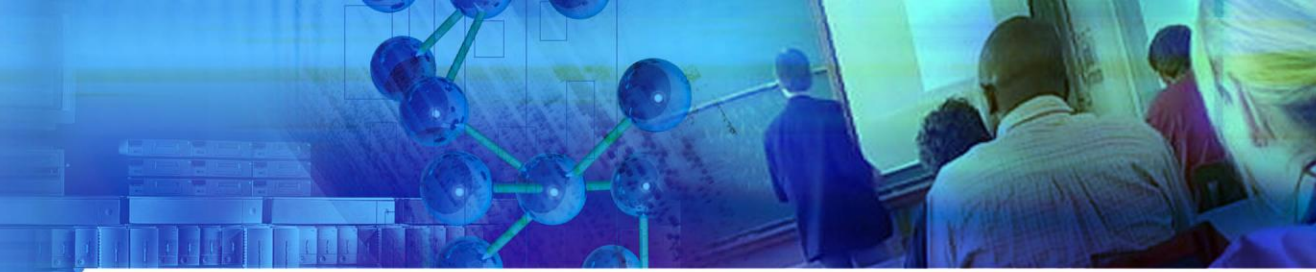

# $CO_2$ in vapor compression systems

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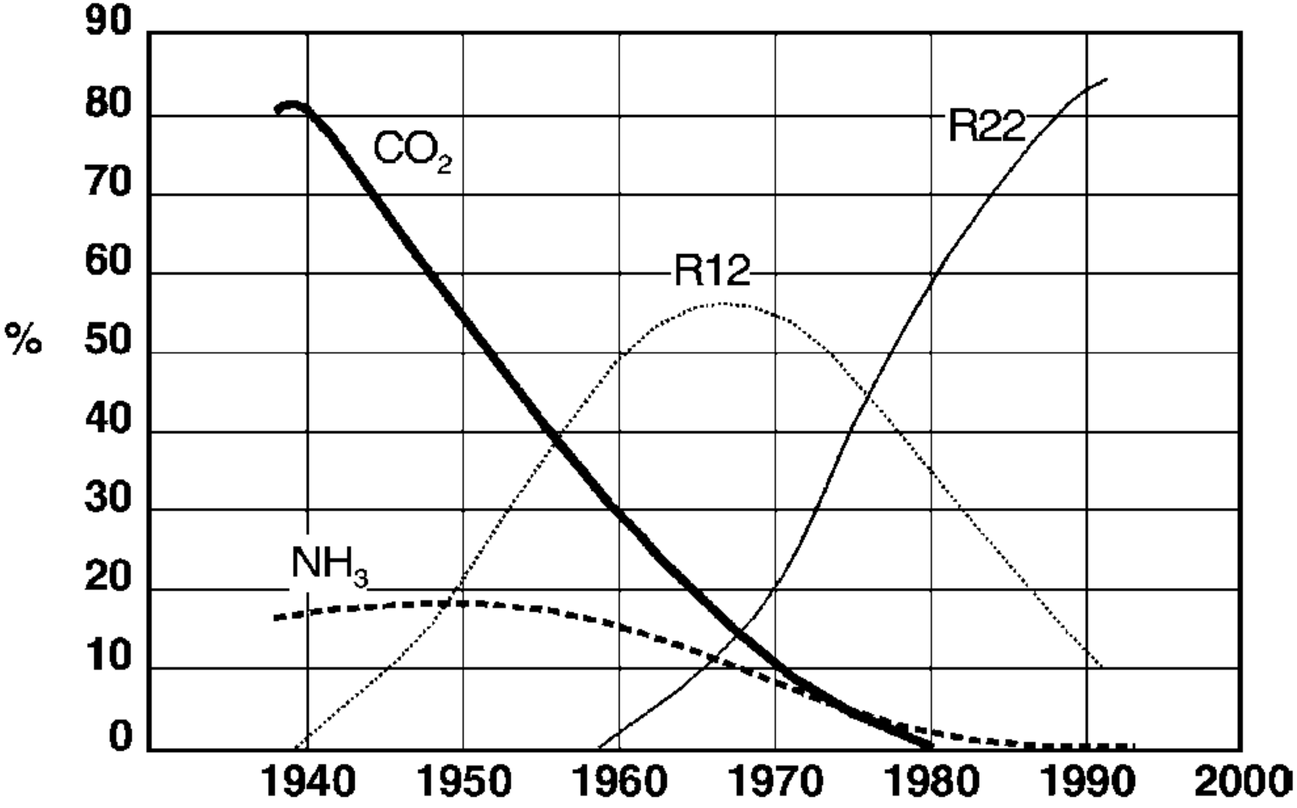
# Contents

# Why use $CO_2$ ? (1/3)

- In the past, $CO_2$ has been widely used as refrigerant until 1940, before CFC’s were discovered. It was used mainly in marine systems and in building air conditioning. The second big refrigerant at that time was ammonia ($NH_3$).
- $CO_2$ was replaced by CFC’s and HCFC’s after World War II thanks to their easy use (no toxicity, lower pressures, etc.)

# Why use $CO_2$ ? (2/3)



Primary refrigerants in existing marine cargo installations

# Why use $CO_2$ ? (3/3)

- Since 1990, ban of CFC's, decrease of use of HCFC's because of their ODP
- Future ban of HFC's ? (R134a, etc.) because of their GWP
- Which refrigerants for tomorrow ? New interest for natural fluids : $H_2O$, $NH_3$ ,$CO_2$ instead of search for new refrigerants

| | R-12 | R-22 | R-134a | R-407C | R-410A | NH3 | Propane | CO2 |
|---|---|---|---|---|---|---|---|---|
| ODP | 1 | 0,05 | 0 | 0 | 0 | 0 | 0 | 0 |
| GWP | 8500 | 1700 | 1300 | 1600 | 1900 | 0 | 3 | 1 |
| Flammability | N | N | N | N | N | Y | Y | N |
| Toxicity | N | N | N | N | N | Y | N | N |

# $CO_2$ transcritical cycle – Introduction (1/8)

- $CO_2$ is different from conventional refrigerants :

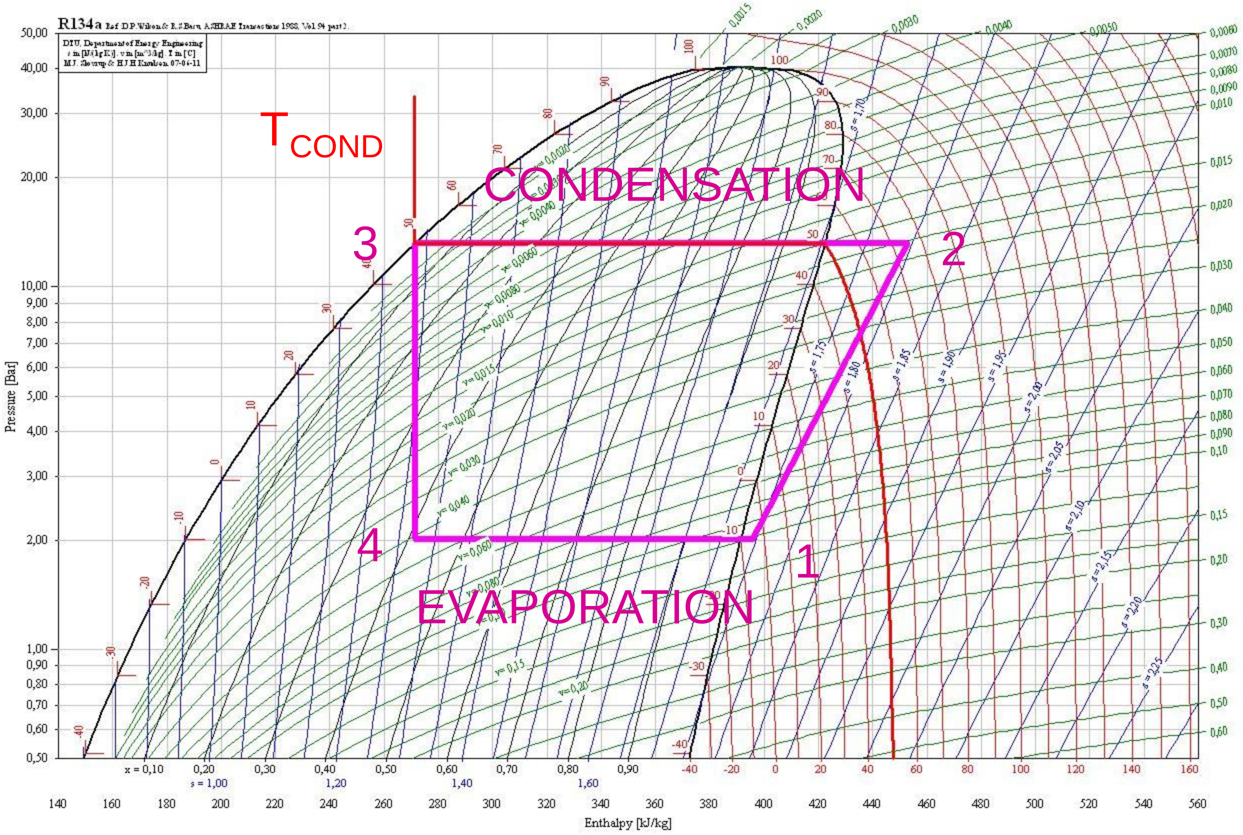
1) $CO_2$ has different thermodynamic properties :

- High gas densities, close to liquid densities
- $T_{CRIT}$ = 31.1 °C, $P_{CRIT}$ = 73.8 bar : no condensation above 31.1 °C, the thermodynamic cycle is then transcritical : the high pressure heat exchanger is not a condenser but a gas cooler

# $CO_2$ transcritical cycle – Introduction (2/8)

- Conventional cycle (Rankine) (R134a) :

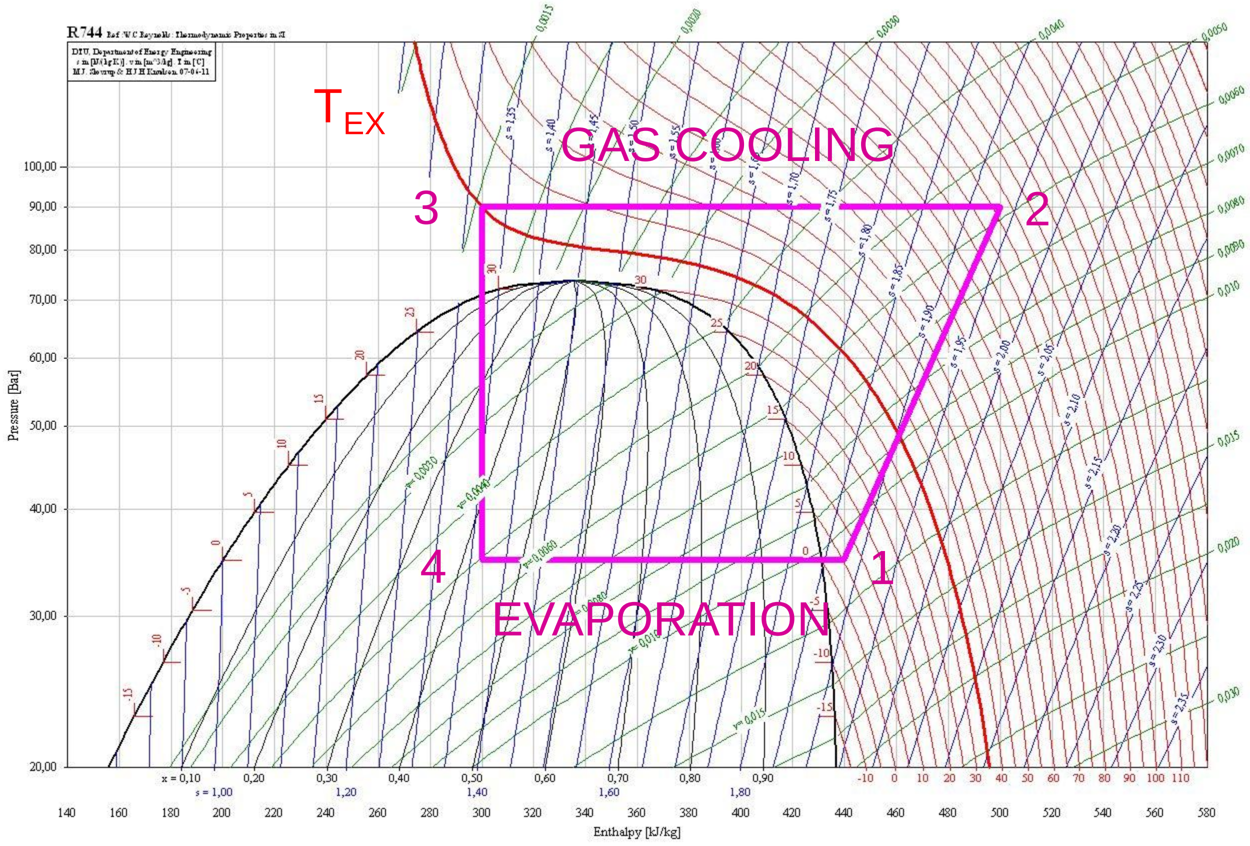
- High pressure is a function of the condensation temperature : 1 degree of freedom



# $CO_2$ transcritical cycle – Introduction (3/8)

- $CO_2$ transcritical cycle :

\- High pressure and temperature are independent : 2 degrees of freedom (HP, $T_{EX}$)



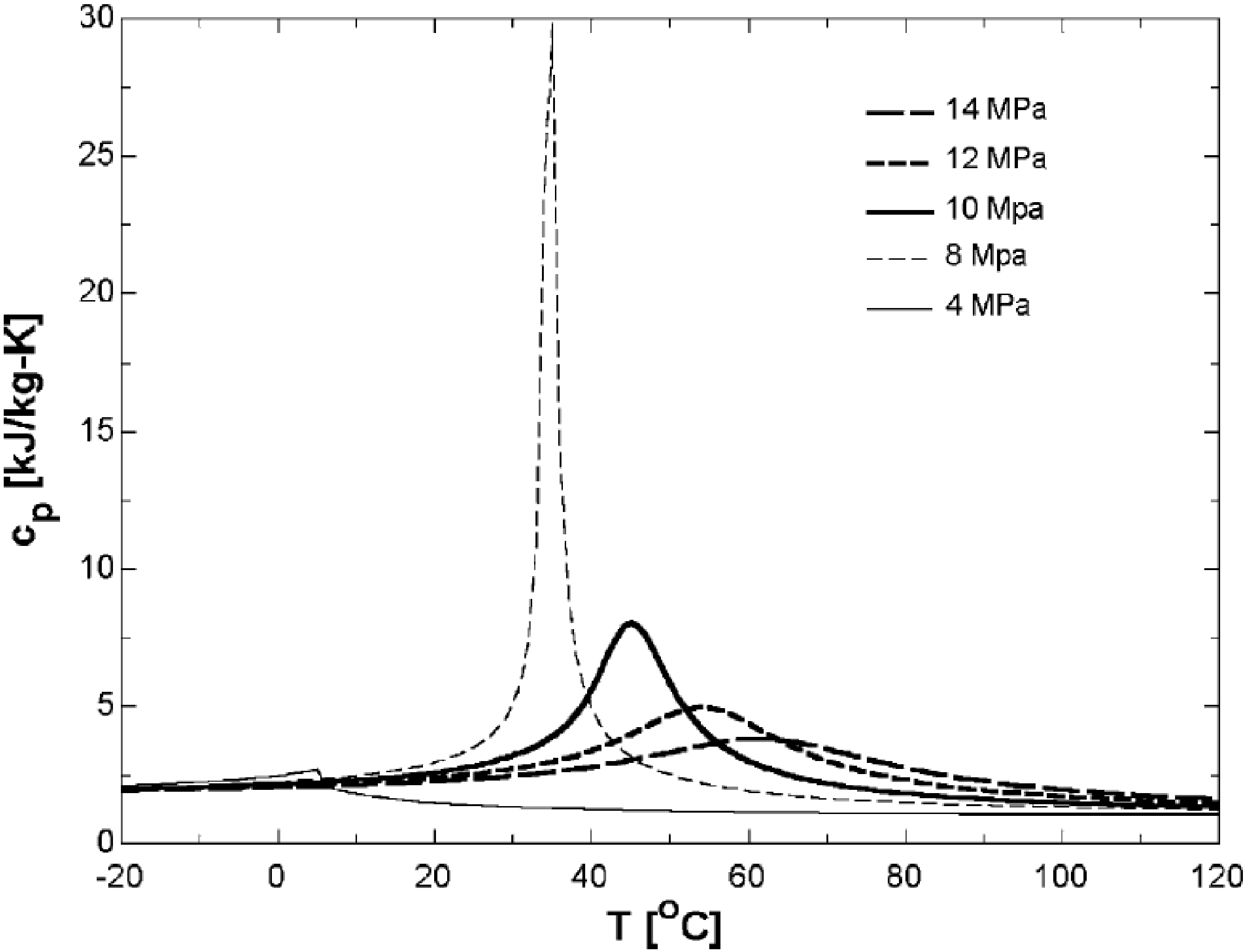
# $CO_2$ transcritical cycle – Introduction (4/8)

- $CO_2$ is different from conventional refrigerants :

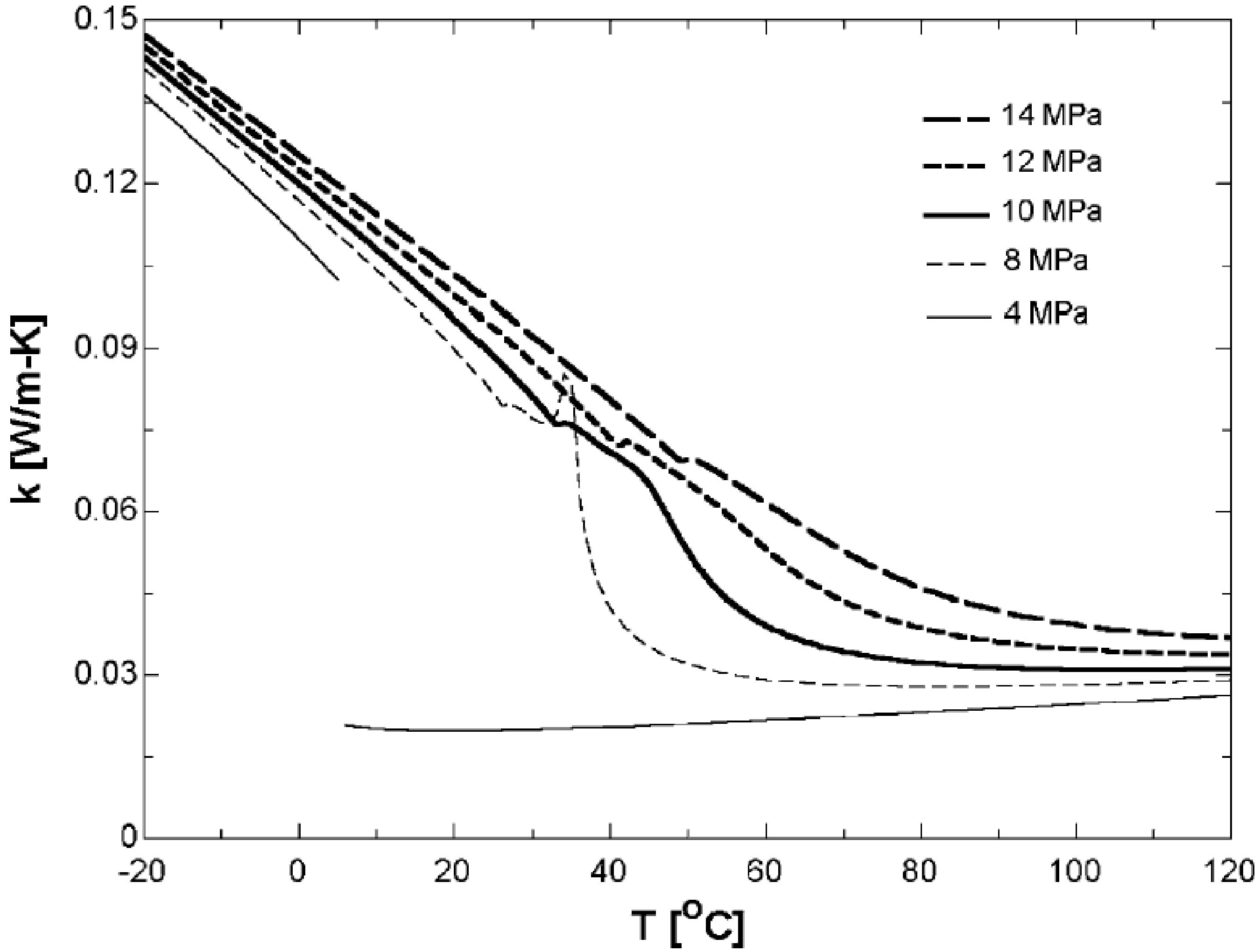
2) $CO_2$ physical properties change rapidly with pressure in supercritical state :

- design of heat exchangers more complicated
- $\varepsilon$-NTU method not easily used ($c_p$ not constant)

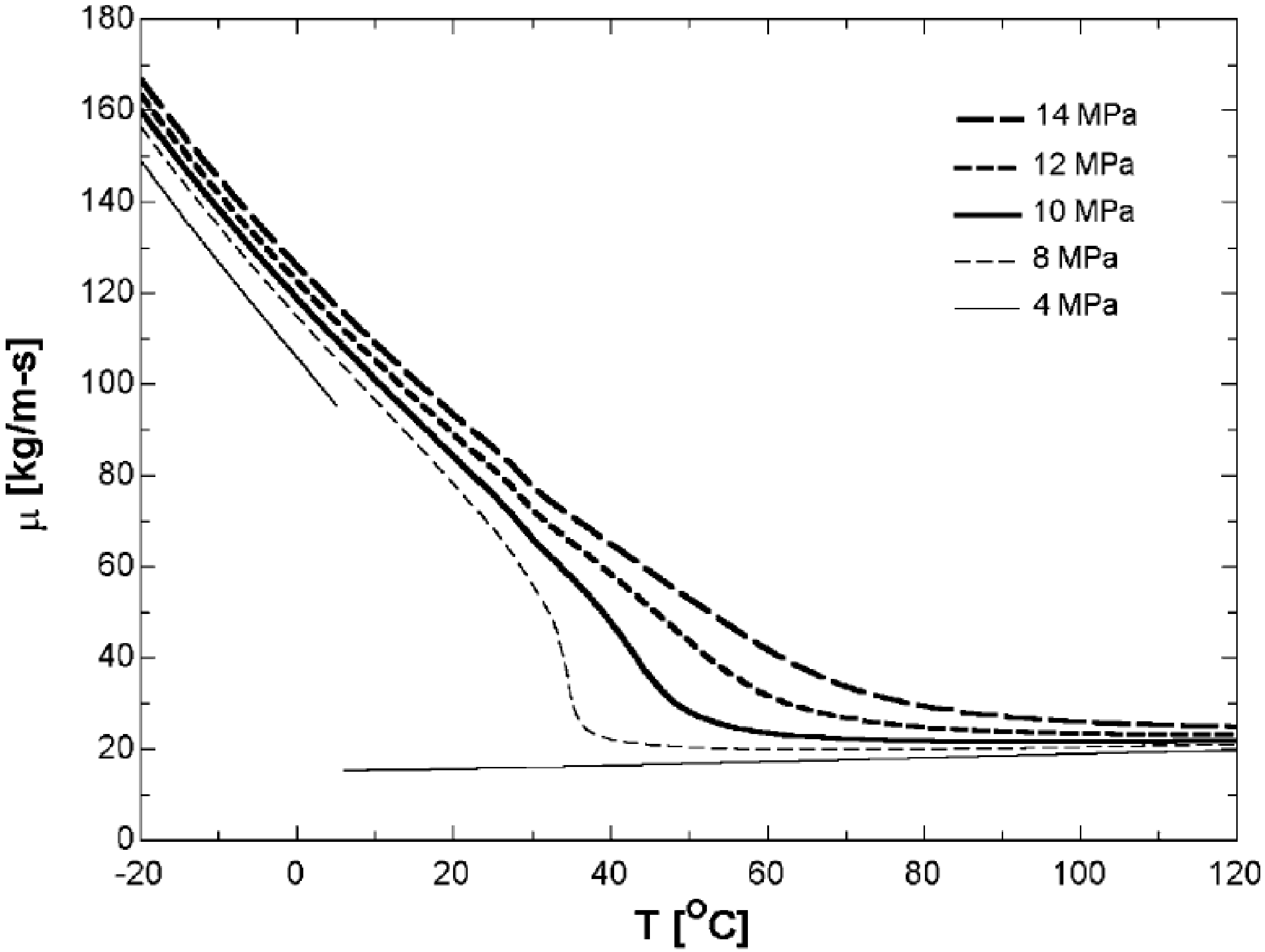
# $CO_2$ transcritical cycle – Introduction (5/8)



# $CO_2$ transcritical cycle – Introduction (6/8)



# $CO_2$ transcritical cycle – Introduction (7/8)



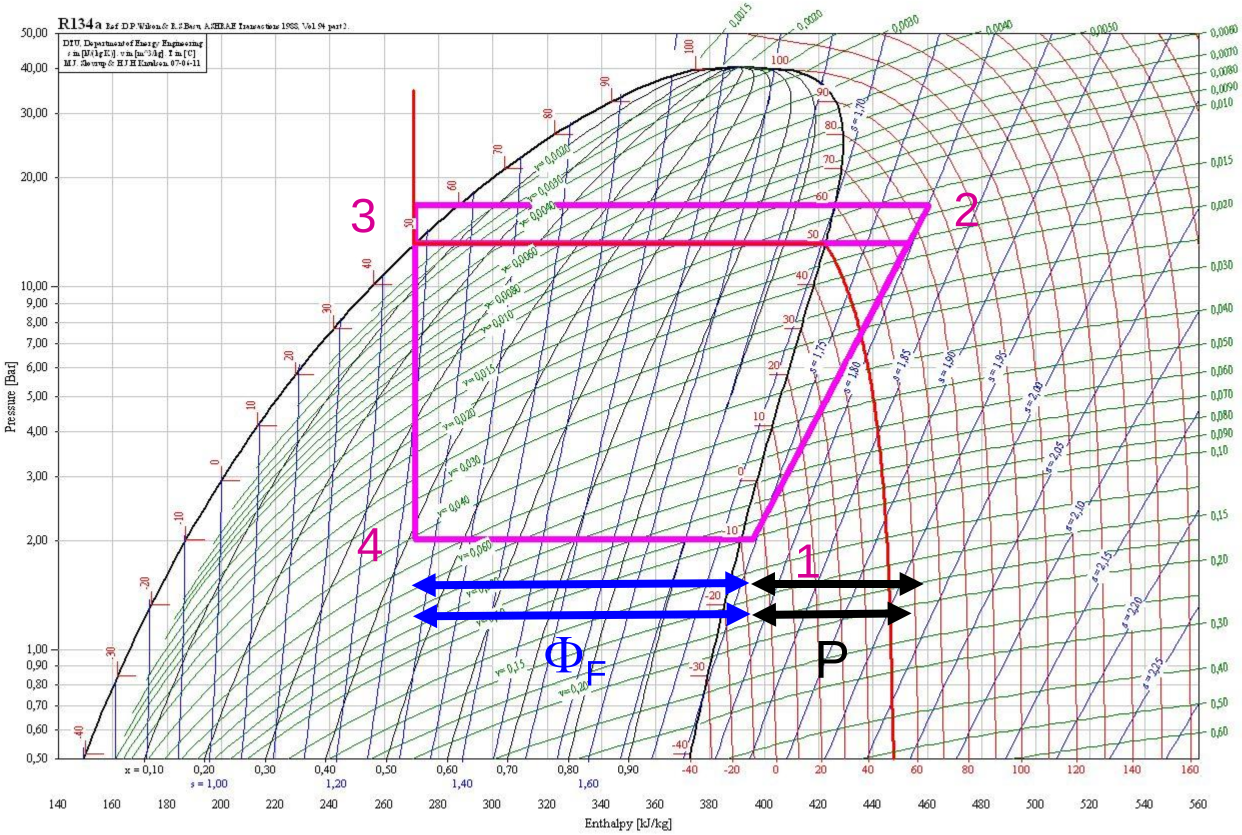
# $CO_2$ transcritical cycle – Introduction (8/8)

- $CO_2$ is different from conventional refrigerants :

3) High pressure (HP) is 5 to 10 times higher than with conventional refrigerants : safety and leakage problems
4) COP and refrigerating capacity decrease in supercritical state : the basic single-stage cycle doesn’t match the performance of a subcritical cycle with conventional refrigerant

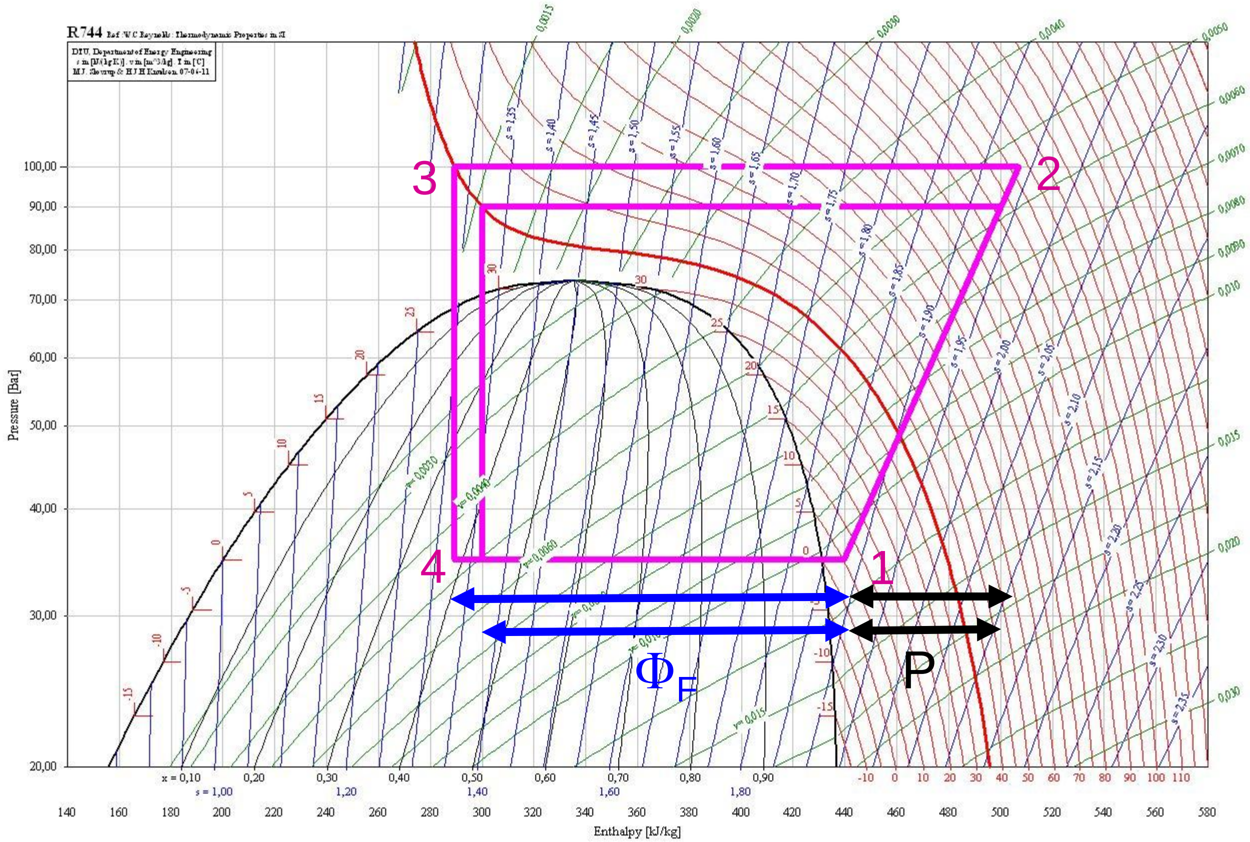
# $CO_2$ transcritical cycle – Cycles (1/10)

- Conventional cycle (Rankine) (R134a) :
- High pressure (HP) has little influence on refrigerating capacity



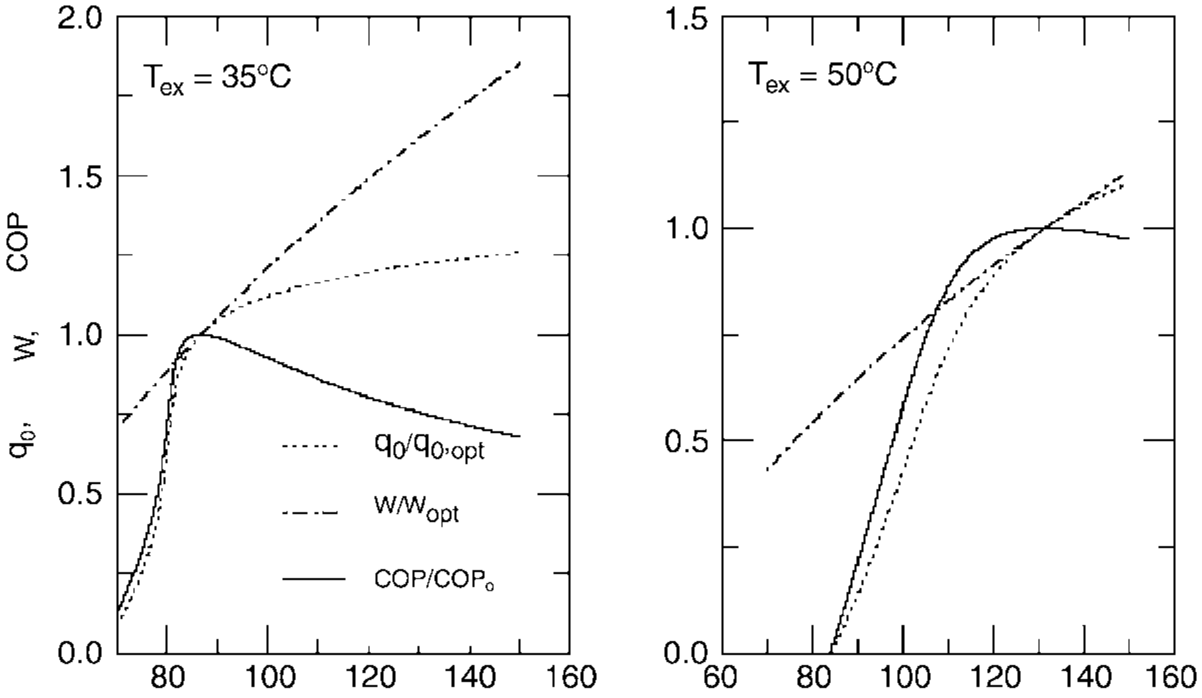
# $CO_2$ transcritical cycle – Cycles (2/10)

- $CO_2$ transcritical cycle :
  - High pressure (HP) has a marked influence on refrigerating capacity



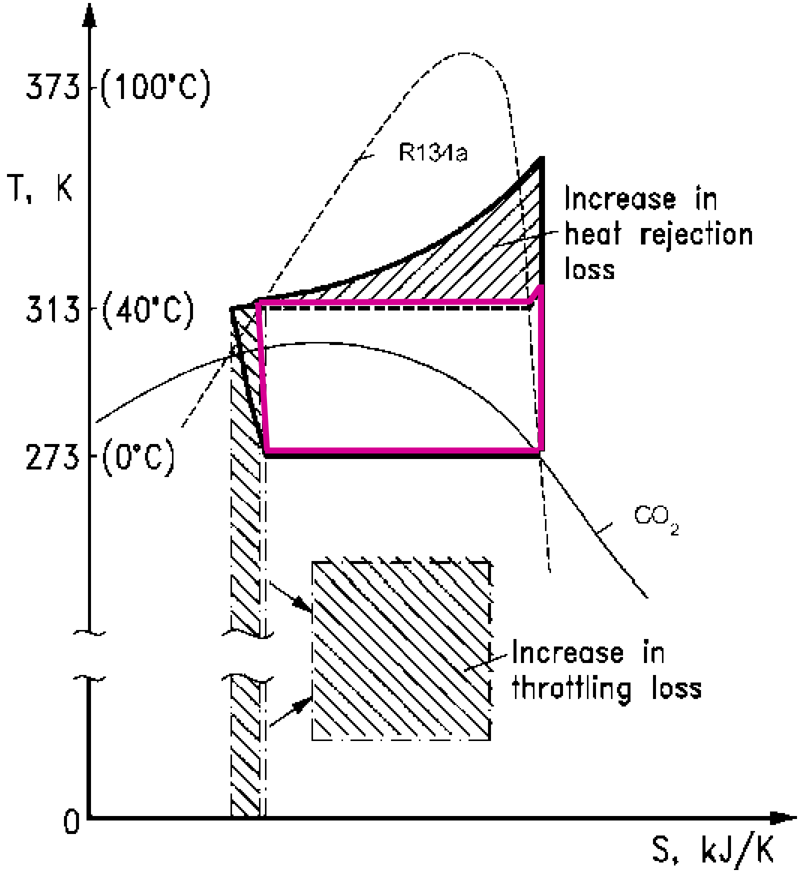
# $CO_2$ transcritical cycle – Cycles (3/10)

- Behavior of the basic cycle :
- the COP reaches a maximum value when high pressure increases



# $CO_2$ transcritical cycle – Cycles (4/10)

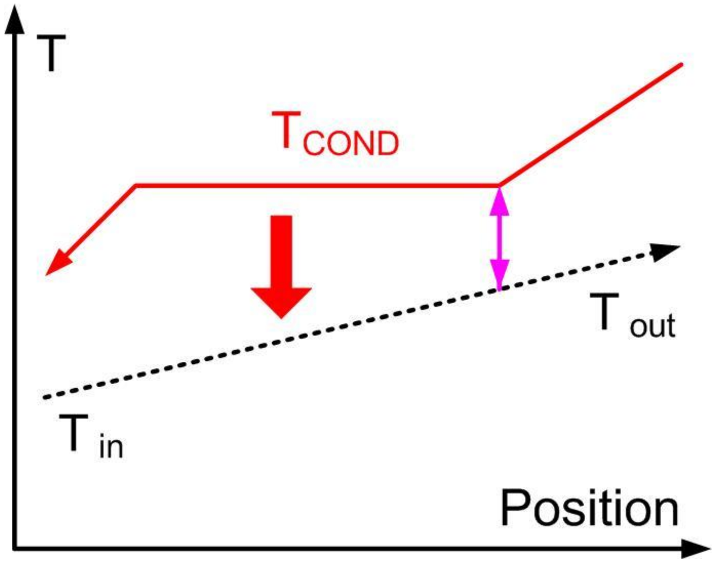
- Behavior of the basic cycle :
- Thermodynamic losses are higher in a $CO_2$ transcritical cycle. COP's are lower in a transcritical cycle

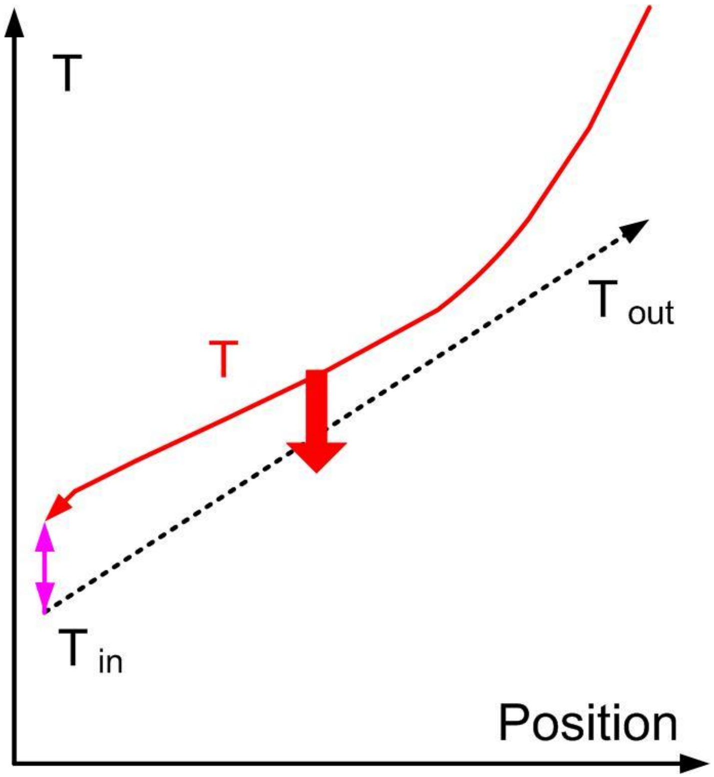


# $CO_2$ transcritical cycle – Cycles (5/10)

- Behavior of the basic cycle :

\- temperature profiles in a gas cooler is different from profiles in a condenser

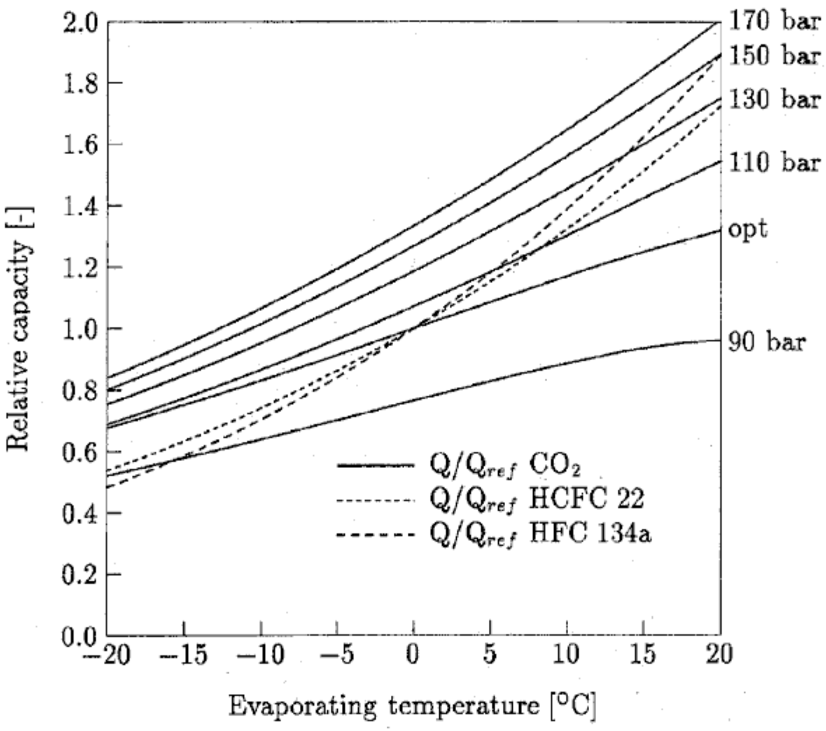


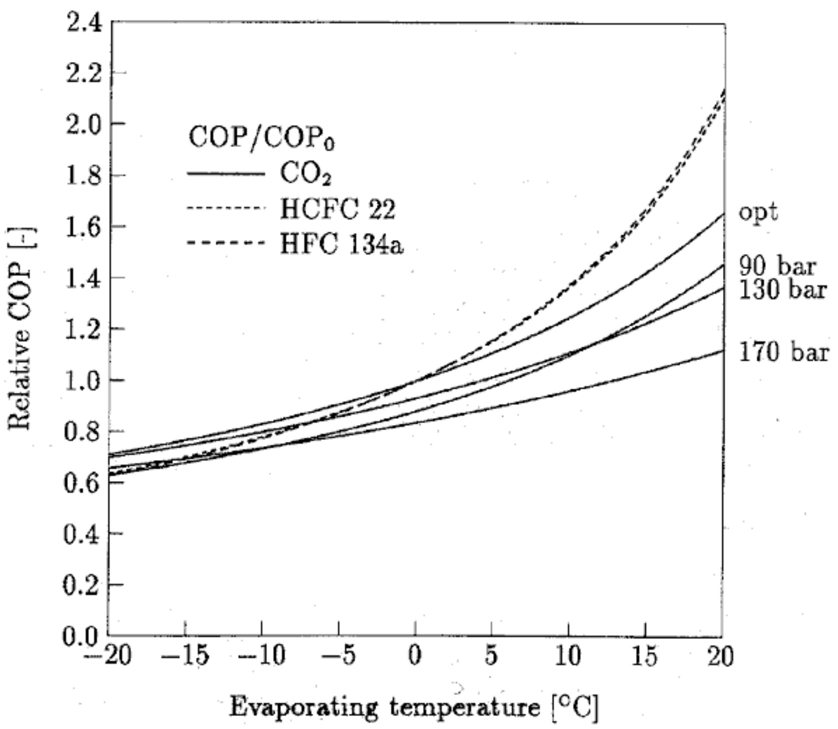


# $CO_2$ transcritical cycle – Cycles (6/10)

- Behavior of the basic cycle :

- The extra degree of freedom allows to operate with constant capacity or optimum COP





# $CO_2$ transcritical cycle – Cycles (7/10)

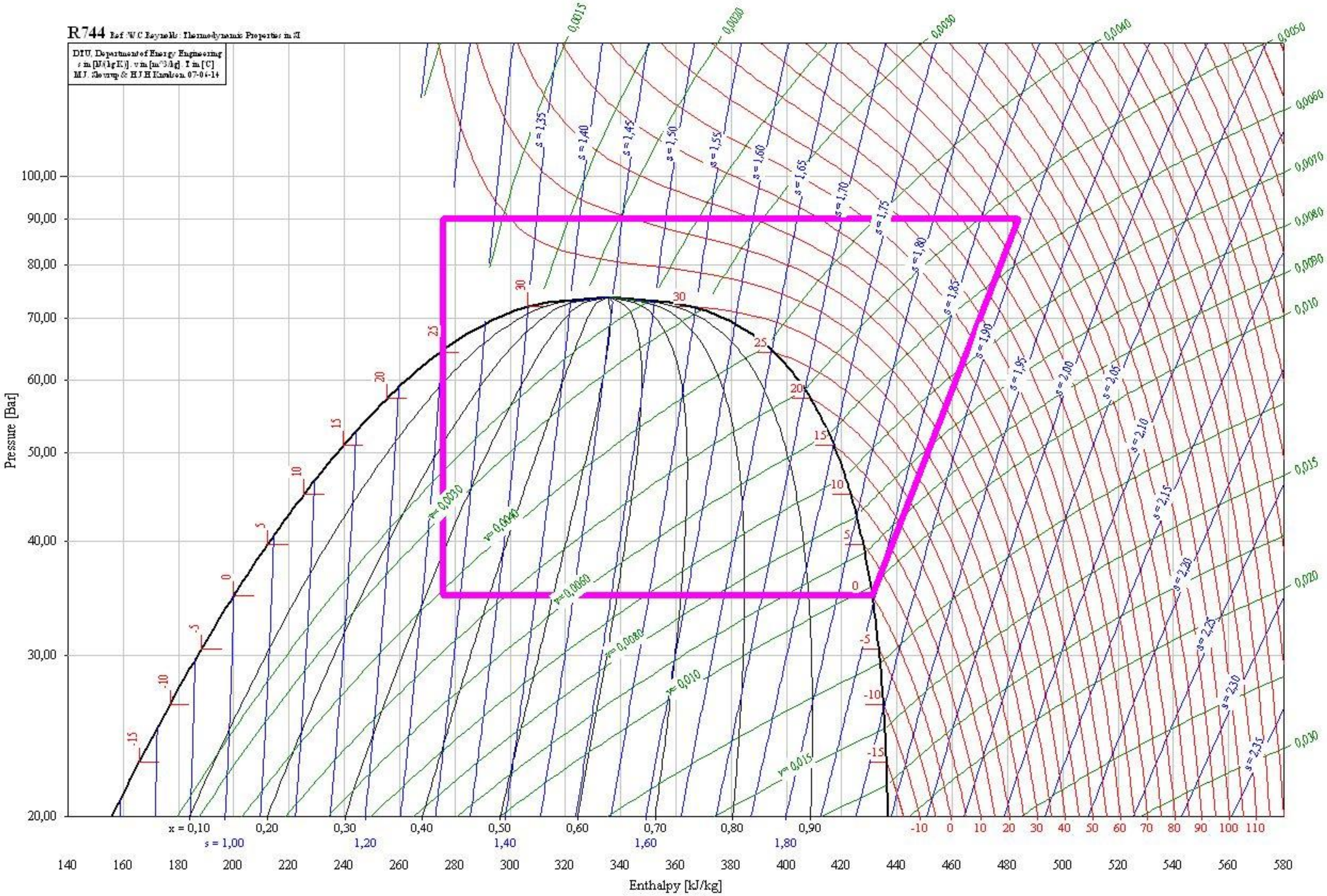
- Modified cycles are used because the basic cycle has lower COP's than with conventional refrigerants :

1) Work-generating expansion instead of throttling, e.g. use of the work recovered in the upper stage of compression (prototypes only)
2) Internal heat exchanger

   - for conventional refrigerants, no sound benefits

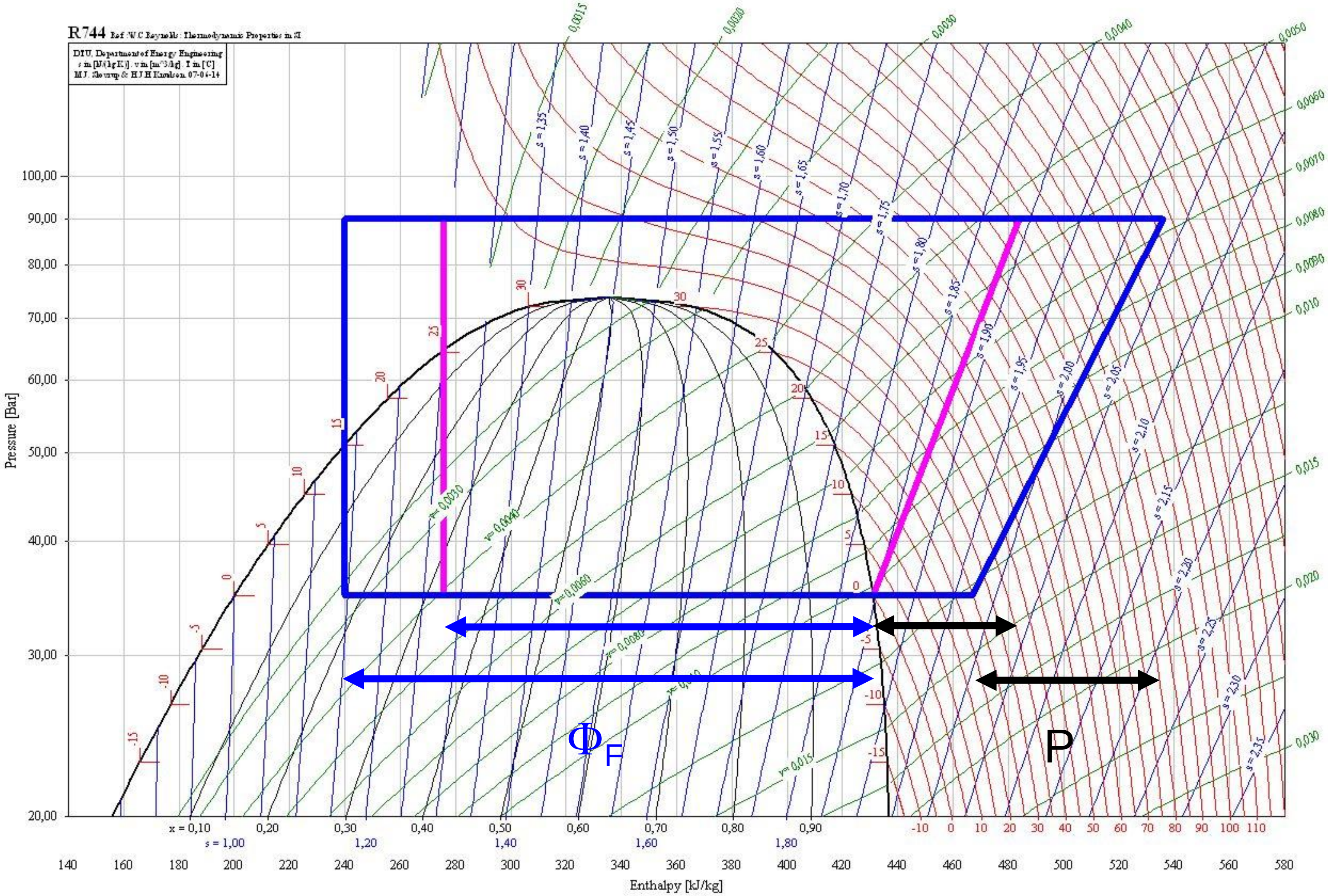
   - for $CO_2$ transcritical cycle, some benefits observed because of lower high pressure and throttling losses decrease. Benefits increase with higher pressures

# $CO_2$ transcritical cycle – Cycles (8/10)



Cycle without internal heat exchanger

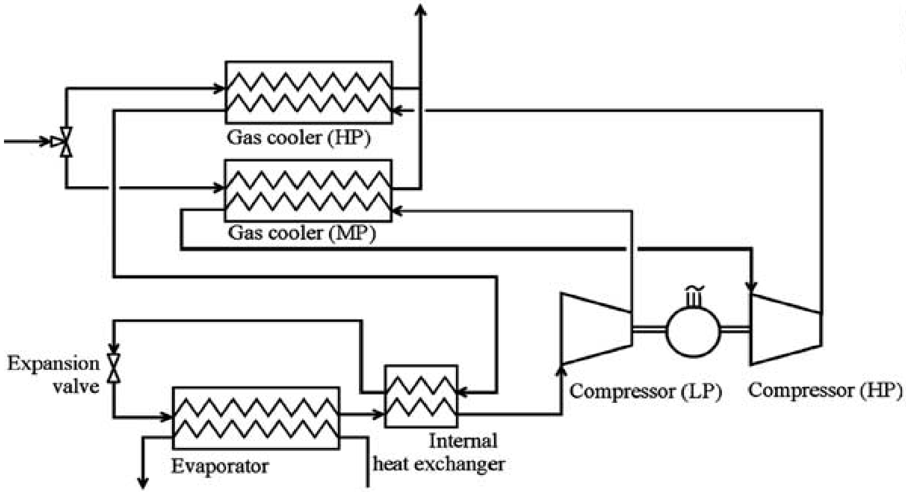
# $CO_2$ transcritical cycle – Cycles (9/10)

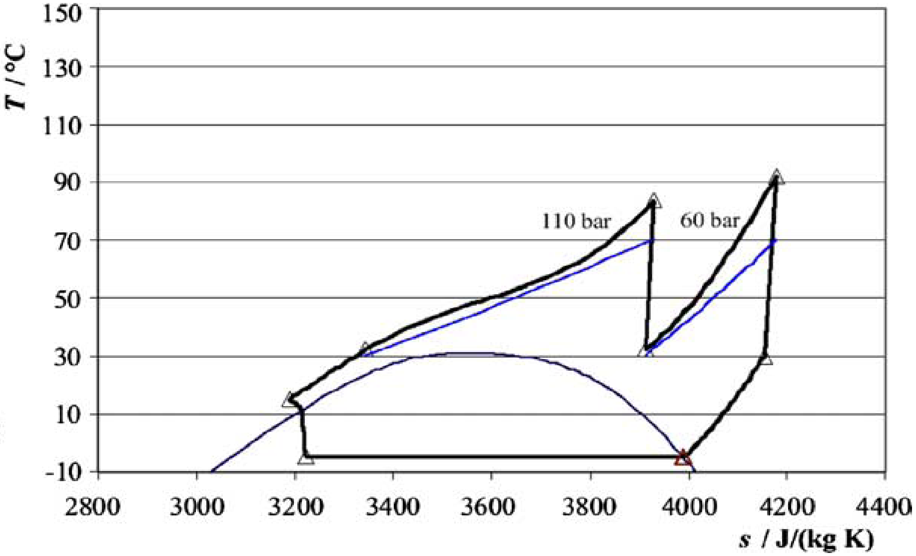


Cycle with internal heat exchanger

# $CO_2$ transcritical cycle – Cycles (10/10)

3) Modified cycle with two-stage compression (several arrangements)

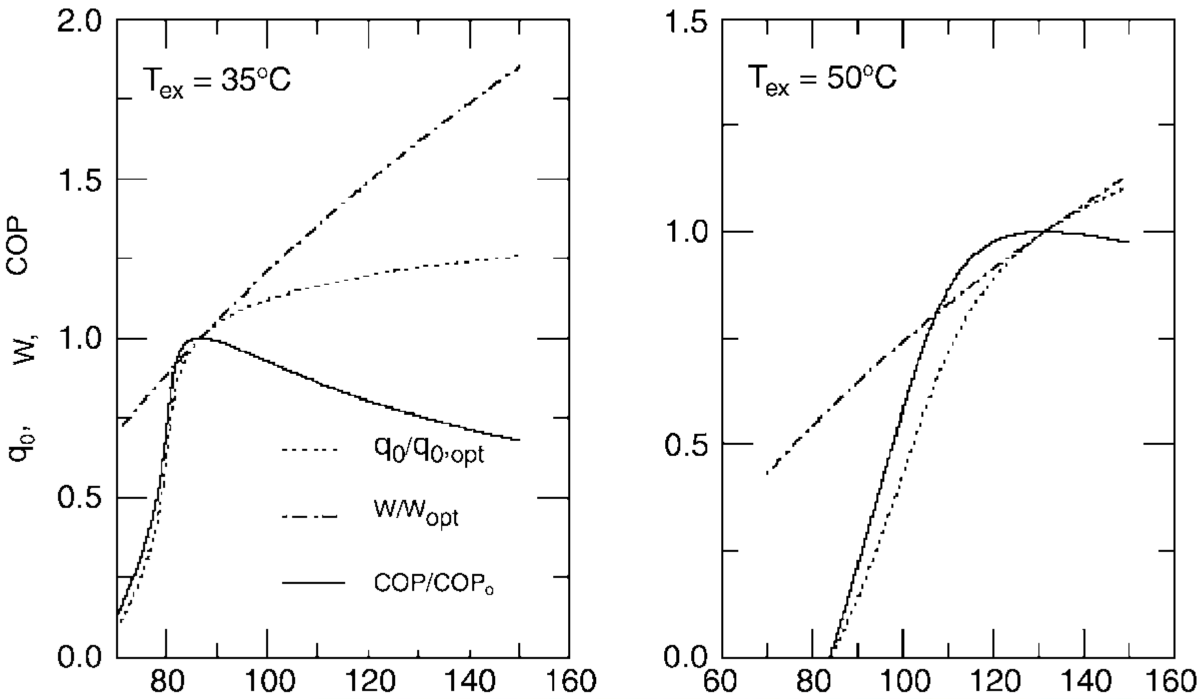




In comparison with the basic cycle, increase of 5% to 60% in COP’s, depending on the high pressure value

# $CO_2$ transcritical cycle – Control (1/4)

- $CO_2$ transcritical cycle :
- Need for high pressure (HP) control in order to obtain stable operation conditions
- HP control either to keep optimum COP’s or to keep constant refrigerating capacity



# $CO_2$ transcritical cycle – Control (2/4)

- High pressure control methods :

1) If subcritical cycle :
   $HP = P_{COND} = f(T_{COND})$
2) If transcritical cycle, $HP = f(v,T) = f(V/M,T)$. One can then control :

- temperature $T_{EX}$
- $CO_2$ inside volume (V)
- $CO_2$ charge (m)

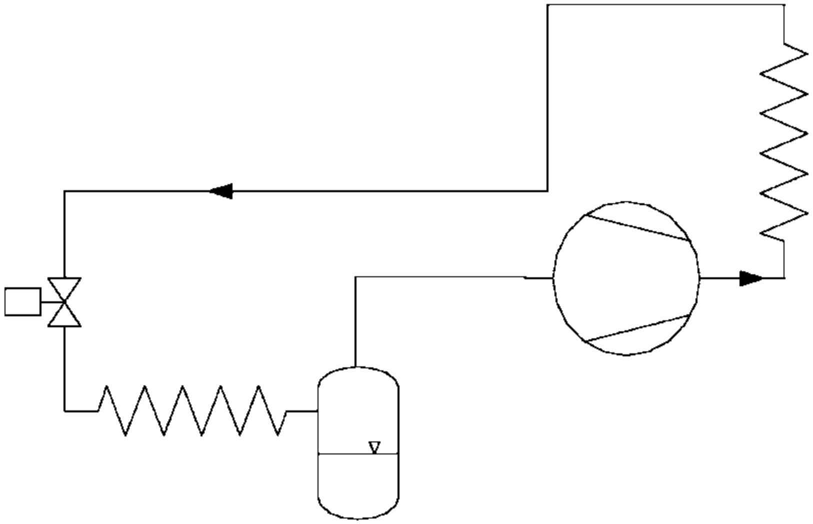
# $CO_2$ transcritical cycle – Control (3/4)

- HP controlled by temperature control (T) :
- CO$_2$ charge determined so that the variations of HP with T keep COP always optimum (passive control)
- for optimum COP, HP increases almost linearly with $T_{EX}$
- problem if $CO_2$ leakage !

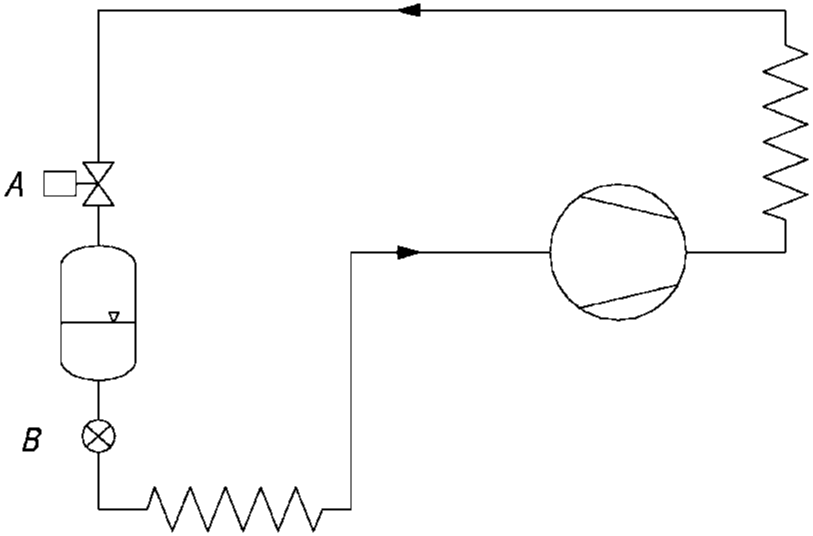
- HP controlled by inside volume control (V) :
- control of a part of the gas cooler volume (at the exit, where the density is higher), e.g. with a cylinder-piston system

# $CO_2$ transcritical cycle – Control (4/4)

- HP control by charge control (m):
- $CO_2$ charge in the gas cooler regulated with a receiver (buffer)
- open/close of the throttling valve for pressure control
- several arrangements



System with low-pressure receiver



System with in-line medium-pressure receiver

# $CO_2$ transcritical cycle – Components (1/6)

- Component design in a refrigeration system with $CO_2$ are different from conventional components because of :

  - higher pressure values

  - different thermodynamic and heat transfer properties for $CO_2$

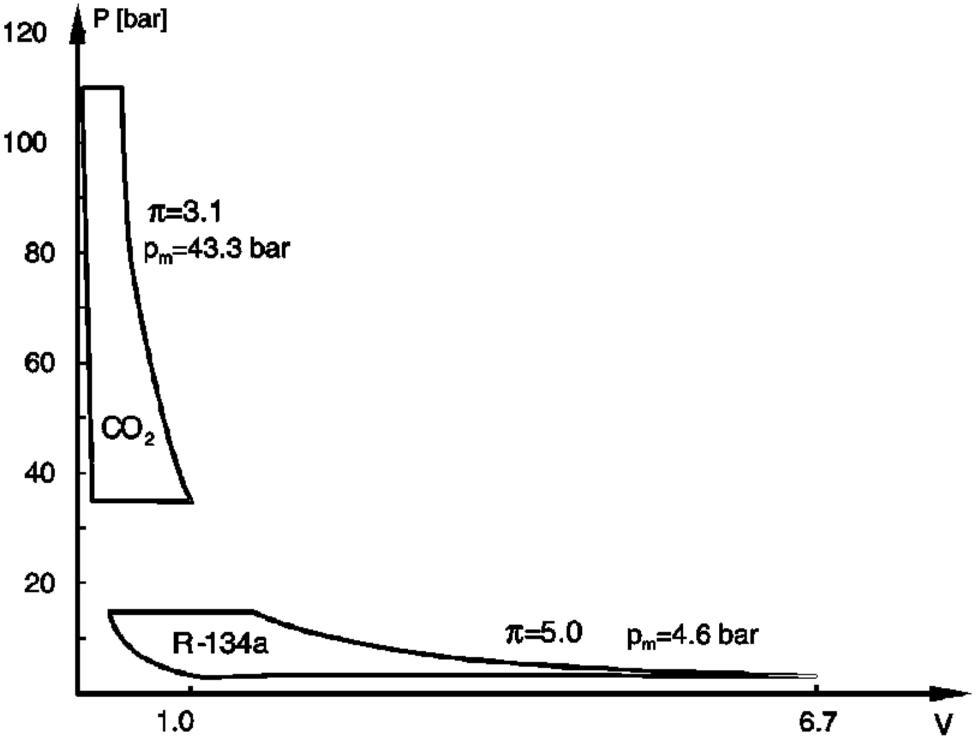
1) Pipework

   - smaller inner diameter because of high density of $CO_2$
   - thicker walls

# $CO_2$ transcritical cycle – Components (2/6)

2) Compressor

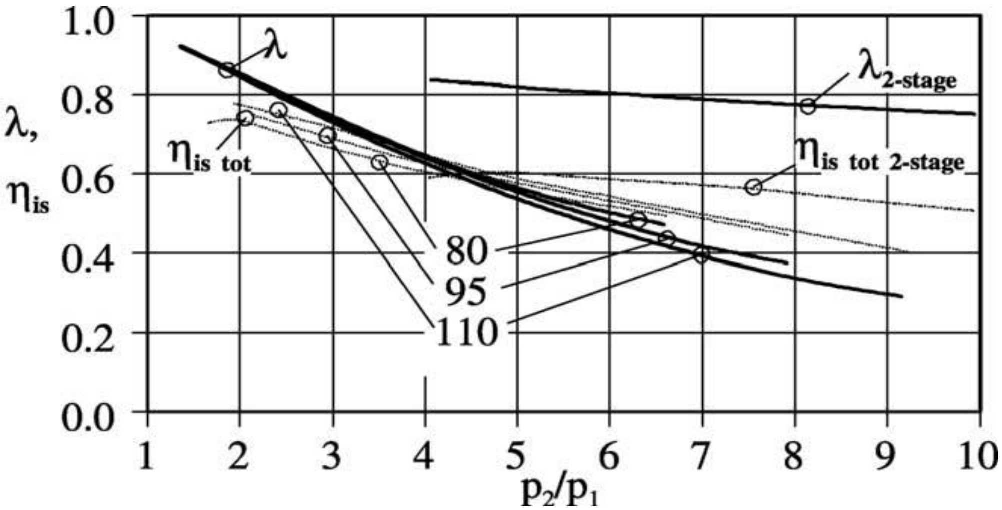
- high density for $CO_2$ , hence small volumes
- high pressures (LP : 30-40 bar, HP : 100-140 bar)
- small compression ratio



# $CO_2$ transcritical cycle – Components (3/6)

2) Compressor

compact, small displacement rate compressors, with thick walls.



DORIN compressor $V_s$ = 2.7 $m^3/h$

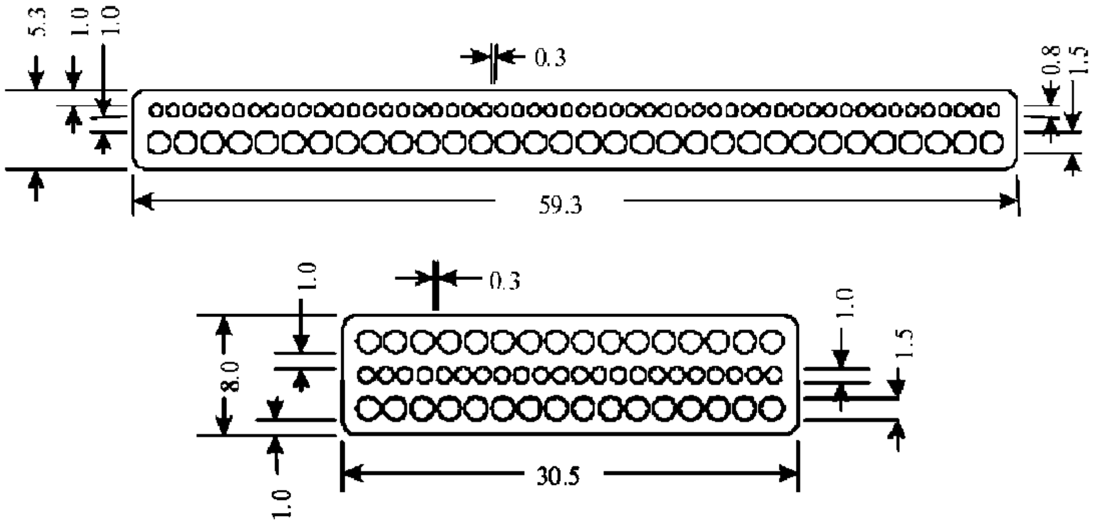
isentropic and volumetric efficiencies

# $CO_2$ transcritical cycle – Components (4/6)

2) Heat exchangers (HX’s)

- often compact microchannel HX’s because of high pressures (LP and HP) and high density for $CO_2$

2a) Internal heat exchanger



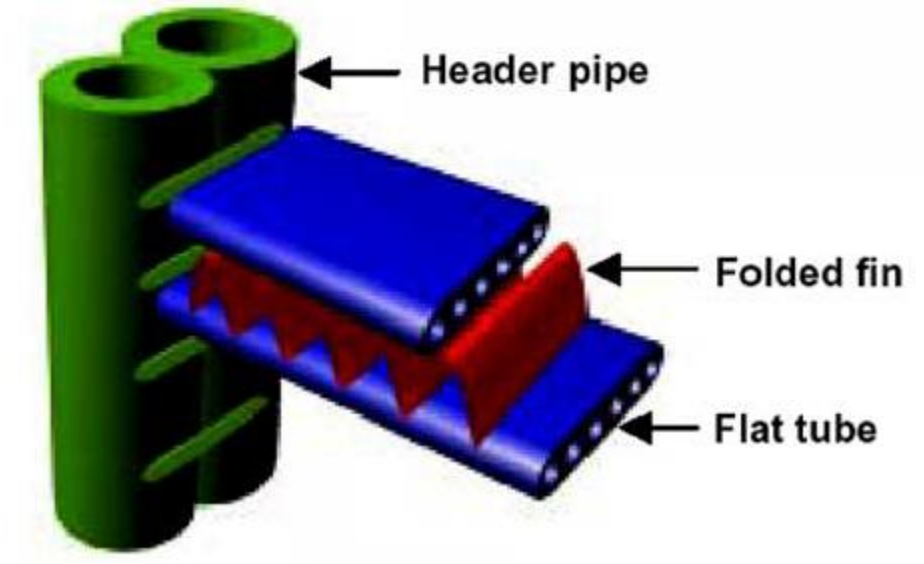
Dimensions in mm

Illustration of new designs of internal heat exchanger

# $CO_2$ transcritical cycle – Components (5/6)

2b) Gas cooler

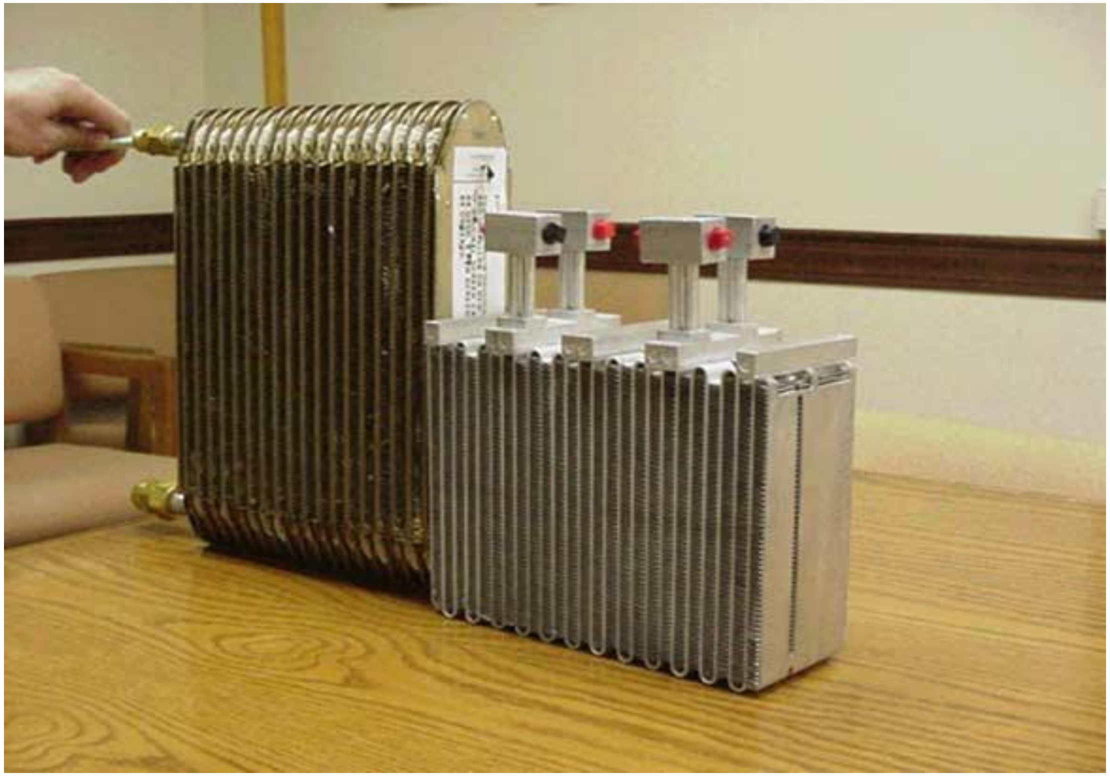
- Design very important to control the $CO_2$ exhaust temperature



Prototype of a car air-conditioning gas cooler

# $CO_2$ transcritical cycle – Components (6/6)

## 2c) Evaporator



Conventional evaporator (R134a) and $CO_2$ microchannel evaporator (car air-conditioning)

# $CO_2$ transcritical cycle – Applications (1/4)

1) Automotive air-conditioning

   - historically first system investigated because of high leakage rate of R12 (and R134a) in conventional systems

   - optimized design for compressor and heat exchangers allowed to obtain COP’s similar or better than R134a air-conditioning systems

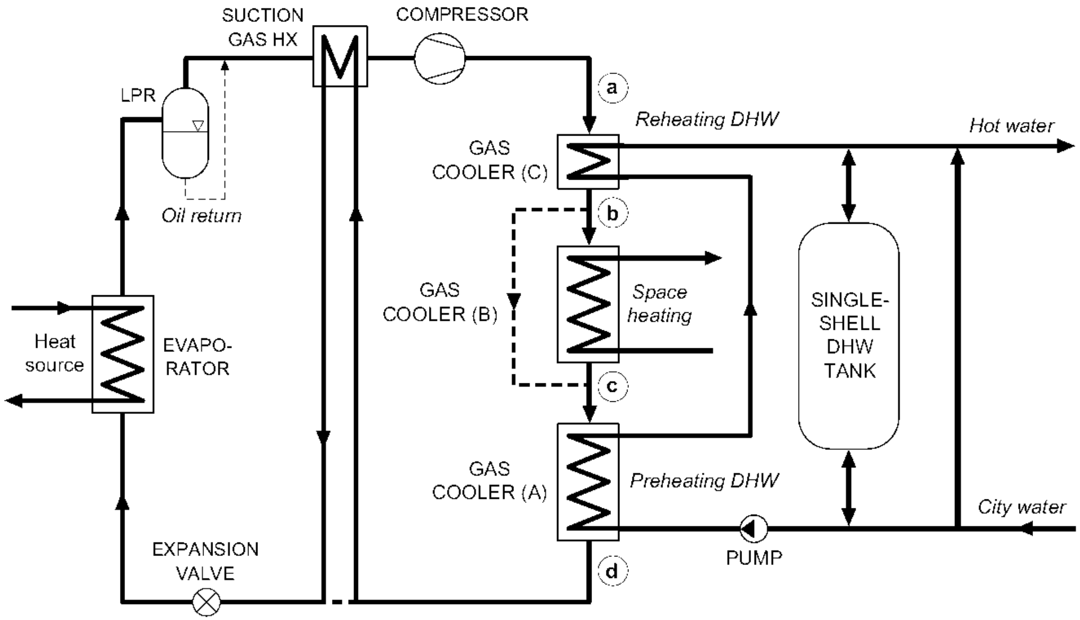
# $CO_2$ transcritical cycle – Applications (2/4)

2) High temperature heat pumps :

- the $CO_2$ high temperature at the compressor exit and the use of a gas cooler allow to obtain high temperature water

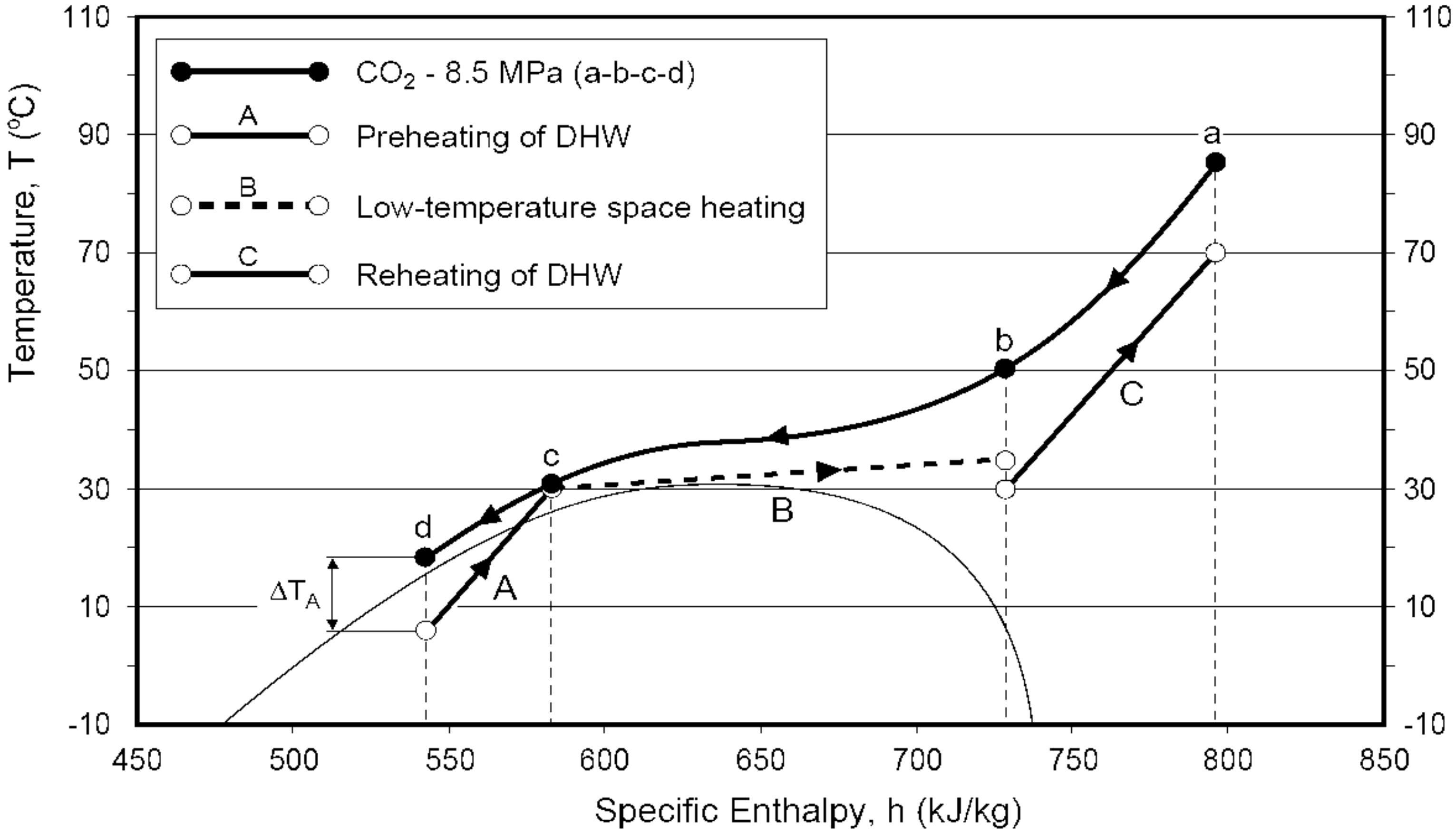
- heating of buildings (air heating and radiators)

- domestic hot water production (hospitals, hotels)



# $CO_2$ transcritical cycle – Applications (3/4)

## 2) High temperature heat pumps



# $CO_2$ transcritical cycle – Applications (4/4)

2) Commercial refrigeration :

- few field installations

- example in Italy (operation since 2003) : annual energy costs are a bit higher than for a conventional installation with R404A (+10%), installation costs are also higher (+20%) (lack of mass-produced components)

- in the future : integrated installation equipped with heat recovery for space heating and hot water production (e.g., supermarkets)

# $CO_2$ in cascade systems (1/2)

- $CO_2$ in cascade systems

  - $CO_2$ used in the low-temperature stage

  - the high-temperature stage is a conventional stage (HFC, HC, $NH_3$)

- Benefits with $CO_2$

  - low mass flow rates (high evaporation heat) and high density, hence small compressor, small pipes, small surfaces in evaporators

  - higher refrigerating capacity (lower freezing periods)

  - low conventional refrigerant charge (in the high-temperature stage)

  - no damage to the cold source if leakage

# $CO_2$ in cascade systems (2/2)

- Drawbacks with $CO_2$

  - higher pressure than pressure with conventional refrigerants (higher than in the high-temperature stage !)

  - $CO_2$ management when increase of temperature

  - mixing of $CO_2$/$NH_3$ when leakage between both stages

- Cost for a cascade system with $CO_2$

  Study from Johnson Controls, comparison with a conventional installation :

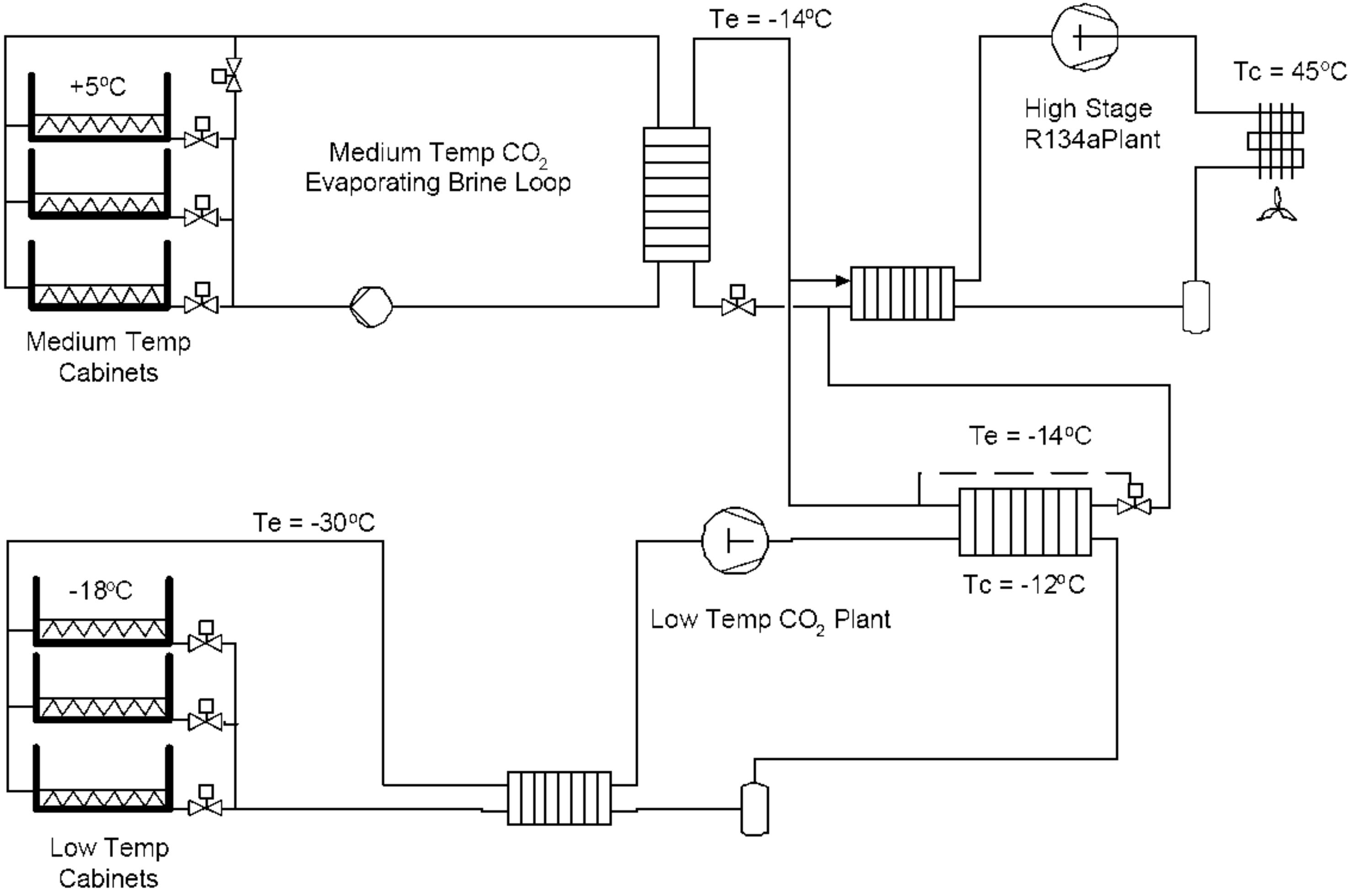
  - installation costs from –10% to +15%

  - energy consumption from -5 to -20%

# $CO_2$ as a secondary fluid (1/2)

- $CO_2$ behavior as a secondary fluid :
  - same as conventional secondary fluids
  - many existing installations
- Benefits and drawbacks for $CO_2$ similar to those of $CO_2$ in cascade systems
- Annual energy consumption is always reduced

# $CO_2$ as a secondary fluid (2/2)



**HFC134a $CO_2$ cascade system**

# Conclusions

- Use of $CO_2$ as a secondary fluid and as refrigerant in the low-temperature stage of a cascade system without trouble (better physical properties)
- Special properties of $CO_2$ as a refrigerant because of the transcritical cycle
- Use as a refrigerant in a transcritical cycle not obvious because of low COP’s or high-cost modified cycles, except in special applications (high temperature water production)
- No problems if leakage (environment, availability)
- Massive use of transcritical $CO_2$ installations depend on future law changes concerning HFC use !