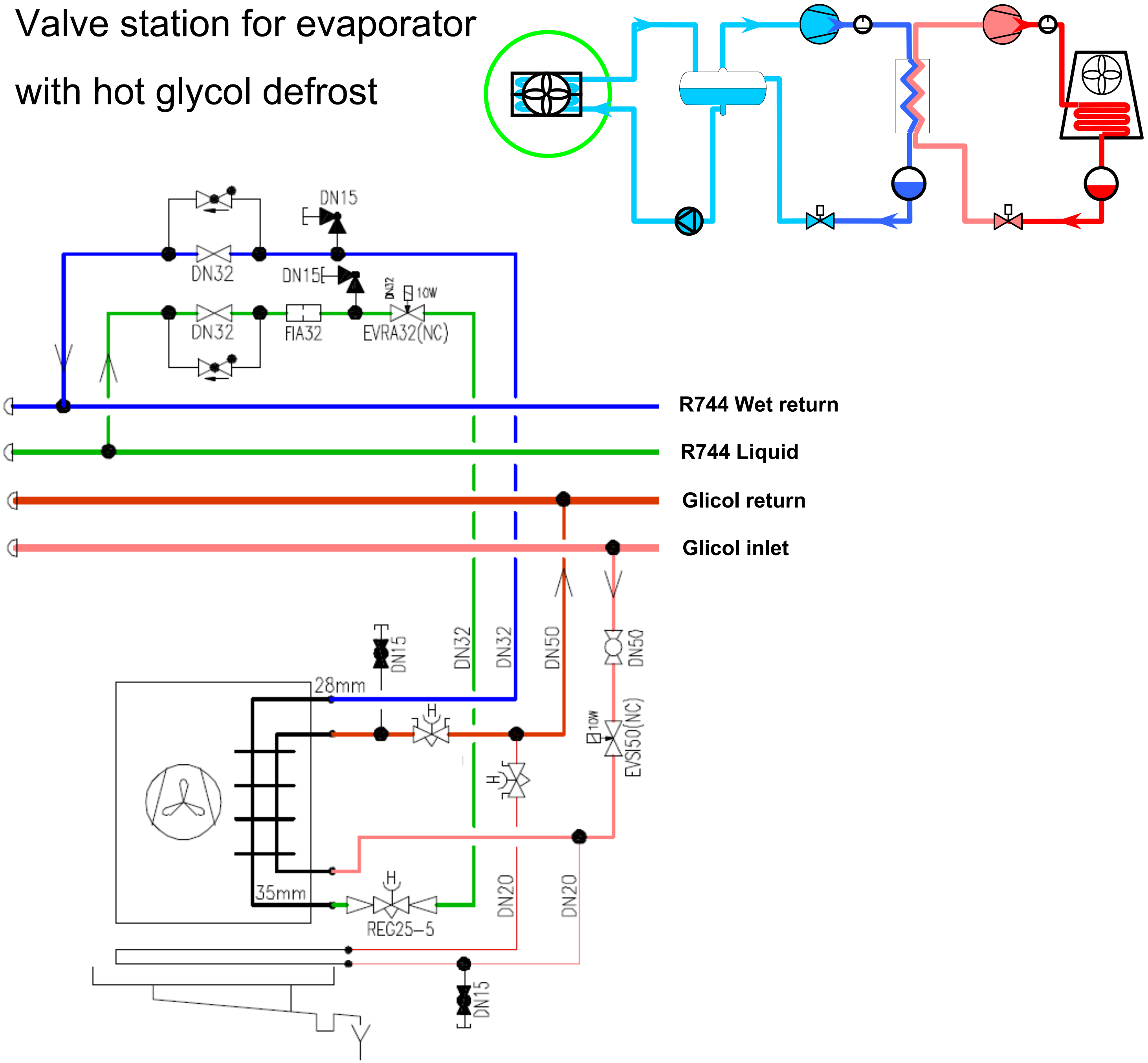
Defrost – considerations

CO2 system with Electrical or Glycol defrosting
(<u>without</u> drained liquid (remaining CO2 need to evaporate))



Design pressure 40 bar (580 psi)

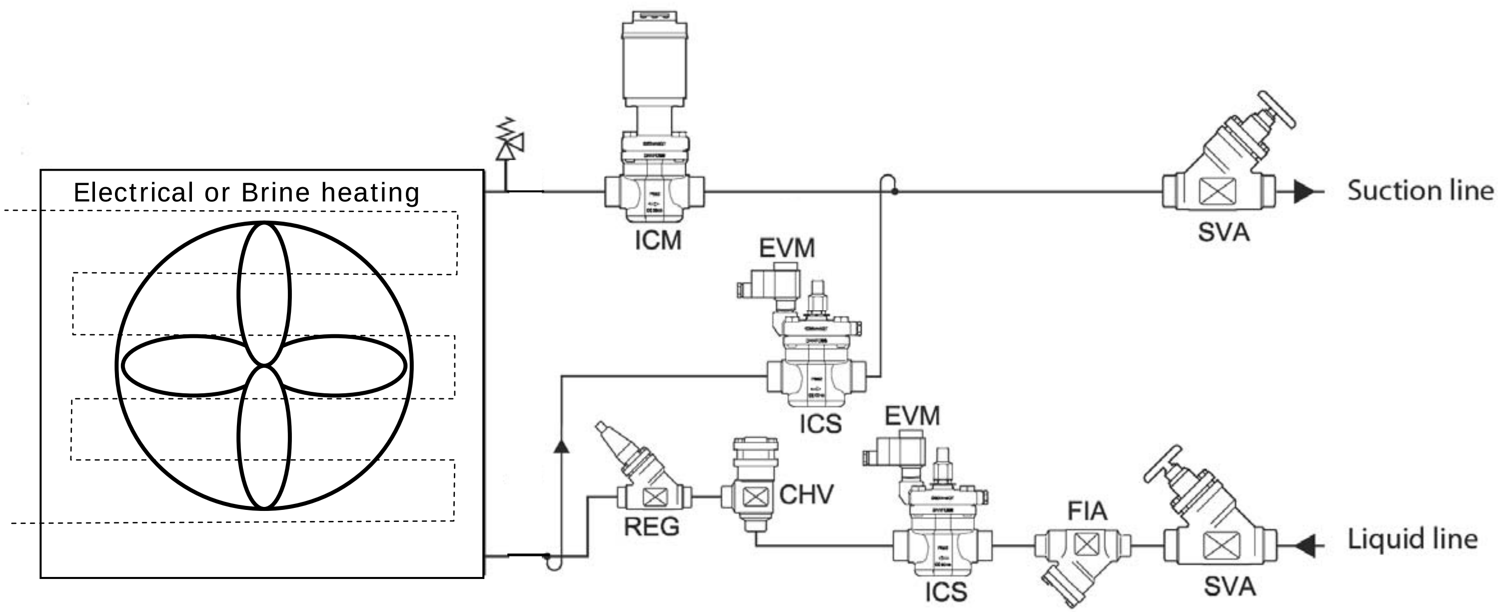
Valve station for evaporator with hot glycol defrost



5. Technical solutions

Defrost – considerations

CO2 system with Electrical or Brine defrosting (drained liquid - 40 bar)

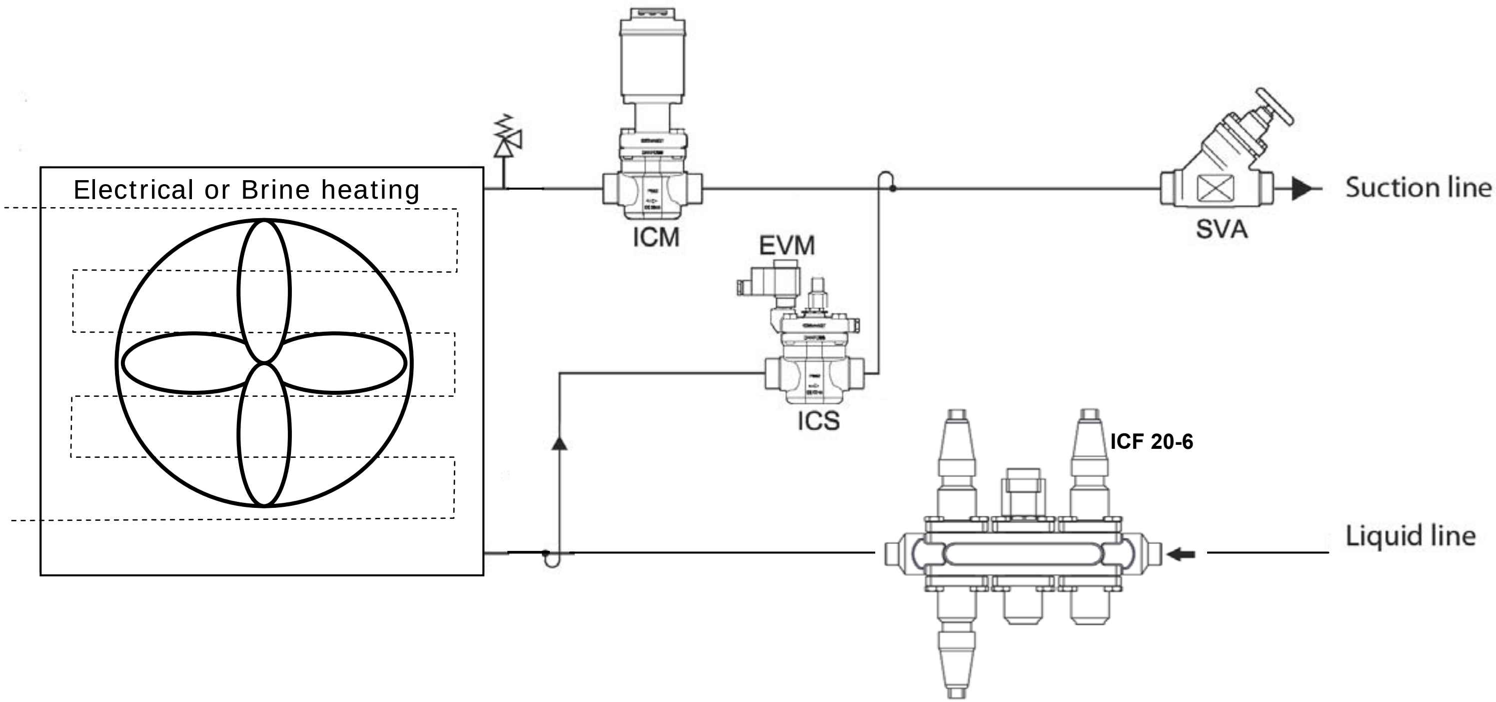


All valve direct coupled (welded)
Design pressure 40 bar (580 psi)

5. Technical solutions

Defrost – considerations

CO2 system with Electrical or Brine defrosting (drained liquid - ICF)



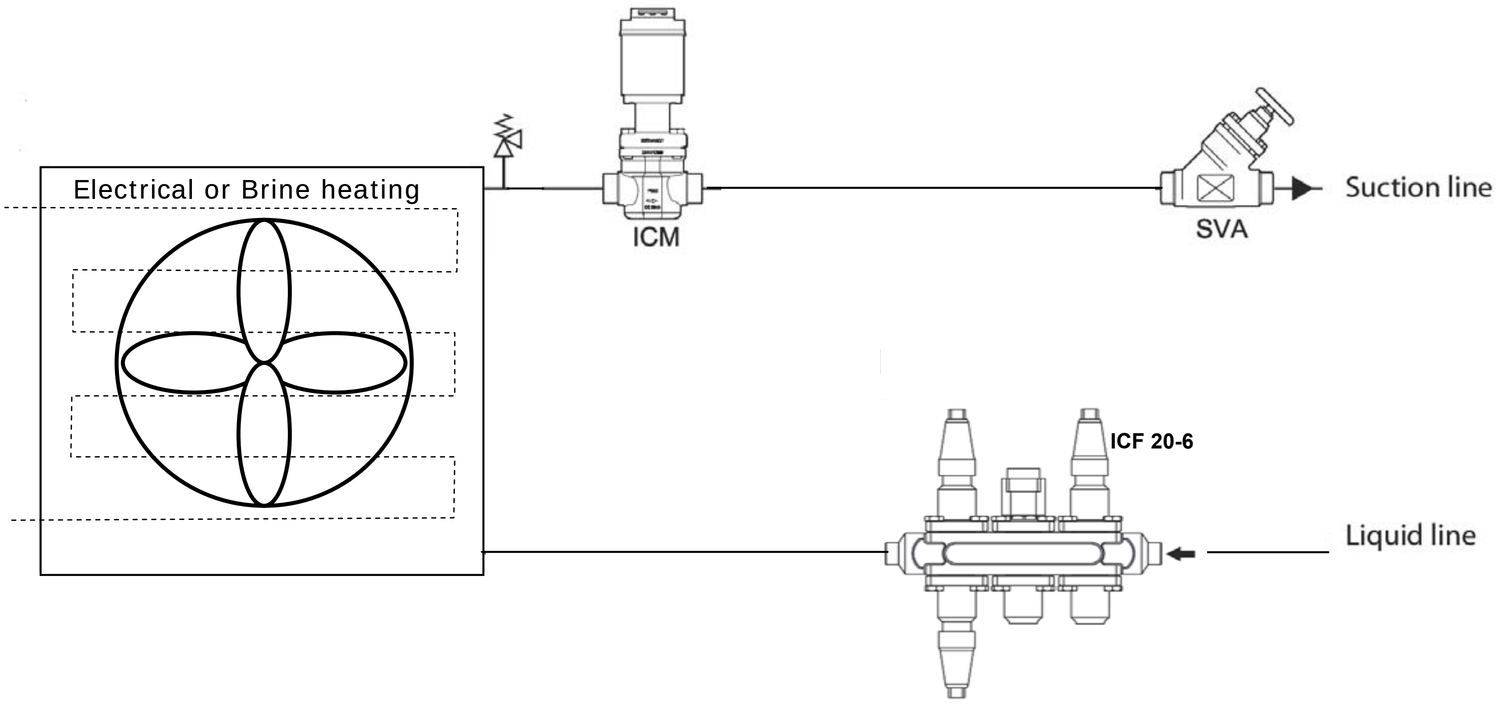
All valve direct coupled (welded)
Design pressure 40 bar (580 psi)

5. Technical solutions

Defrost – considerations

CO2 system with Electrical or Brine defrosting

(<u>without</u> drained liquid (remaining CO2 need to evaporate))



All valve direct coupled (welded)

Design pressure 40 bar (580 psi)

6. Case stories
Canada

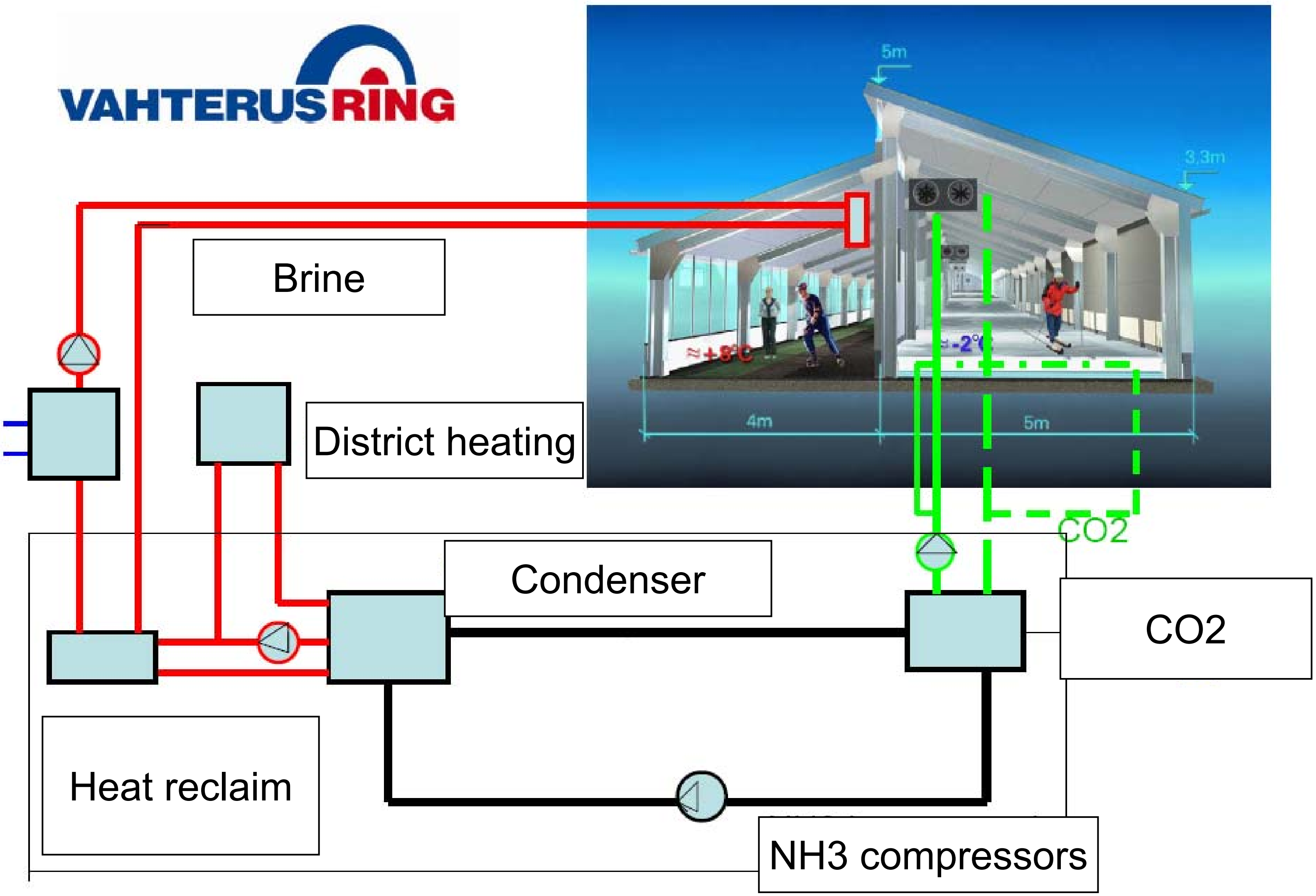
- NH_3 – CO_2 brine systems, both LT and MT
  - Started Spring 2009
  - 4.600 m^2 total area of storage
  - MT: 360 kW, -17^{0}C
  - LT: 130 kW, -28^{0}C
  - Alternative to HFC/Brine solution
  - Variable speed drives on pumps and compressors
  - ICF valves stations for evaporators
  - copper piping

6. Case stories
VahterusRing – Finland (1)

- VAHTERUSRING SKI TUNNEL
- * versatile sports facility
- * ideal conditions around the year
- * cross-country skiing track (-3 °C): Classical and freestyle/skating techniques
- * exercise track (+8 °C in winter): Roller-skating, jogging, Nordic walking
- * 150 metre long lane for athletes
- * curling rink
- * the longest covered building in the Nordic countries
- * modern technology
- DIMENSIOS
- * length 1057 metres
- * width of the ski track 5 metres
- * width of the exercise track 4 metres
- * height differences 16 metres
- TECHNOLOGY
- * CO2 brine system. On the ground there is about 20 km of 15 mm copper tube to keep the ground cold enough
- * There are also several CO2 air oolers to maintain the air temperature at -30C
- * The pumping cost is about 10 -15% compared to traditionally brine systems
- * Ammonia refrigeration system: cooling capacity 400 kW, charge less than 50 kg, heating capacity 150 kW. Vahterus plate and shell heat exchangers
- * Warm brine is used to heat the exercise track and defrosting the air coils in skiing track
- * There is aslo energy efficient ventilation system that is equipped with dehumidification system o minimise the need of defrosting.
-

6. Case stories

VahterusRing – Finland (2)



6. Case stories
Holland – H.M. de Jong

- NH_3 – CO_2 brine systems, fruit storage
  - 20 m high
  - 12,500 pallets
  - Total ground surface area: 13,000m2
  - Hot gas defrost by separate compressors

7. Danfoss products

NH_3/CO_2 brine systems

- NH_3
  - ICM/ICF motorized valves for DX ammonia expansion
  - EKC 315A DX controllers
- CO_2
  - ICF valve stations for evaporators
  - DCR filter driers
  - Line components, both steel, stainless steel (50/52 bar pressure rating) and copper (45 bar pressure rating)
  - Evaporator controllers AK-CC 450
  - Variable speed drives VLT and AKD 102
  - AKV pulse modulating valves – an alternative to fixed setting REG valves

HTEF

$$HTEF = \frac{h}{E^{0.29}} \cdot D^{0.14} = C \cdot c_p^{0.33} \cdot k^{0.67} \cdot \rho^{0.57} \cdot \mu^{-0.52} \qquad (A.15)$$

So HTEF is equal to $\dfrac{Heat\ transfer\ coefficient}{(Pump\ power\ per\ unit\ heat\ transfer\ area)^{0.29}} \cdot Diameter^{0.14}$

It is convenient to operate with a dimensionless HTEF, so HTEF is normalized to water at 10°C:

$$HTEF = \frac{c_p^{0.33} \cdot k^{0.67} \cdot \rho^{0.57} \cdot \mu^{-0.52}}{\left(c_p^{0.33} \cdot k^{0.67} \cdot \rho^{0.57} \cdot \mu^{-0.52}\right)_{water,10}} \qquad (A.16)$$

or

$$HTEF = \frac{c_p^{0.33} \cdot k^{0.67} \cdot \rho^{0.57} \cdot \mu^{-0.52}}{176.74} \qquad (A.17)$$