Natural Refrigerants in different applications

Pega Hrnjak
pega@illinois.edu
Res. Professor, U. of Illinois, Urbana-Champaign
Co-Director ACRC,
President, CTS

Natural refrigerants

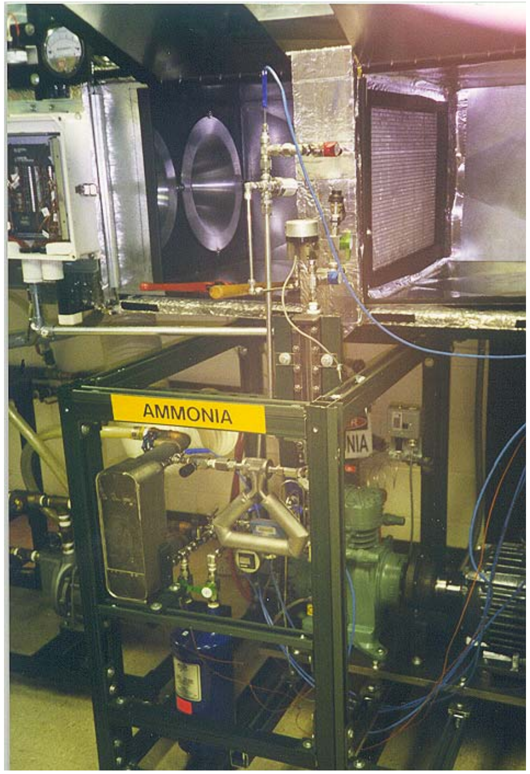
- In **vapor compression** systems:
  - Ammonia: R717
  - Hydrocarbons: R600a, R290, ….
  - Carbon Dioxide: R744

  Serious potential to become mainstream option

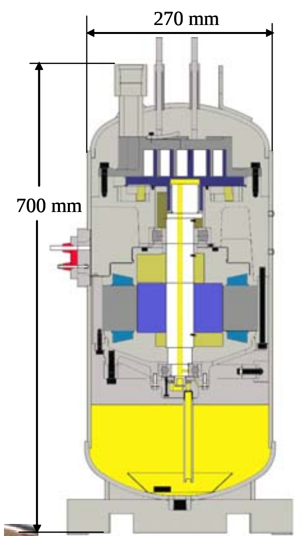
  - Air: R729 (aircrafts, low temperatures,..)
  - Water: R718 – low pressures and large equipment per capacity
  - Helium (Stirling) – cooling issues, niche applications
- In **absorption** systems: (niche applications, inexpensive heat)
  - Ammonia – water
- In **ejector** systems: (when steam is almost free)
  - Steam
- Other **niche refrigeration options**:
  - Magnetic, acoustic, electrochemical, …

Ammonia

- The only natural refrigerant that was continuously in use (in industrial refrigeration)
- Not appropriate for populated areas when charge is significant
- Low charge chillers for a/c or refrigeration with secondary coolant or cascade
- Lowest published charge 18 g/kW@15kW, - aircooled



Current advances



- Hermetic compressor
- Microchannel condenser
- Ni brazed plate evaporator

Needed:

Lower cost – different materials – Aluminum as an option

Hydrocarbons

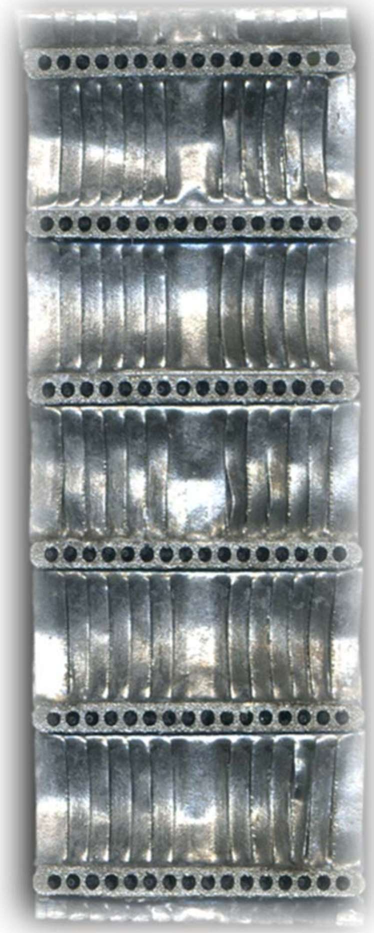
- The lowest cost alternative
- Almost drop-in replacement for R22 (R290)
  - a/c or commercial refrigeration
- Easy replacement for R12 or R134a (R600a)
  - refrigerators
- Flammable
- Charge limits 50g (?) or 150 g (?)
- Lowest charge known: 48g/kW @ 1kW, aircooled

Carbon Dioxide

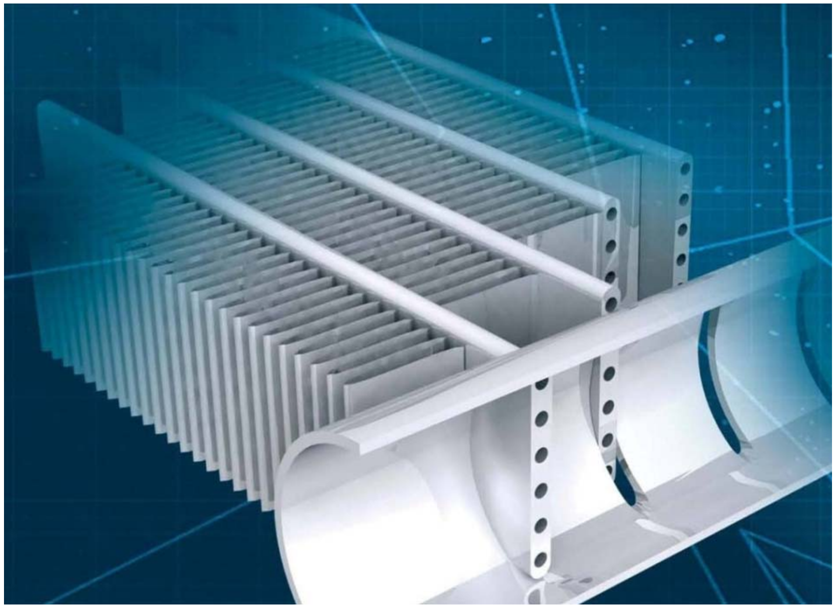
- Very old refrigerant
- Abandoned because of high pressures and bulkiness;
- Microchannel HXs and better materials reopen the door
- Assumed to be low efficient refrigerant – new systems high efficiency

Why are MC HEs important

- Refrigerant charge reduction
  - Reduced internal volume
  - Increased mass fluxes
  - Reduced need for refrigerant accumulator
- Suitable for high pressure working fluids
- High level of compactness
  - Large surface-area-to-volume ratio
- Light-weight, low-cost aluminum components



MC HEs brought new life for CO_2



Assembly for brazing

Header tubes

Extruded multiport microchannel tubes

Folded louver fins

About efficiency (COP)

Because many think that CO_2 is not efficient

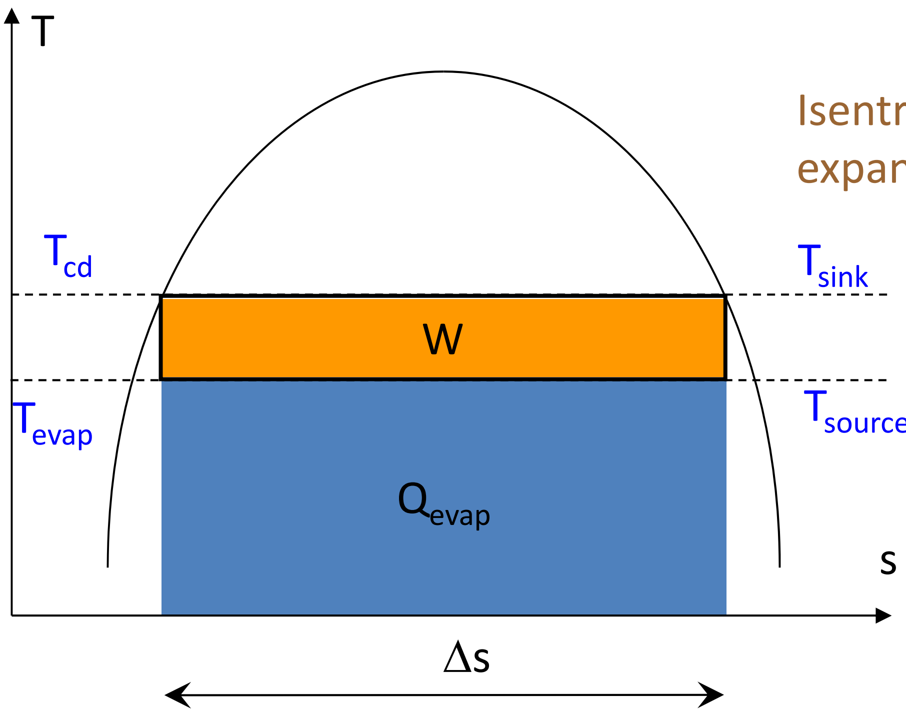
Very often same word is used for different efficiencies:

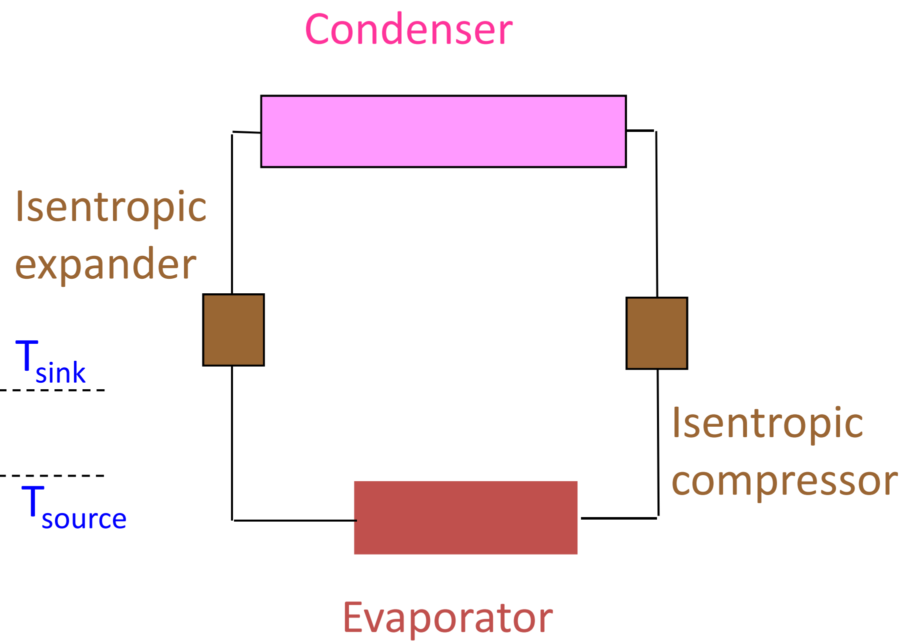
1. Cycles (**refrigerants**)
2. Systems (add effects of **components**)
3. In application (add effects of **operation**)

Cycle analysis

- Use tools of Thermodynamics:
  - Cycle analysis – determines efficiency
  - Thermodynamic properties of the fluid
  - Second law (entropy generation)
- Ignores realities of HX and Cp design: heat transfer, pressure drop, local sink and source change in temperature, fluid interactions, controls, …
- Attractive because it is “clean”
- Just appears to be unbiased if pretends to give the complete answer
- Excellent to evaluate options, as the first of the steps

Carnot Cycle





$Q_{cd}=T_{cd}*\Delta s$

$Q_{evap}=T_{evap}*\Delta s$

$W= Q_{cd}-Q_{evap}=(T_{cd}-T_{evap})*\Delta s$

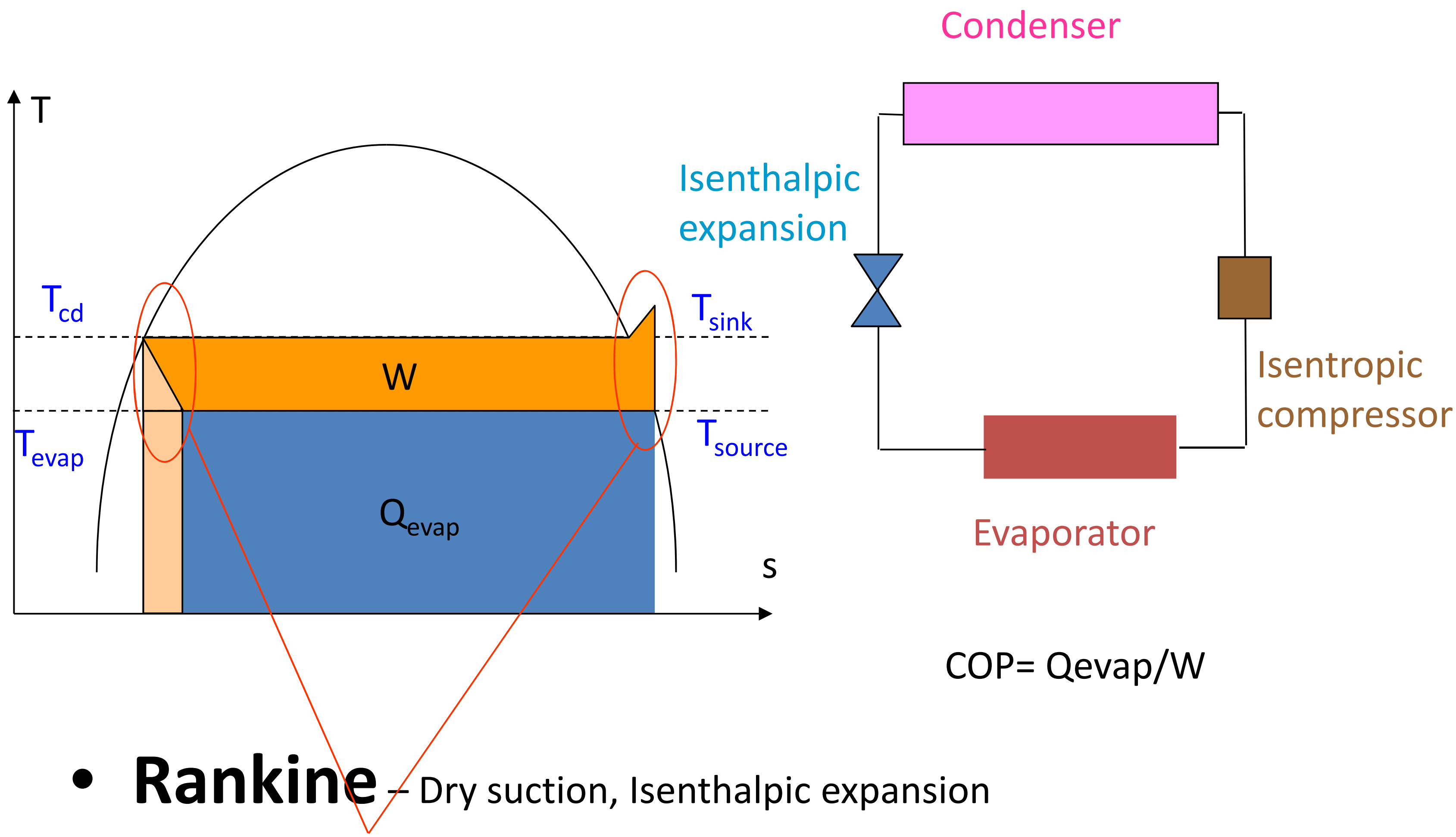
$COP= Q_{evap}/W$

- **Carnot cycle** – ideal
  - Reversible (DT=0, friction=0, slow,…)
- **All fluids are equal!**

So,

- **ALL REFRIGERANTS ARE EQUALLY EFFICIENT IN CARNOT CYCLE**
- They start to differ when designers move a bit away from Carnot for technical reasons
- Let’s have a reminder:

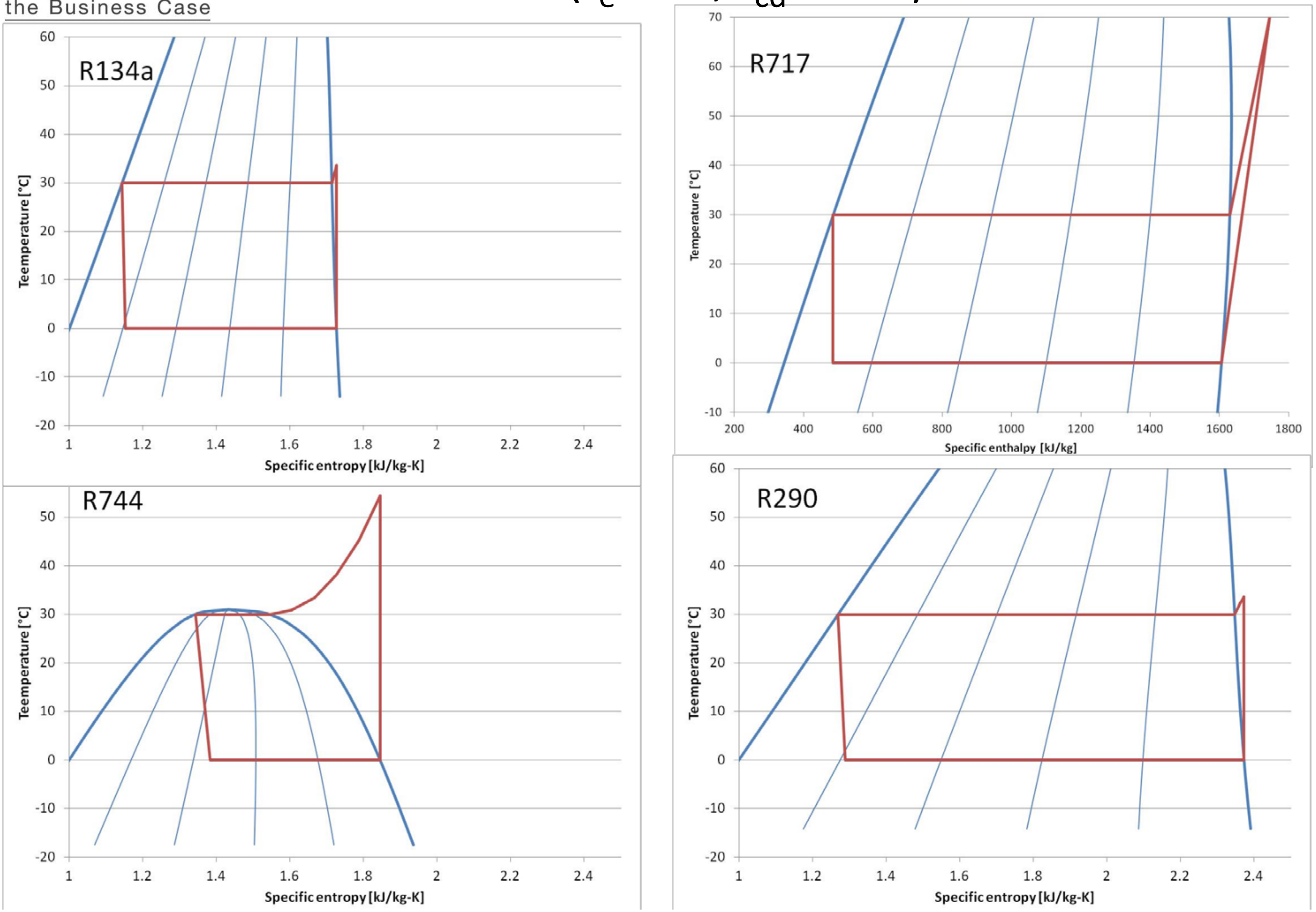
Rankine (Evans-Perkins) Cycle



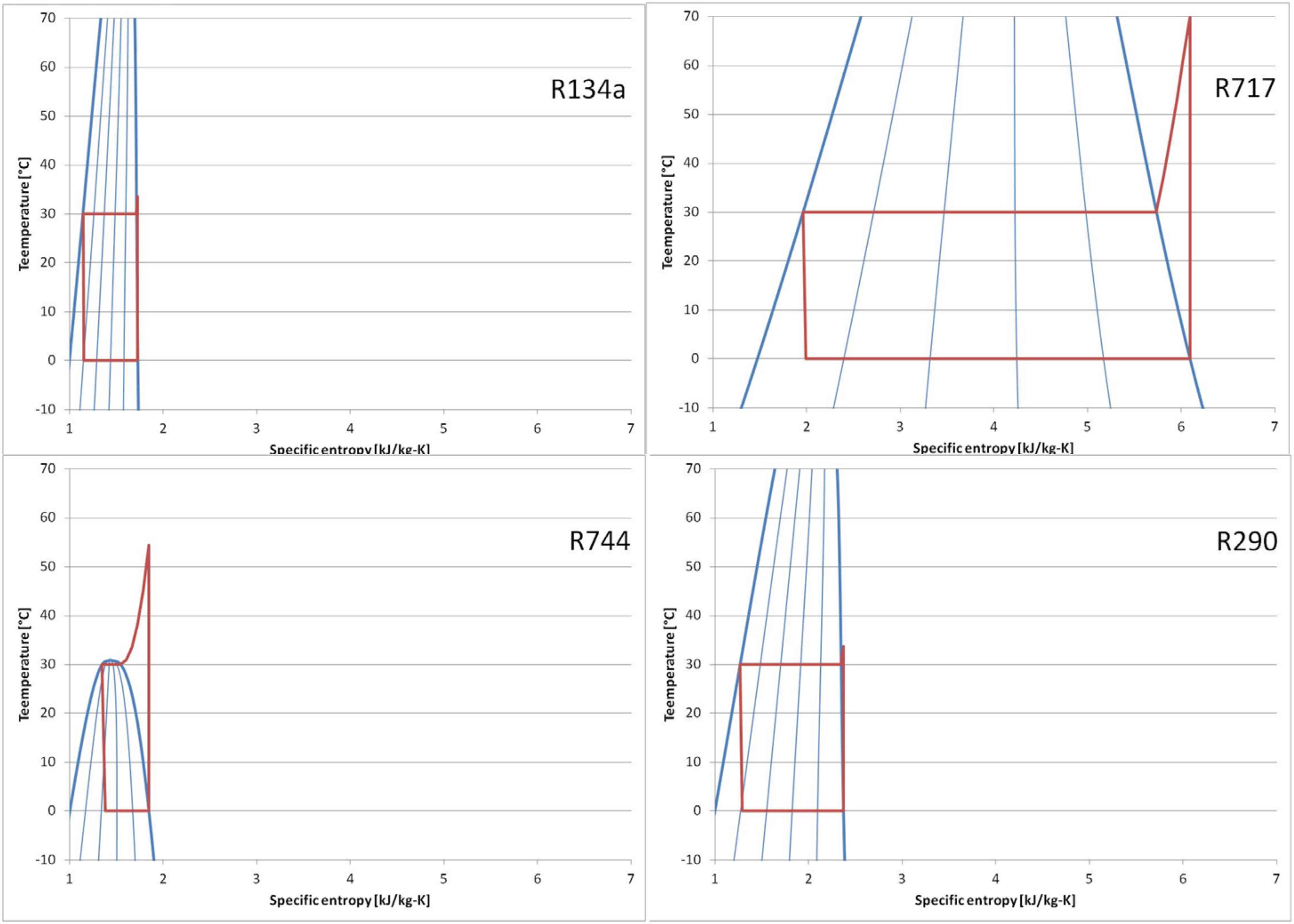
COP= Qevap/W

- **Rankine** – Dry suction, Isenthalpic expansion
- Fluids are **NOT** equal – begin to differentiate

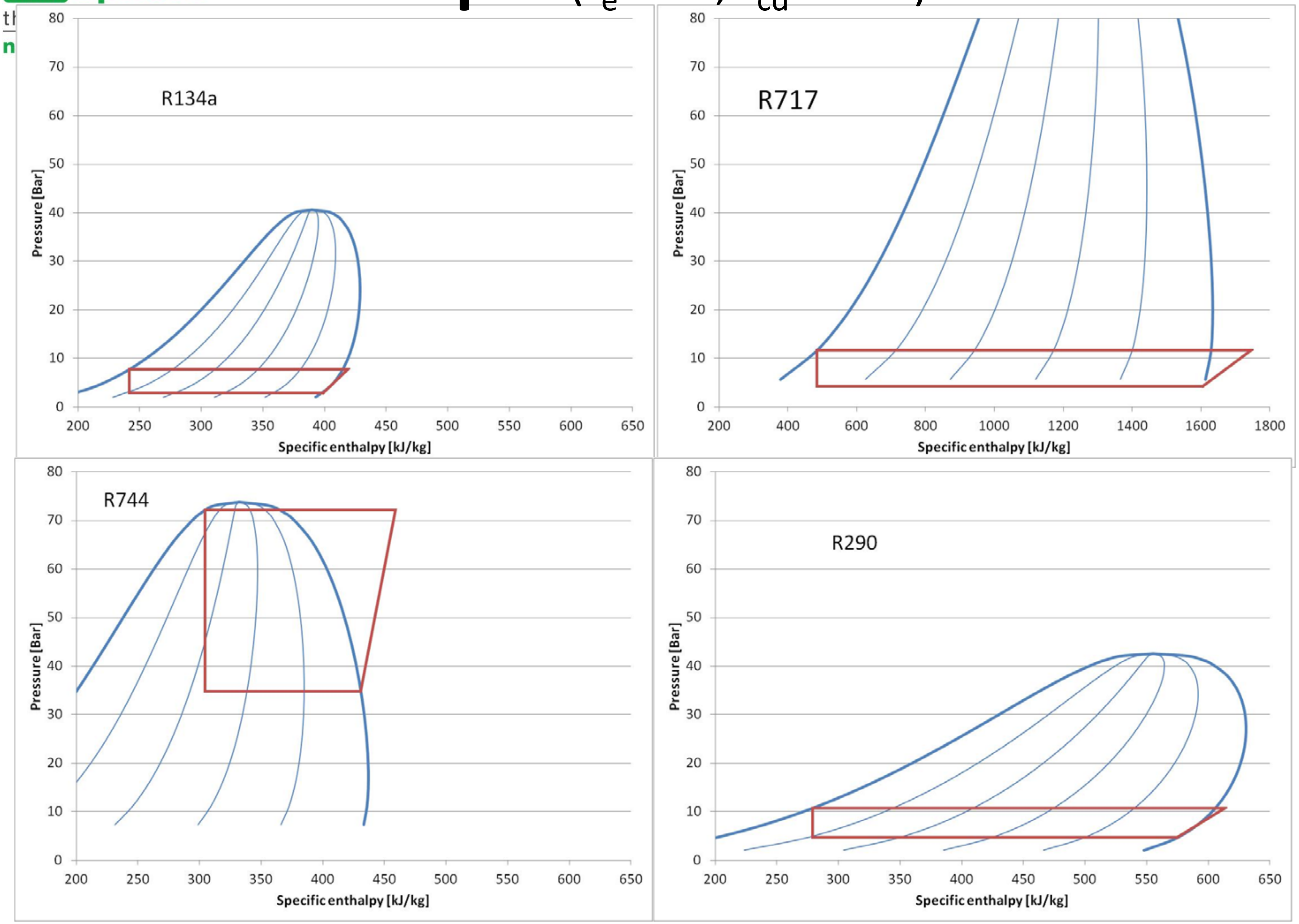
ln T-s (t_e=0°C, t_{cd}=30°C)



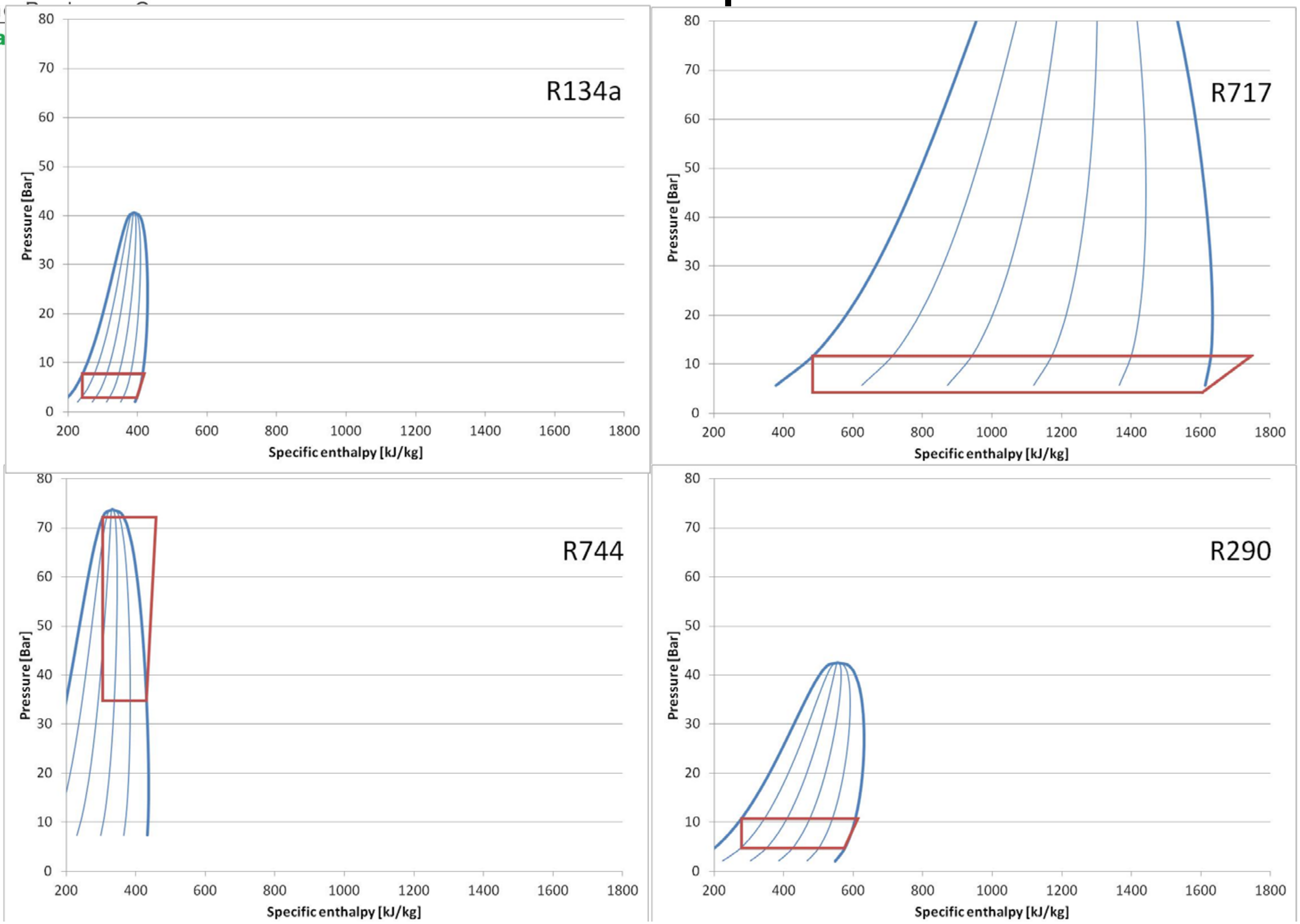
In scale: T-s


R134a
R717
R744
R290
Teemperature [°C]
Specific entropy [kJ/kg-K]
70
60
50
40
30
20
10
0
-10
1
2
3
4
5
6
7

ln **p-h** (t_e=0°C, t_{cd}=30°C)



In scale: p-h

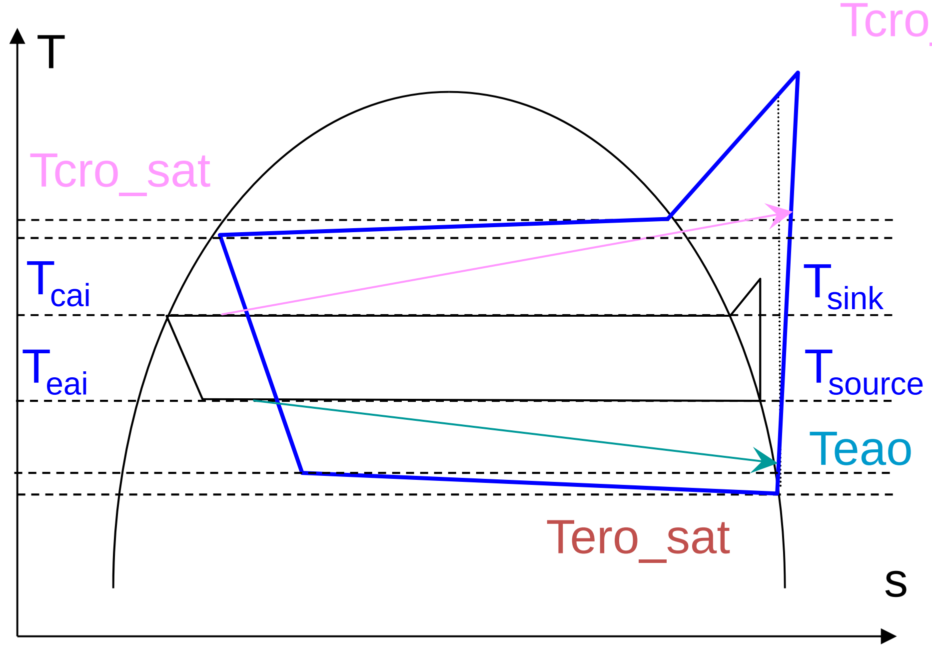

R134a
R717
R744
R290
Pressure [Bar]
Specific enthalpy [kJ/kg]
0
10
20
30
40
50
60
70
80
200
400
600
800
1000
1200
1400
1600
1800

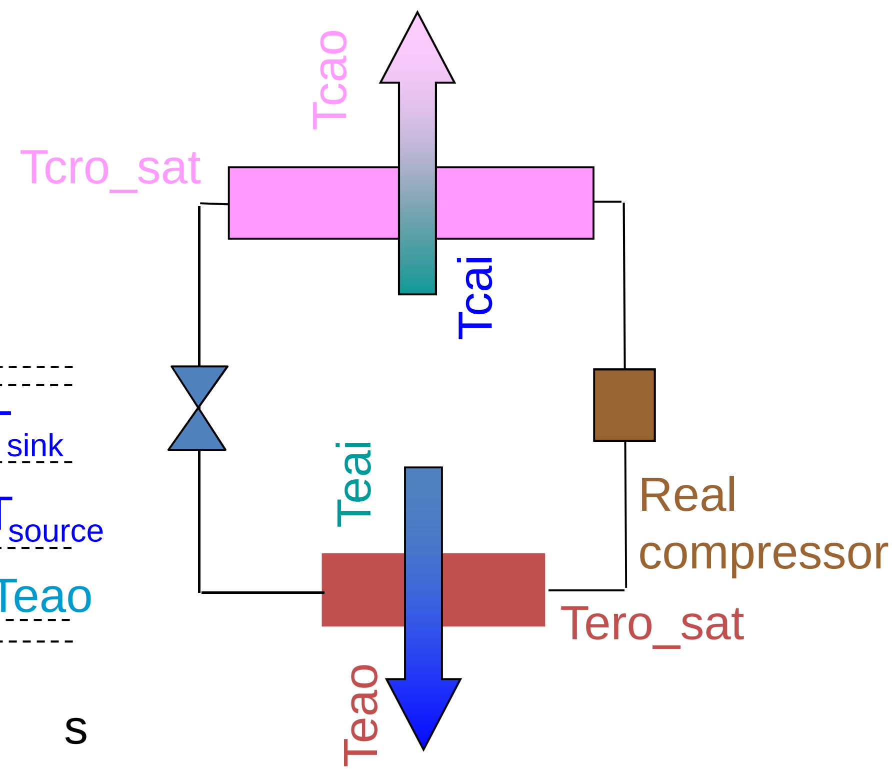
When reality of HXs, compressor, expansion devices come into a play

- This is when THERMOPHYSICAL properties become way more important that THERMODYNAMIC properties
- That is where CO_2 and typically all natural refrigerants are good

System,
based on Rankine cycle

Takes in account realities of: heat exchangers, compressors, expansion devices





Rankine system – measured on the test bench

Why is this important?

- COPs of the CYCLE is dramatically reduced in the SYSTEM by effect of:
  - Heat transfer (thermophysical properties of the fluid)
  - Heat exchanger design
  - Compressor design and manufacturing
  - Expansion device (work recovery)
  - System architecture (two stage compression, IHX, subcooling, ….)
- **Good selection can totally change initial expectations**

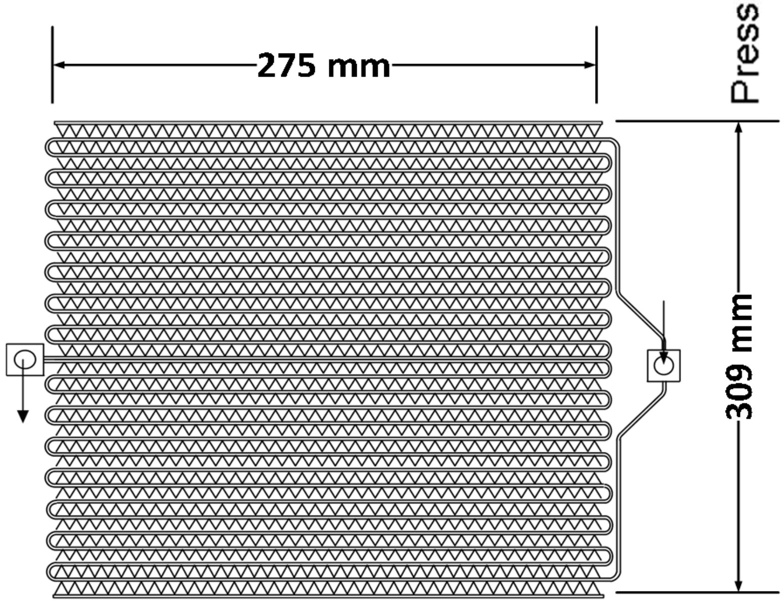
Situation

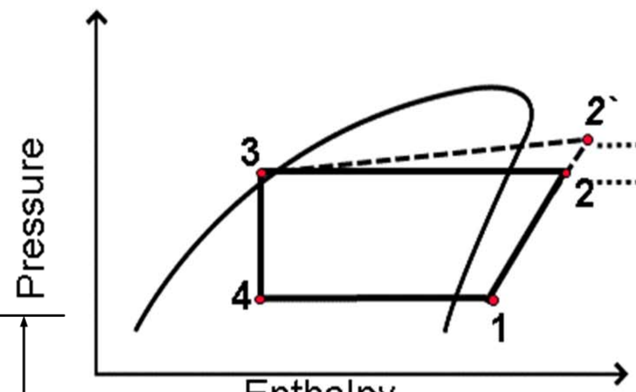
- R744 is very different than R134a, R717, or R290
- Has to be treated as such
- Possible but more difficult to achieve higher COPs
- Better thermophysical properties – heat transfer advantages have to be utilized
- Lesser sensitivity to pressure drop – easier to make HXs

NH_3, CO_2, excellent for charge reduction

- Cooling capacity identical
- Modify only the size of the microchannel so that

DP causes 1% reduction in COP for each refrigerant

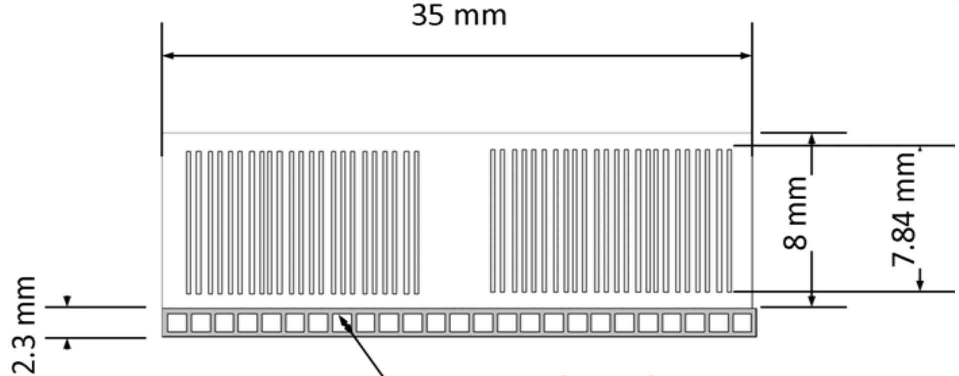




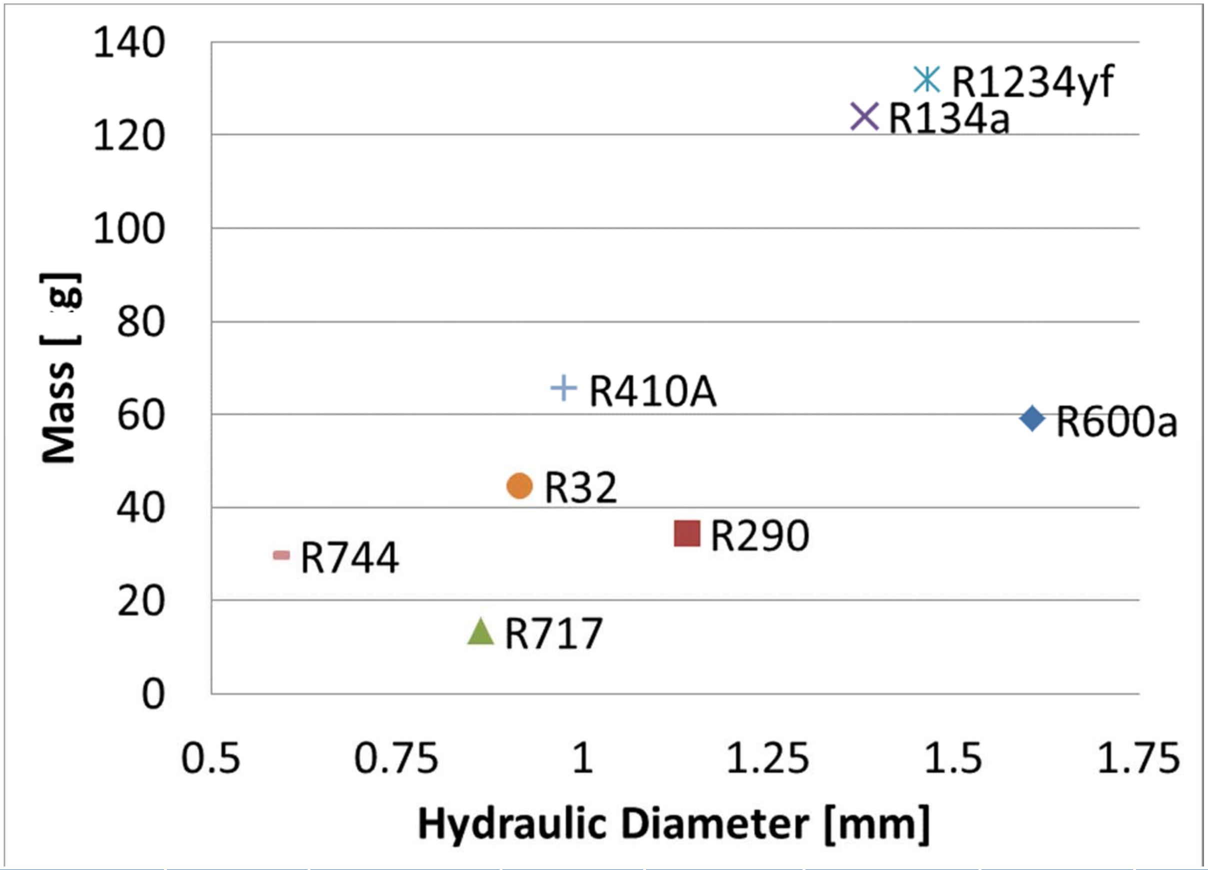
Δp 1% Δ COP

$$COP_{ideal} = \frac{h_1 - h_4}{h_2 - h_1}$$

$$COP_{non\ ideal} = 0.99 * COP_{ideal}$$



Results



Fluid	Ref. Mass	Hydraulic Diameter	Mass Flow Rate	ΔP [1 % COP reduction]	COP Ideal	Cond. Temp.	Rejected Heat	Sat. Liquid Density	Sat. Vapor Density	Latent Heat
	[g]	[mm]	[g/s]	[kPa]	[-]	[C]	[kW]	[kg/m³]	[kg/m³]	[kJ/kg]
R717	13.4	0.8625	0.862	7.45	10.04	24.6	1.043	603.9	7.72	1169
R744	29.8	0.586	5.943	35.79	7.01	24.3	1.103	724.8	234.7	125.9
R290	34.4	1.14	3.150	6.58	9.57	25.2	1.048	492.2	20.72	335.7
R32	44.9	0.915	3.636	11.46	9.41	24.8	1.054	962.8	47.12	271.7
R600a	59.1	1.606	3.310	3.17	9.76	25.5	1.067	550.2	9.285	329.4
R410A	65.6	0.975	5.320	11.65	9.37	25.1	1.067	1063	66.15	187.8
R134a	124.2	1.38	5.962	5.52	9.54	25.6	1.094	1206	32.88	177.7
R1234yf	132	1.464	7.520	5.41	9.31	25.6	1.077	1091	38.42	145.6

Conclusion

- There was no time with only one refrigerant being used - none of the refrigerants were ever universal
- When treated with understanding each of the main alternatives are excellent and competitive.
- Major remaining tasks to be completed:
  - Ammonia: charge reduction and better materials
  - HCs: extremely low charge, make it safe
  - CO_2: Reduce expansion losses, improve HXs
- Main issue: how to overcome initial higher cost if advantages are desirable