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CO_2 as a working fluid

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Content

CO_2 in a HSE perspective

- CO_2 is **not acutely toxic** at low concentrations. Bodily reactions (difficulties breathing, increased pulse, headache, etc.) appear when the concentration exceeds 2-3 %. Concentrations above 10 % can be lethal.
- Similar to the traditional high GWP*-HFCs, **CO_2 has the ASHRAE safety classification A1** (non-flammable, non-toxic).
- High operational pressure (up to 130 bar).
- Dry ice formation can appear at pressures < 5.2 bar (triple point pressure), which can block valves and pipes. Important with sufficient routines regarding refilling and service of CO_2 systems.
- Dry ice at atmospheric pressure is very cold (~ -78 ℃) and can cause:
  - Brittle fractures in equipment
  - Frostbite injury

* GWP = global warming potential

INFLUENCES ON THE HUMAN BODY

PPM	EFFECTS ON HEALTH
400	Average value in the atmosphere
< 800	EN13779: Good indoor air quality
5000 (0.5 Vol-%)	Maximum Workspace Concentration (MAK) Threshold Limit Value, 8 hours, weighted average
10,000	Short Time Exposure Limit (Germany) 60 min, 3 times per shift
20,000	50% increase in breathing rate! Can affect the respiration function & cause excitation followed by depression of the central nervous system
30,000	100% increase in breathing rate after short term exposure
50,000	Immediate Danger to Life or Health (IDLH) "Escape" after exposure time of 30 min without irreversible health effects
100,000	Lowest lethal concentration Few minutes exposure produces unconsciousness
200,000	Death accidents have been reported
300,000	Quick results in unconsciousness & convulsions

CO_2 in a HSE perspective

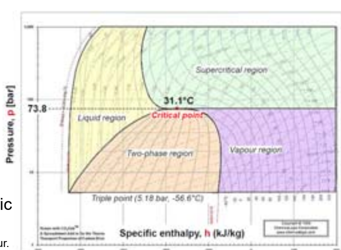
- CO_2 is a natural and environmentally friendly working fluid:
  GWP = 1 (0)*, ODP = 0

Refrigerant	Component(s)	Classification	Concentration limit kg/m³	GWP
R-744	Carbon dioxide	A1	0.1	1*
R-22	Chlorodifluoromethane	A1	0.3	1810
R-23	Trifluoromethane	A1	0.68	14800
R-125	Pentafluoroethane	A1	0.37	3500
R-134a	Tetrafluoroethane	A1	0.21	1430
R-404A	R-125/R-143A/R-134a	A1	0.52	3920
R-407C	R-32/R-125/R-134a	A1	0.31	1770
R-407F	R-32/R-125/R-134a	A1	0.32	1820
R-408A	R-125/R-143a/R-22	A1	0.41	3150

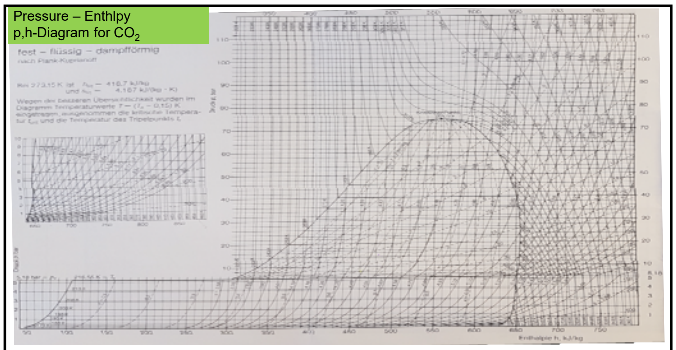
*No formation of CO_2 when used as a working fluid

Fundamental fluid properties

- Low critical temperature (T_C = 31.1℃)
  - 28℃: Practical upper limit for condensation
  - Heat rejection at supercritical pressures except at very low heat sink temperatures
- High critical pressure (73.8 bar)
- High pressures compared to other working fluids
  - Typically 5 to 10 times higher than for HFC
  - Relatively low pressure ratio (P_{gc}/P_E)
- Triple point pressure above atmospheric pressure (5.18 bar)
  - Equilibrium between 3 phases: Solid, liquid and vapour.
  - Sublimation: Dry ice does not melt but rather evaporates. Sublimation temperature at atmospheric pressures for solid CO_2 is -78.5 ℃



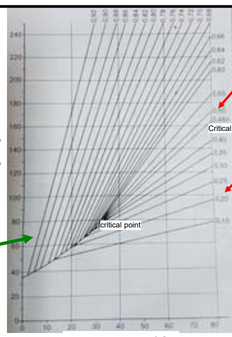
Pressure – Enthlpy
p,h-Diagram for CO_2



Phase diagram for CO_2
Danfoss Video

search on youtube

Consequences of charge



Isochoric lines:
equal density [kg/dm³]

Consequences of high operational pressure

LP=Low pressure, MP=mid-pressure, HP= high pressure

LP-side, frys [bar]	LP-side, kjøl [bar]	HP-side, underkritisk [bar]	MP-side, transkritisk [bar]	HP-side, transkritisk [bar]	Varmgass-avriming [bar]
26/41/61/(81)	41/61/(81)	41	80-90	80-120	53

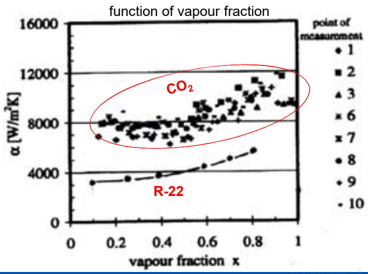
- Dimensioning of equipment is done according to the specific pressures in CO_2 system
- Not economical to dimension all equipment in the system for maximum pressure
- Much smaller dimensions for pipelines and valves –mainly due to low viscosity and very low $\Delta t/\Delta p$
- **20-40 % lower weight of pipelines despite higher wall thickness**

Type of system	Direct expansion (DX) system with R404A	Direct expansion (DX) with CO_2
Suction pipe line, return	76/102mm	42/68mm
Liquid line	35mm	22/48mm
Surface ratio	100 % (reference)	60 %

Heat transfer properties of CO_2

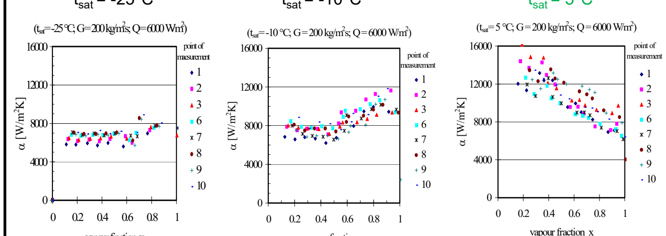
- High conductivity
- High specific heat capacity

Measured heat transfer coefficient as a function of vapour fraction



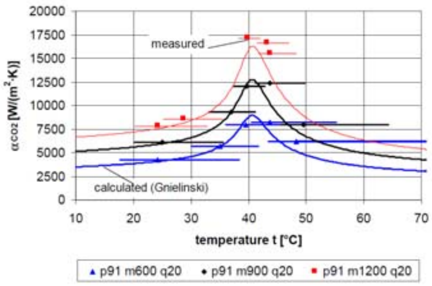
Influence of varying saturation temperature

t_{sat} = -25°C t_{sat} = -10°C t_{sat} = 5°C



+5 °C, → completely new variation, where the heat transfer is decreasing constantly; from a very high value of around 14.000 W/m²K at vapour fraction 0.2, to a value around 8.000 W/m²K near to 1.0.

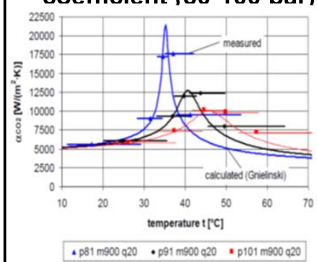
Heat transfer at various mass fluxes [kg/(m²s)]



The influence of the mass flux on the heat transfer coefficient of CO_2 is significant.
If the mass flux is increased from 600 to 900 kg/(m²s) the calculation as well as the measurement show a rise in the heat transfer coefficient of about 40%, and a rise of about 80% if the mass flow is increased to **1200 kg/(m²s).**

The peak in the graph indicates the pseudocritical temperature. At 91 bar the maximum c_p is located at 40.6°C.

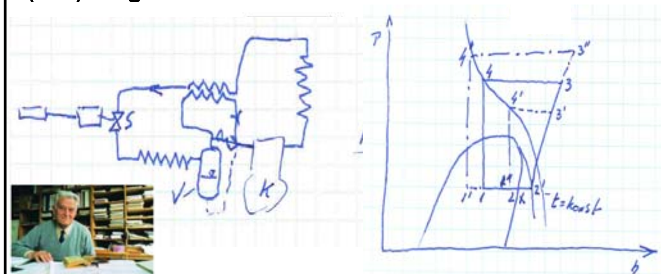
Influence of the pressure on the heat transfer coefficient (80-100 bar)



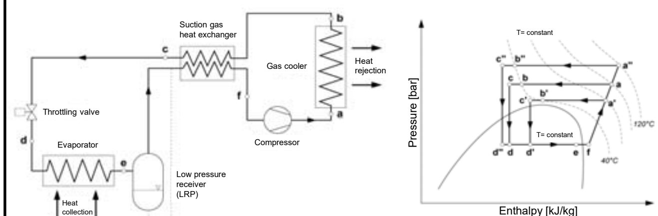
Since the heat transfer coefficient reaches a maximum at the pseudocritical temperature, this maximum will change with varying pressure. As may be observed, **the maximum heat transfer coefficient increases when the pressure approaches the critical pressure of CO_2** (73.8 bar).

For a mass flux of 900 kg/(m²·s) and a heat flux of 20 kW/m², the **peak heat transfer coefficient is about 21,000 W/(m²K)** for a pressure of **81 bar**, and about 10,000 W/(m²K) at 101 bar. This corresponds to a more than 100% rise when the pressure is decreased from 101 to 81 bar. An increase of the pressure from 91 to 101 bar leads to a drop of the maximum heat transfer coefficient of about 20%. A more or less negligible influence of the pressure on the heat transfer coefficient can be seen in case of temperatures "far away" from the pseudocritical value, i.e. at rather low or high temperatures. This is visualised by the asymptotic approach of the curves below 25°C and above 70°C. Again, the deviation between measurement and calculation was small.

Transcritical process in the Pressure-enthalpy (P-h) diagram

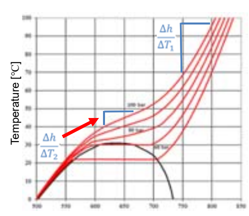


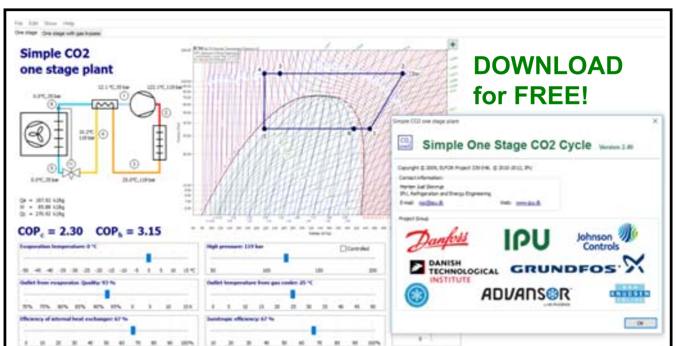
Transcritical process in the Pressure-enthalpy (P-h) diagram



Temperature change in the gas cooler

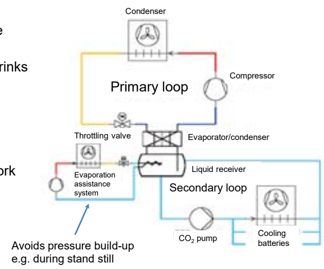
- Cooling of CO_2 in the gas cooler follows the constant pressure lines at gliding temperatures
- The specific heat ($c_p = \frac{\Delta h}{\Delta T}$) is not constant, as ΔT is not proportional with Δh
- The shape of the temperature glide is essential in regards to gas cooler dimensioning





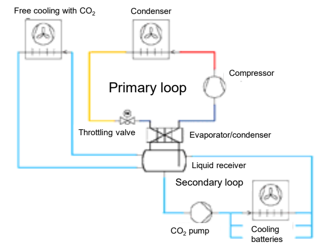
CO_2 as an evaporating secondary fluid

- Application:
  - Subcritical CO_2 system with NH_3 in the primary loop
  - Supermarkets, industrial freezers, ice rinks
- Advantages:
  - Flooded evaporator
  - Oil free CO_2 loop
  - High chiller efficiency
  - Smaller pipe dimensions and pump work compared to glycol circuits
- Disadvantages:
  - Complicated
  - Expensive



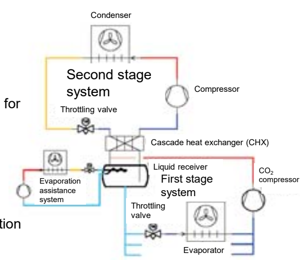
CO_2 as an evaporating secondary fluid

- Free cooling loop included
- System must be dimensioned for standstill pressure (→ No evaporation assistance system!)



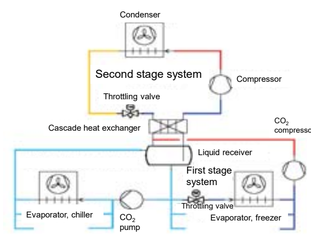
CO_2 in a conventional cooling process - cascade systems

- Application:
  - Two separate refrigeration units
  - First stage subcritical CO_2 system
  - Second stage system with a working fluid suitable for heat rejection (NH_3, propane (R290), etc.)
  - Utilized in supermarkets pre-transcritical cycle
- Advantages:
  - Energy efficient process
  - Small operational cost
  - The indirect system provides NH_3 leakage precaution
- Disadvantages:
  - Problematic if the second stage system is inactive
  - Challenging to regulate the CHX at small capacities without variable speed drive



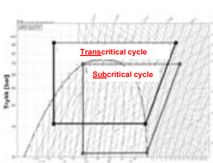
CO_2 in a conventional cooling process - cascade systems

- Application:
  - Large facilities with need for refrigeration at several temperature levels
- Advantages:
  - Flooded chiller evaporator
  - Compact
- Disadvantages:
  - Expensive
  - The CO_2 system fully relies on the second stage system for condensation



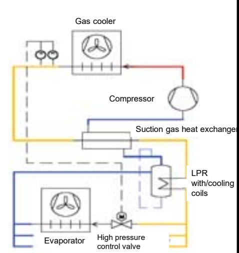
Transcritical CO_2 process: Important considerations

- Gas cooler pressure
- Placement of receivers
- Single vs. several throttling steps
- Mid pressure control
  - Dual throttling steps



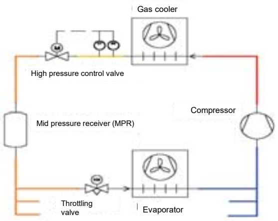
Transcritical CO_2 process with low-pressure receiver

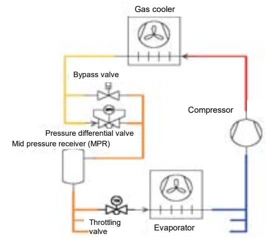
- Application:
  - Single throttling step
  - Smaller installations
  - Suppliers: Norild, Sanyo, Denso, Gree&Cool, etc.
- Advantages:
  - LRP enables flooded evaporation
  - High suction pressure than with TEV
  - Lower vapour quality before throttling due to the suction gas heat exchanger
- Disadvantages:
  - Single evaporator
  - Oil boil-off
  - Slow start-up due to liquid accumulation in LPR



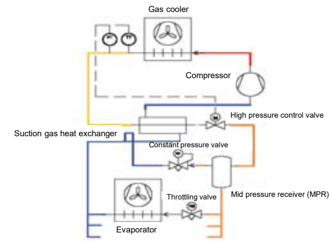
Transcritical CO_2 process with mid-pressure receiver

- Application:
  - Two throttling steps
  - Simple regulated systems
- Advantages:
  - Uncomplicated transcritical process
  - No connection between gas cooler pressure and feed to evaporator
- Disadvantages:
  - Superheat at evaporator outlet
  - Oil boil-off
  - Slow start-up due to liquid accumulation in MPR





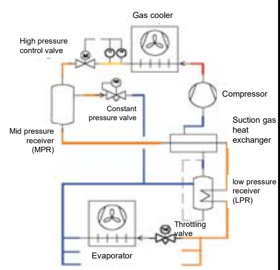
Regulation of gas cooler pressure by constant pressure difference – Passive mid pressure regulation



Active regulation of receiver pressure with flash gas bypass through constant pressure valve

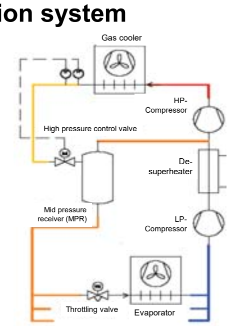
Transcritical CO_2 process with low and mid-pressure receivers

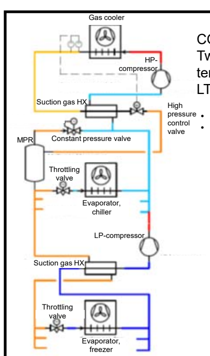
- Benefits from both LPR and MPR
  - Flooded evaporator
  - Enables higher suction pressure
  - No connection between gas cooler pressure control and feed to evaporator



Transcritical two stage compression system

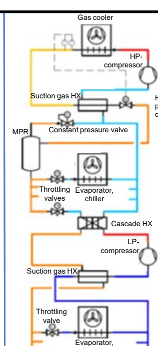
- Application:
  - Two stage compression and throttling
  - Hot water heat pumps
  - Industrial freezing applications
- Advantages:
  - Robust and well developed
  - Standard components and regulation
  - Strong competitor to NH_3 systems in the industry
  - Well known and applicable all over the world
- Disadvantages:
  - When gascooler outlet temperature is above 25℃





CO_2 booster system
Two evaporation temperature levels
LT & MT

- Smaller investment cost
- Higher efficiency

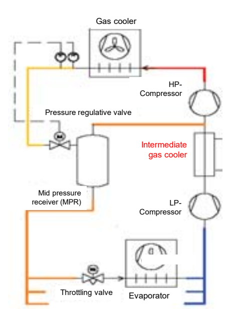


Cascade CO_2 booster system

- Avoid problems due to oil-return
- Possible to utilize oil of different viscosities for chiller and freezer evaporators

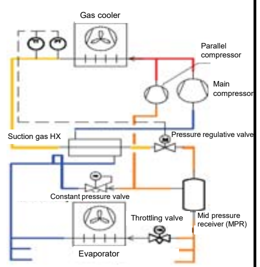
Intermediate gas cooler

- Advantages:
  - Reduces HP-compressor suction gas temperature
  - Reduction in HP-compression work: Increase in compressor capacity of 0.5 % per K reduction in suction gas temperature
- Disadvantages:
  - Extra gas cooler cycle necessary
  - Suitable temperature level of heat sink



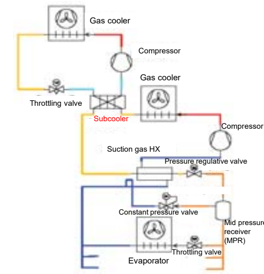
Parallel compression

- Direct compression of flash gas from the MPR in preference to fluid expansion to meet main compressor suction pressure
- Advantages:
  - 10-15 % increase in COP
  - Seasonal deployment of parallel compressor
- Disadvantages:
  - Extra investment costs
  - Higher degree of complexity



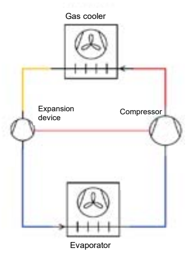
Subcooling

- Direct compression of flash gas from the MPR in preference to fluid expansion to meet main compressor suction pressure
- Advantages:
  - 1-2 % increase in COP per K internal subcooling
  - 2-4 % increase in COP per K with external subcooling
  - Can handle high return temperatures
- Disadvantages:
  - Extra investment costs
  - Higher degree of complexity



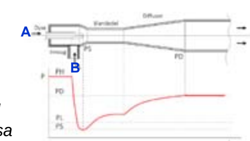
Expansion work recovery

- High CO_2 gas cooler outlet temperature results in large throttling losses
- Great advantage to utilize expansion work to reduce compression work



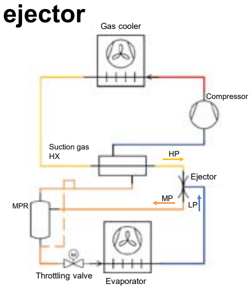
Expansion work recovery with ejector

- "Jet pump"
- No work required – "Free" pressure lift
- No moving parts: easy to install, operate and maintain
- Bernoulli's Principle: *When the speed of a fluid increases its pressure decreases and vice versa*
  - ***High pressure fluid enters the nozzle (A) where pressure energy is converted to kinetic energy. Fluid at low pressures (B) is sucked into the nozzle and the two streams are mixed. The pressure further increases in the diffuser as the velocity of the stream decreases.***



Expansion work recovery with ejector

- Pressure lift from LP to MP
- Ensures continuous fluid stream through evaporator
- Pressure lift: 10-15 bar
- COP increase of up 17%
- Ejector efficiency of 30% under optimum operational conditions



Ejector systems

- Multi Ejectors
  - Liquid (→ flooded evaps)
  - Vapour (→ boost parallel compressors)
- **Always flooded evaps**. -> +10% in COP
- Pressure lift: 10-15 bar
- COP increase of up 17%
- Ejector efficiency of 30% under optimum operational conditions