THE USE OF CO_2 AS REFRIGERANT

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History

- CO_2 was used as refrigerant at the end of the XIX century and the beginning of the XX century.
- It was widely used, specially in naval refrigeration.
- In 1930, when halocarbon refrigerants appeared, practically CO_2 disappeared.

History

- CO_2 lost against halocarbon refrigerants due its very high operating pressures and loss of capacity and low COP when the heat must be rejected close or over the critical point.
- A cycle with CO_2, with similar components has a COP 40% lower (approximately) than one with halocarbons.

Refrigerants Classification

- **Natural:**

  Organics

  Inorganic

- **Synthetics:**

  CFC

  HCFC

  HFC

  HFO

CO_2

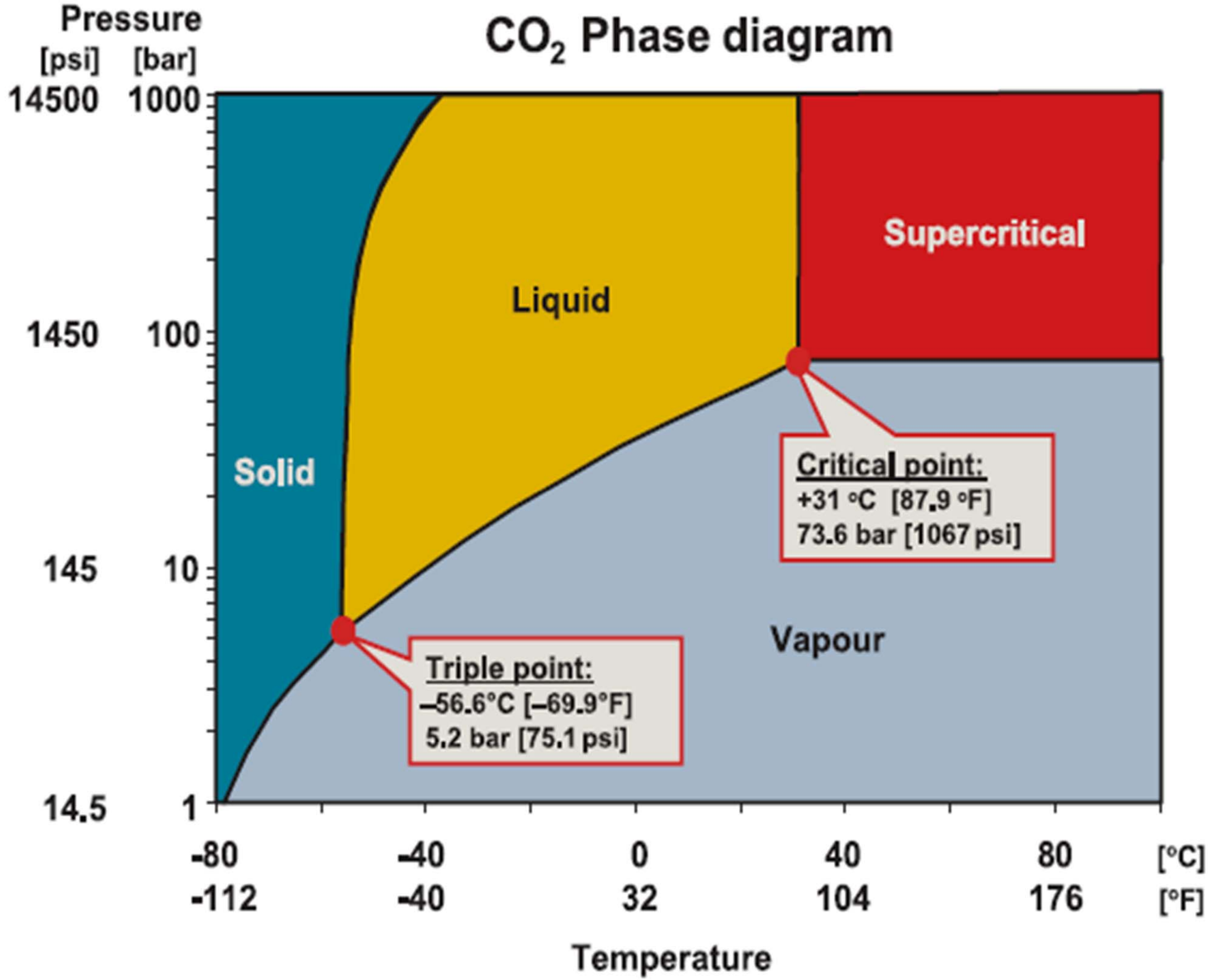
- It is a natural gas that is found in the atmosphere .
- The critical point has a temperature of 30,98ºC (87,9°F) and a pressure of 73,6 bars (1067psi).
- At atmospheric pressure does not exist in liquid state, so it changes from solid state to gaseous state in a process of sublimation.

CO_2

- It is odorless, non-flammable, and non-toxic.
- It is heavier than air, so if large quantities escape in a closed room the highest concentrations will typically be found close to the floor.
- If the concentration of carbon dioxide rises above the normal level in atmospheric air, it will cause the human breathing rate to increase.

Effects of CO_2 in Persons

Concentration (ppm)	Effects
350	Normal Value in air
1000	Maximum Value recommended for comfort
5000	TLV - TWA
20000	Breath afected 50% increased
30000	100 % increased
50000 (40000)	IDLH
100000	Minimum lethal concentration
300000	Immediately loss of conscious and convulsions


CO2 Phase diagram
Pressure
[psi] [bar]
14500 1000
1450 100
145 10
14.5 1
Solid
Liquid
Supercritical
Vapour
Critical point:
+31 °C [87.9 °F]
73.6 bar [1067 psi]
Triple point:
–56.6°C [–69.9°F]
5.2 bar [75.1 psi]
-80 -40 0 40 80 [°C]
-112 -40 32 104 176 [°F]
Temperature

Properties of Refrigerants

	Pressure	Latent Heat	Density	Espec. Vol.	Thermal Conductibility		Viscosity	
a -40°C			Liquid	Vapor	Liquid	Vapor	Liquid	Vapor
	bar	kJ/kg	kg/m3	m3/kg	mW/m K	mW/m K	μpa. s	μpa. s
R 744 - CO2	9,91	322,42	1116,4	0,0382	159,3	12,54	193,8	11,87
R 404 A	1,28	198,12	1290,1	0,1448	95	9,6	304	9,32
R 410 A	1,78	262,23	1311,3	0,1395	143	9,5	289,9	10,41
R717	0,71	1388,59	690,2	1,5533	688,1	20,64	281,2	7,86

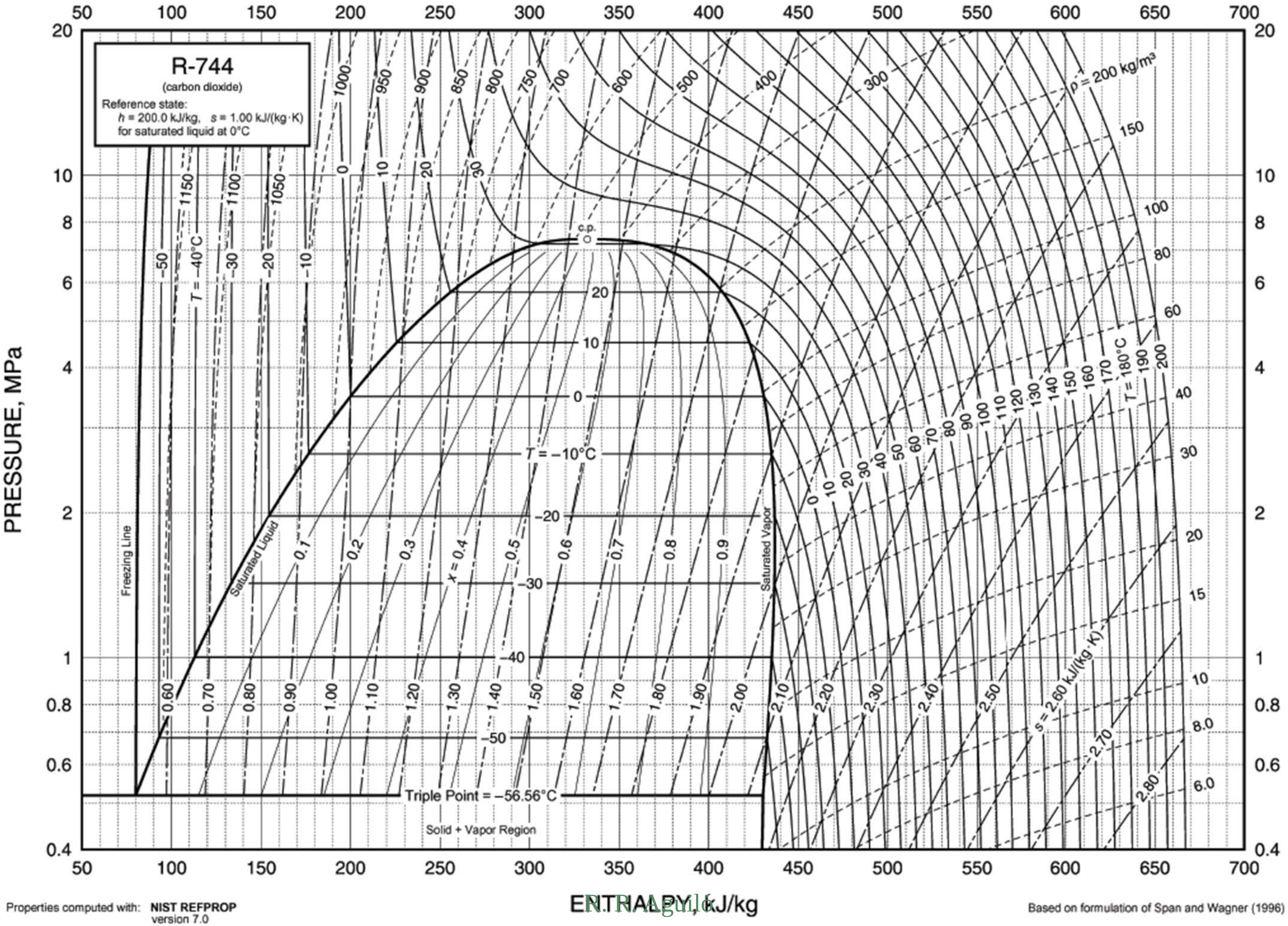
Compression Ratios

	Compression Ratio	
Refrigerant	ev 14F/cond 86F ev-10C/cond 30C	ev -22F/cond 86F Ev-30/cond 30C
R22	3,36	7,27
R134a	3,84	9,13
R404A	3,26	6,76
R717	4,01	9,77
R744	2,72	5,05

Applications with CO_2

- Subcritical Cycle
- Transcritical Cycle
- Use as secondary refrigerant

- Double Stage Cycle
    - Cascade
    - Booster

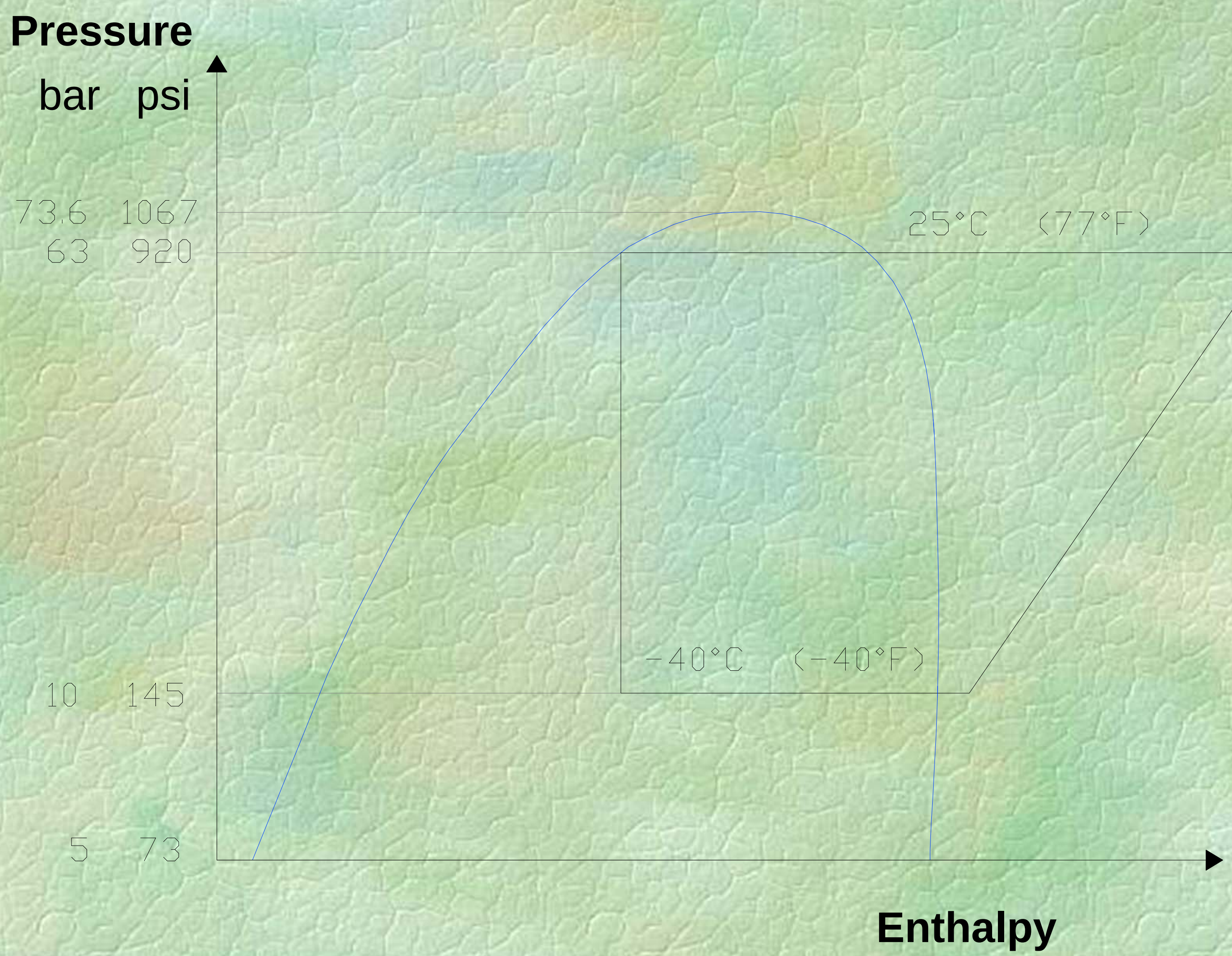


Properties computed with: **NIST REFPROP** version 7.0

Based on formulation of Span and Wagner (1996)

Fig. 18 Pressure-Enthalpy Diagram for Refrigerant 744 (Carbon Dioxide)

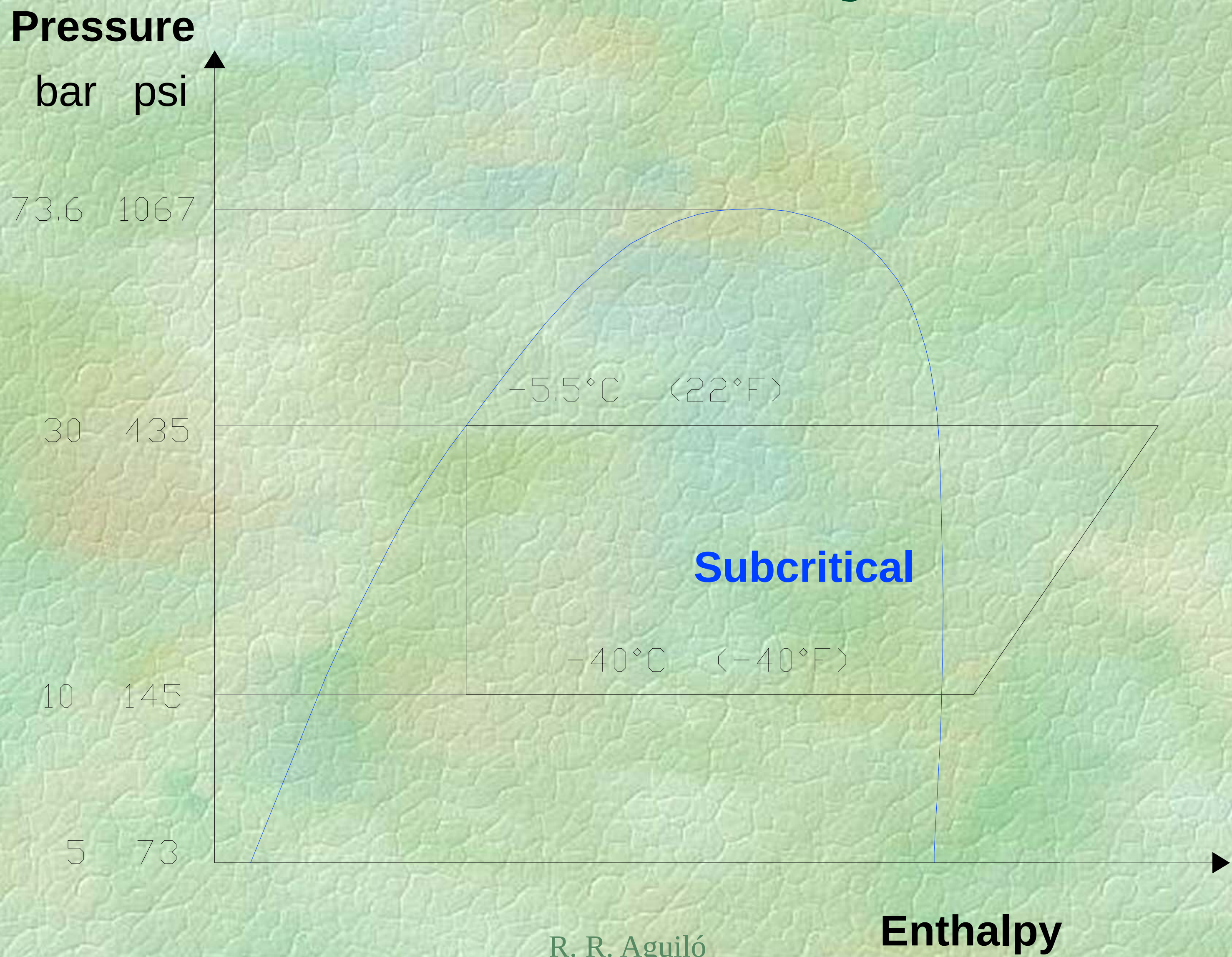
Subcritical Cycle



Subcritical Cycle

- Normal refrigeration components can be used for temperatures between -50°C (-58°F) to 0°C (32°F).
- In these conditions working pressures will be between 6,7 and 35 bar (100 to 500 psi)
- In hot gas defrost systems, pressure will be 10 bars (145 psi) higher.

Subcritical Cycle



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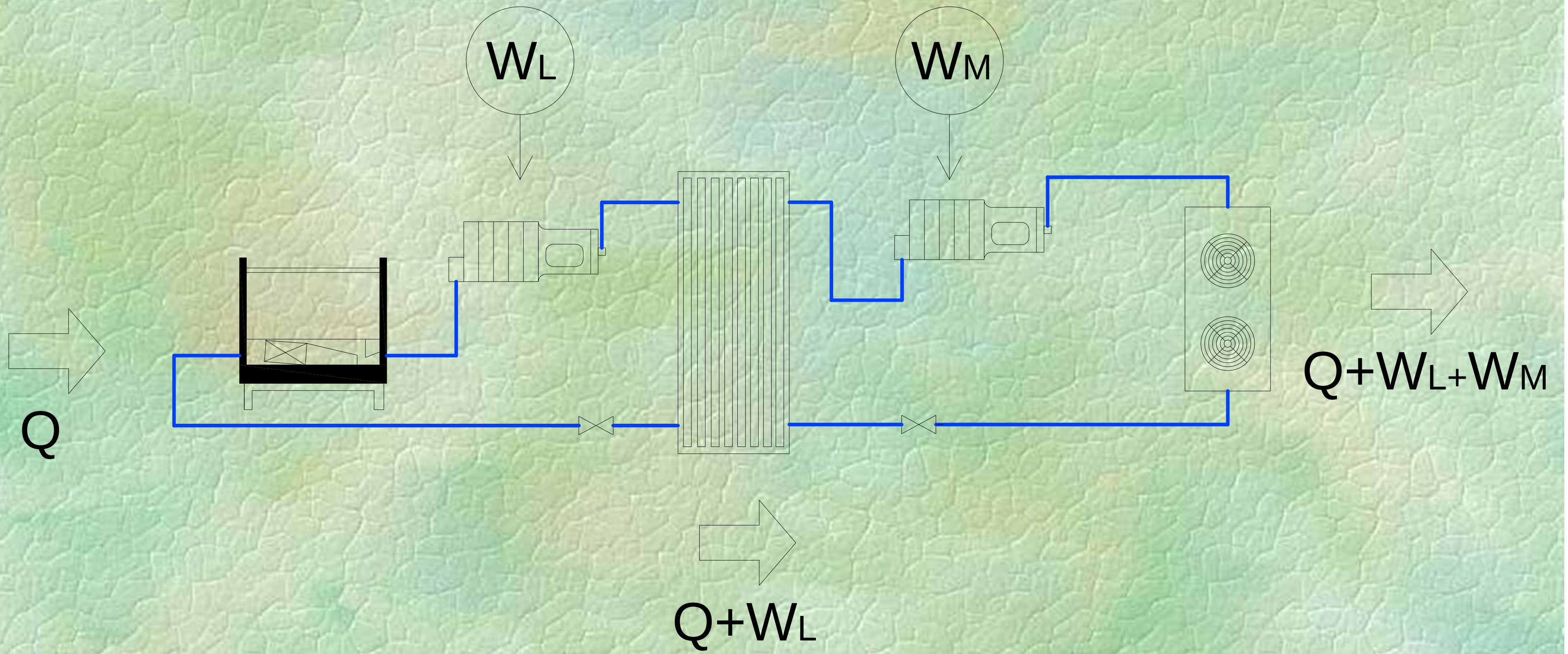
Subcritical Cycle

- To work in these conditions, practically the only way is doing it, in a cascade double stage system.
- In this way, working high pressure is limited to values similar to actual ones, so we can use normal refrigeration components.

Cascade Double Stage Systems

- Working pressures of CO_2 in cascade systems are low (typically 40 / 45 bar – 580 / 650 psi).
- Efficiency of the system is high even in hot climates.
- Only a small amount of other refrigerant is needed for high temperature stage.
- Temperature difference for cascade heat exchanger is relatively low.

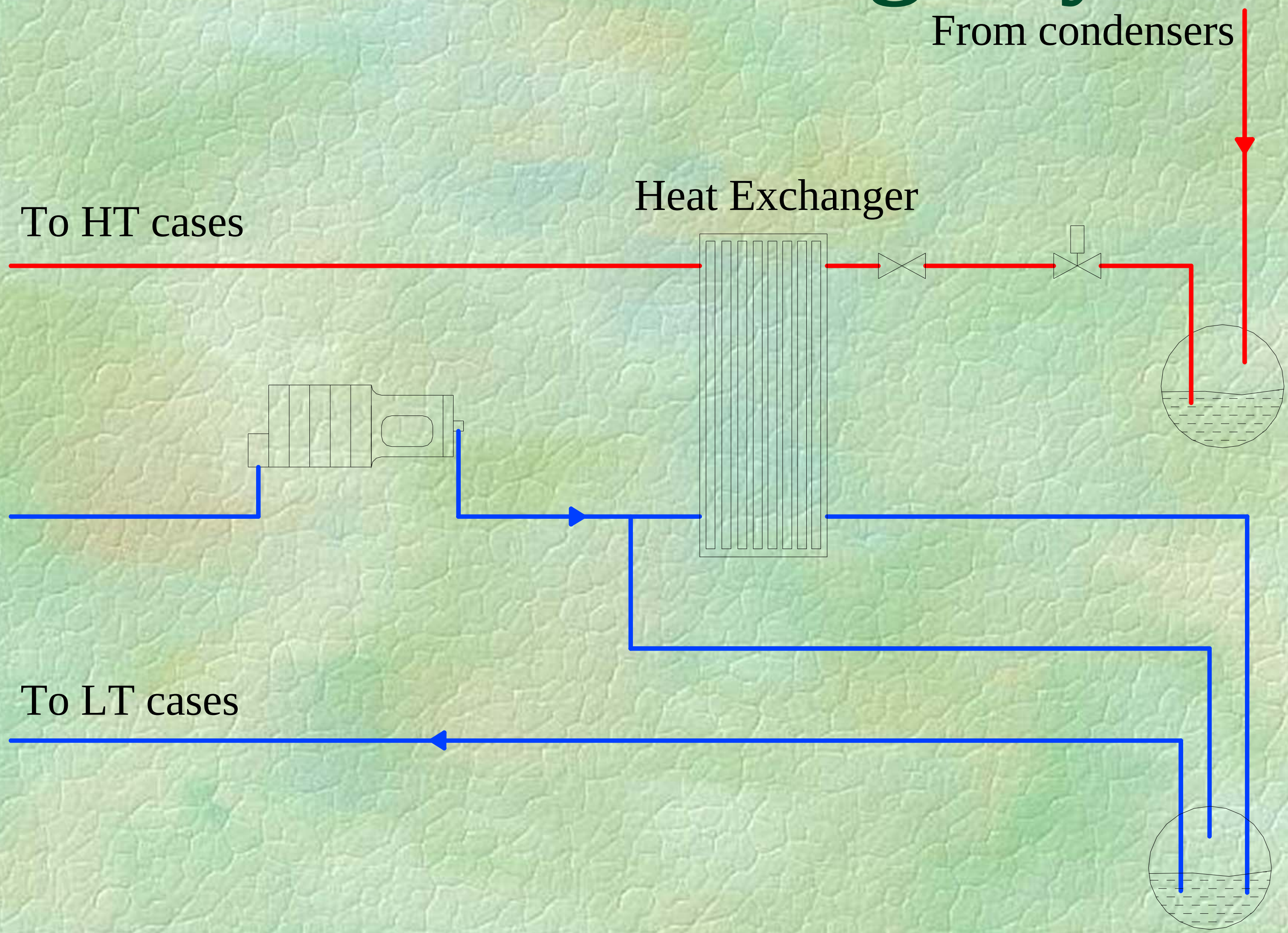
Cascade Double Stage Systems



Cascade Double Stage Systems

- It is very important the selection of the heat exchanger that is used as condenser of the low temperature system, that at the same time is the evaporator in the high temperature system.
- For selection it must be consider that there are phase change in both sides.
- Plates heat exchangers are commonly used in commercial systems.

Cascade Double Stage Systems



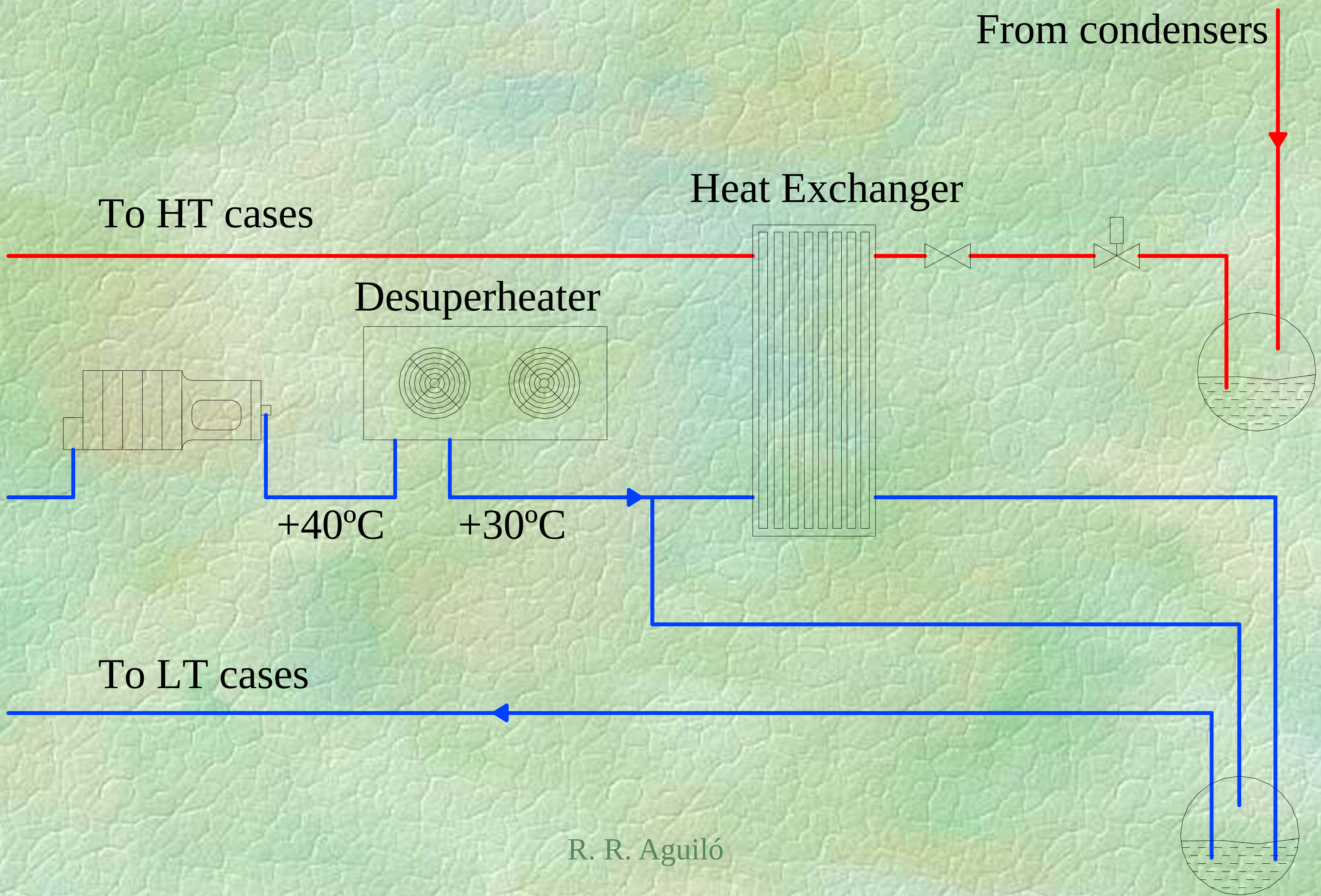
Cascade Double Stage Systems

- It is important that condensed liquid in the heat exchanger drain correctly. It is advisable to use an equalization line.
- It must be assured that liquid injection in the side working as high temperature evaporator begins before low temperature compressor starts.

Cascade Double Stage Systems

- Injection to the cascade heat exchanger is done by a motorized valve, controlled by an electronic control. It is enabled when compressor on the CO_2 side starts up.
- This is monitored by a rack controller running the system, which in turn, initiates the electronic control and the motor valve.

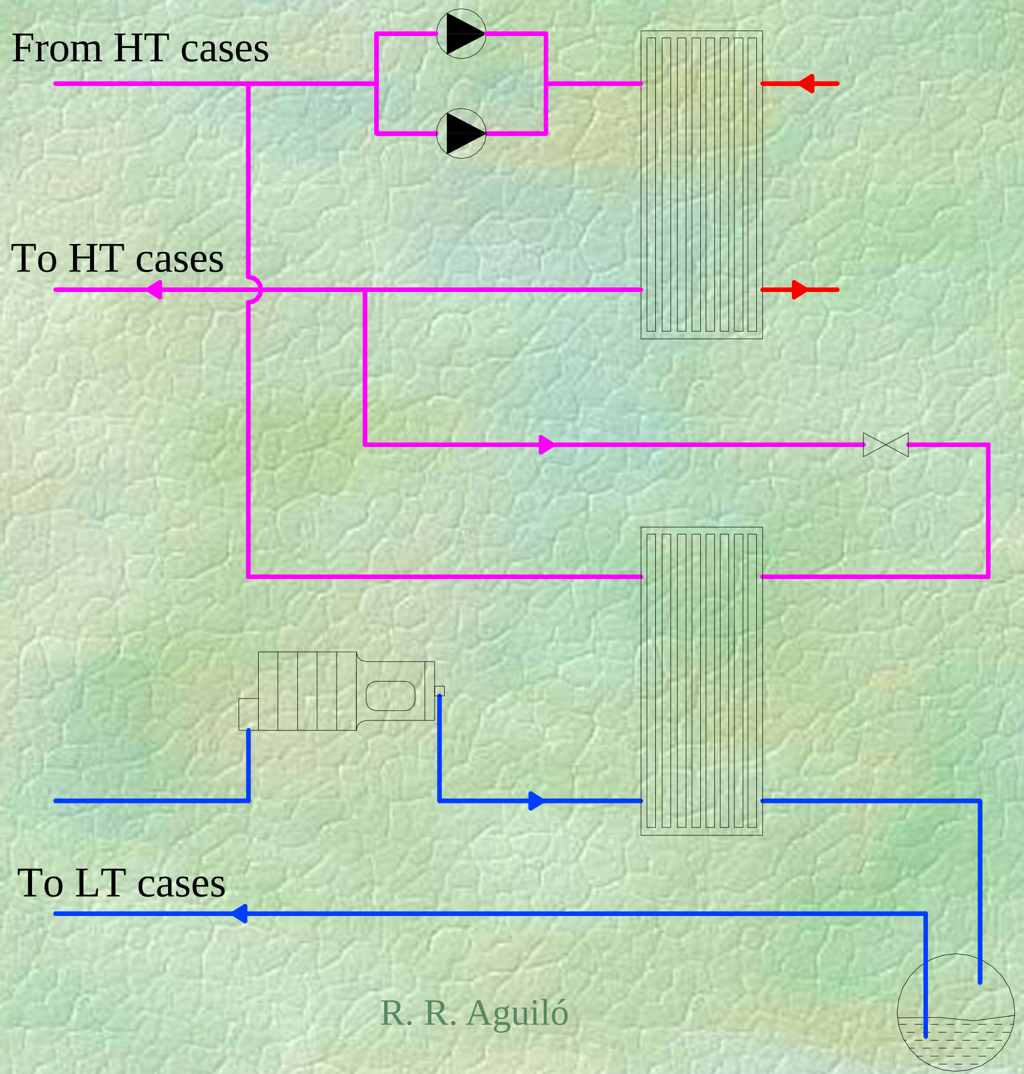
Cascade Double Stage Systems
Desuperheater



Cascade Double Stage Systems

- Inter-stage heat exchanger can be cooled using a glycol solution in the high temperature side.
- With the glycol solution, heat exchanger regulation is much easier.
- Generally, the same glycol installation is used for the medium temperatures loads.

Cascade Double Stage System with Glycol



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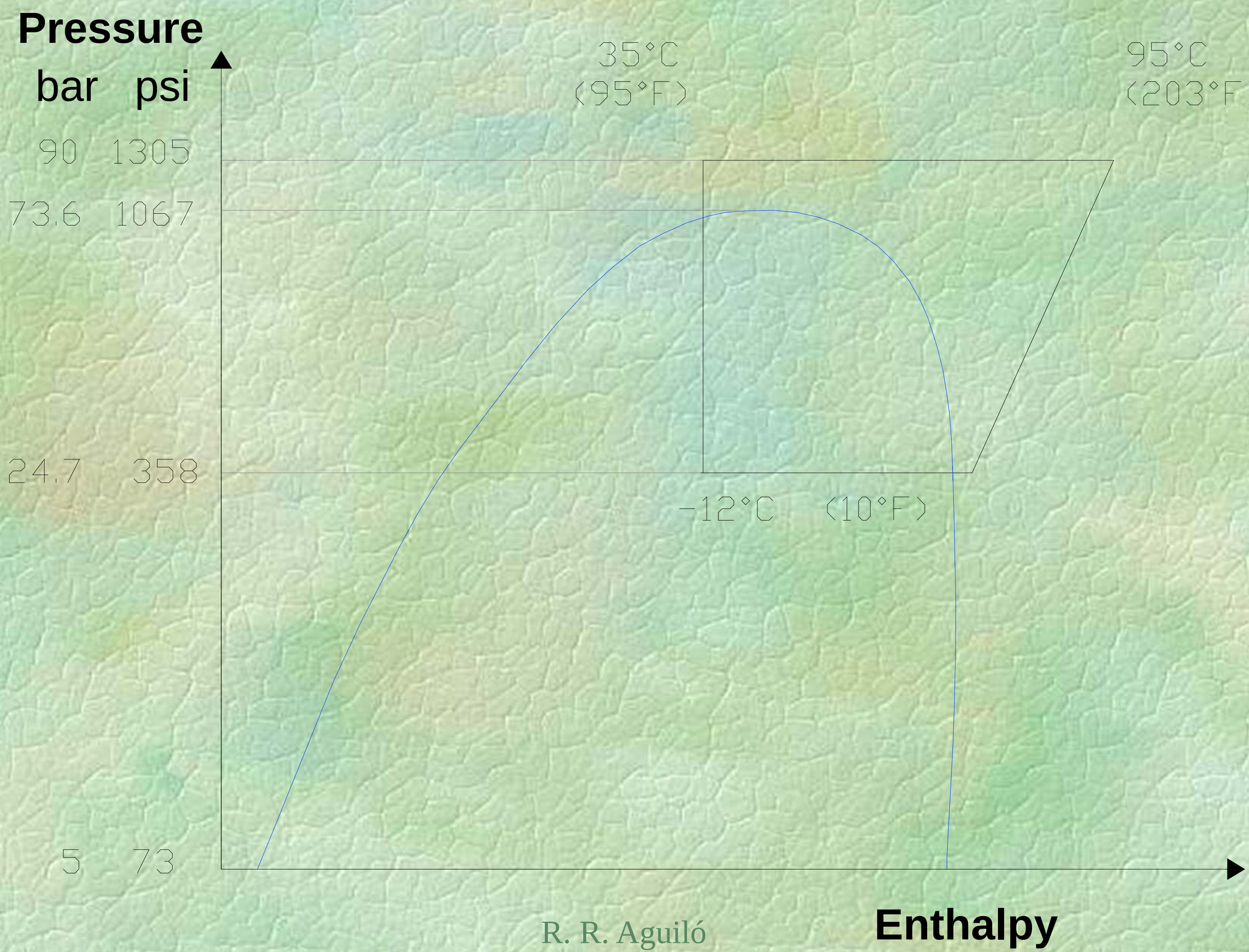
Transcritical Cycle

- In a transcritical cycle the condensation of the refrigerant doesn´t appear in the equipment where heat is rejected to the cooling media.
- It happens in this way because heat rejection occurs over the critical point and in this condition it is impossible to condense the refrigerant despite how much pressure goes up.

Transcritical Cycle



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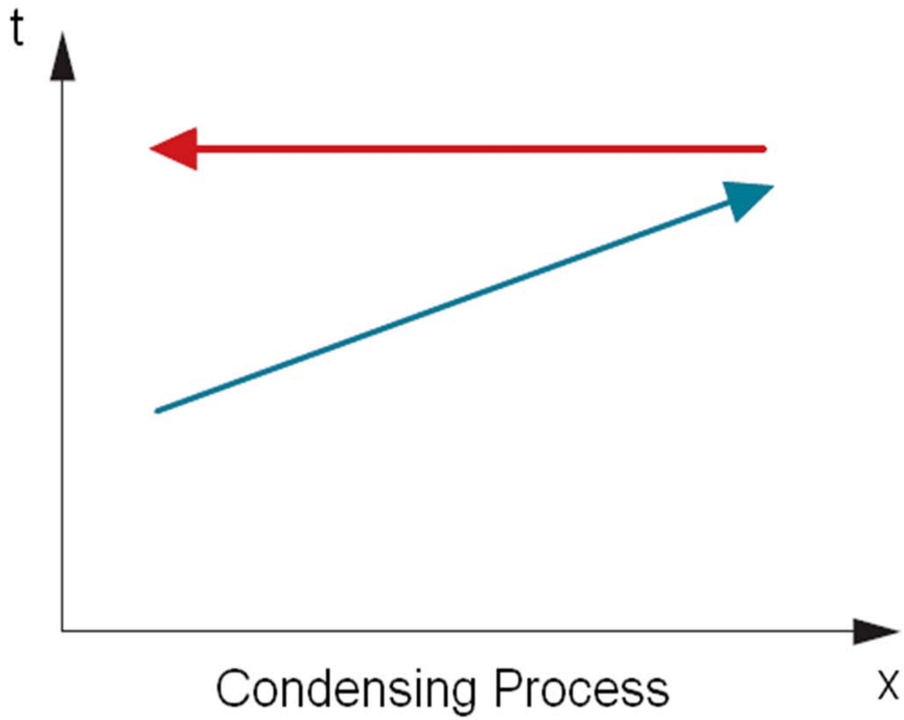
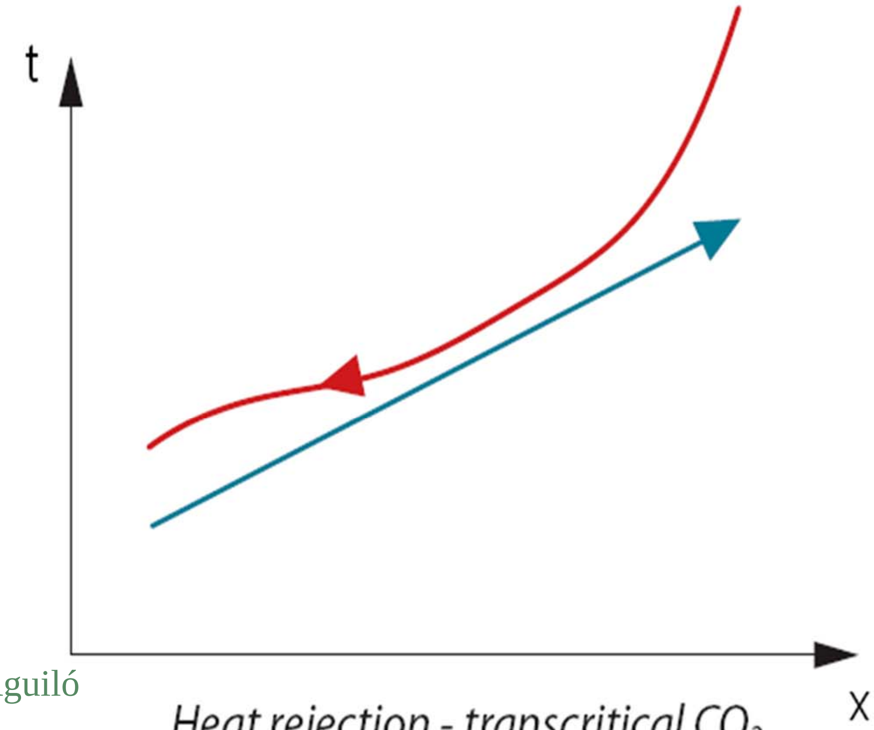
Transcritical Cycle

- When the cooling media has a temperature higher than 20°C (68°F) surely the cycle will be transcritical.
- CO_2 can´t condense over 31°C (88°F).
- In the high temperature heat exchanger, refrigerant temperature decreases continually.



Condensing Process



Heat rejection - transcritical CO_2

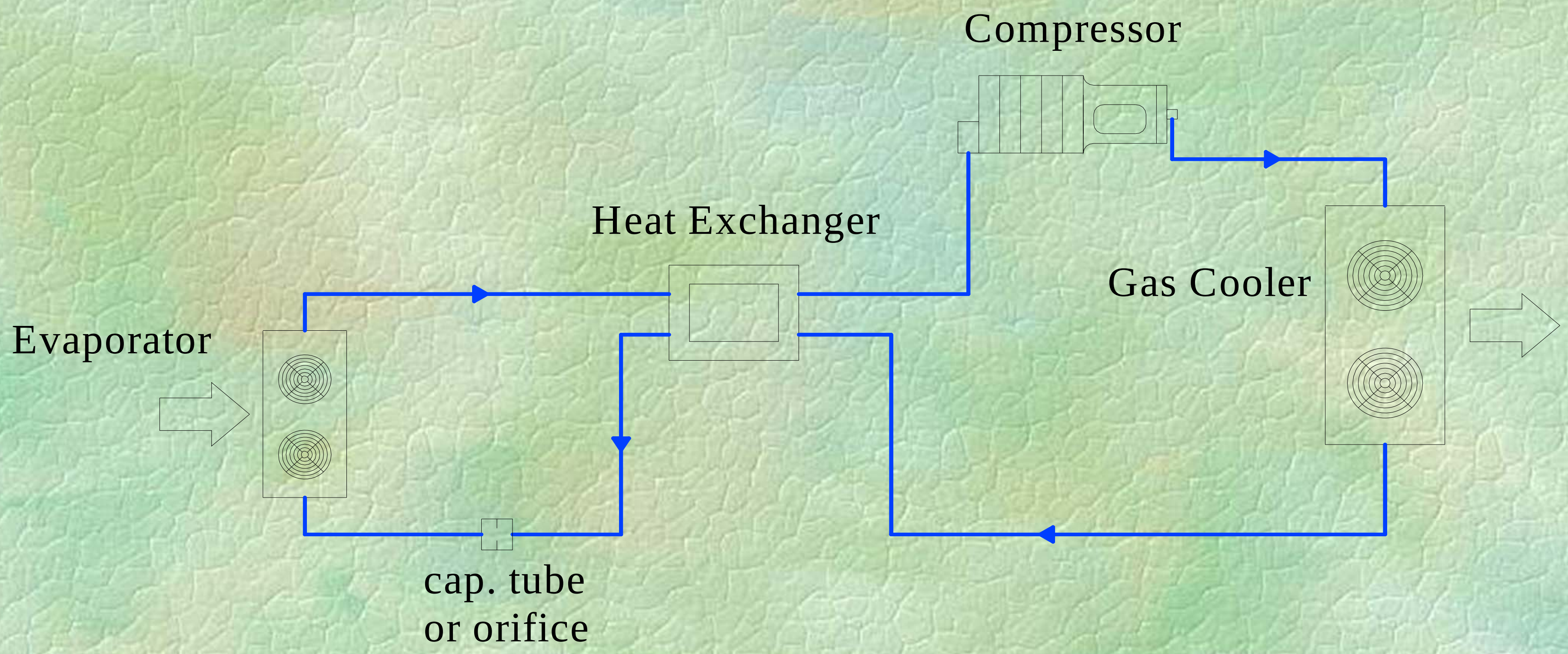
Transcritical Cycle

- The pressure in the gas cooler in a simple system without receiver is determined by the refrigerant charge.
- In a system with a fixed restriction expansion device (e.g. capillary tube), the pressure in the gas cooler will depend on how much refrigerant the system is charged with and its distribution between the components.

Transcritical Cycle
Simple System

- A fixed flow restriction as expansion device can be used for systems that operate with medium variations in ambient temperature but with requirements for capacity or efficiency at only one fixed rating point.
- An internal heat exchanger enhance the performance of the system

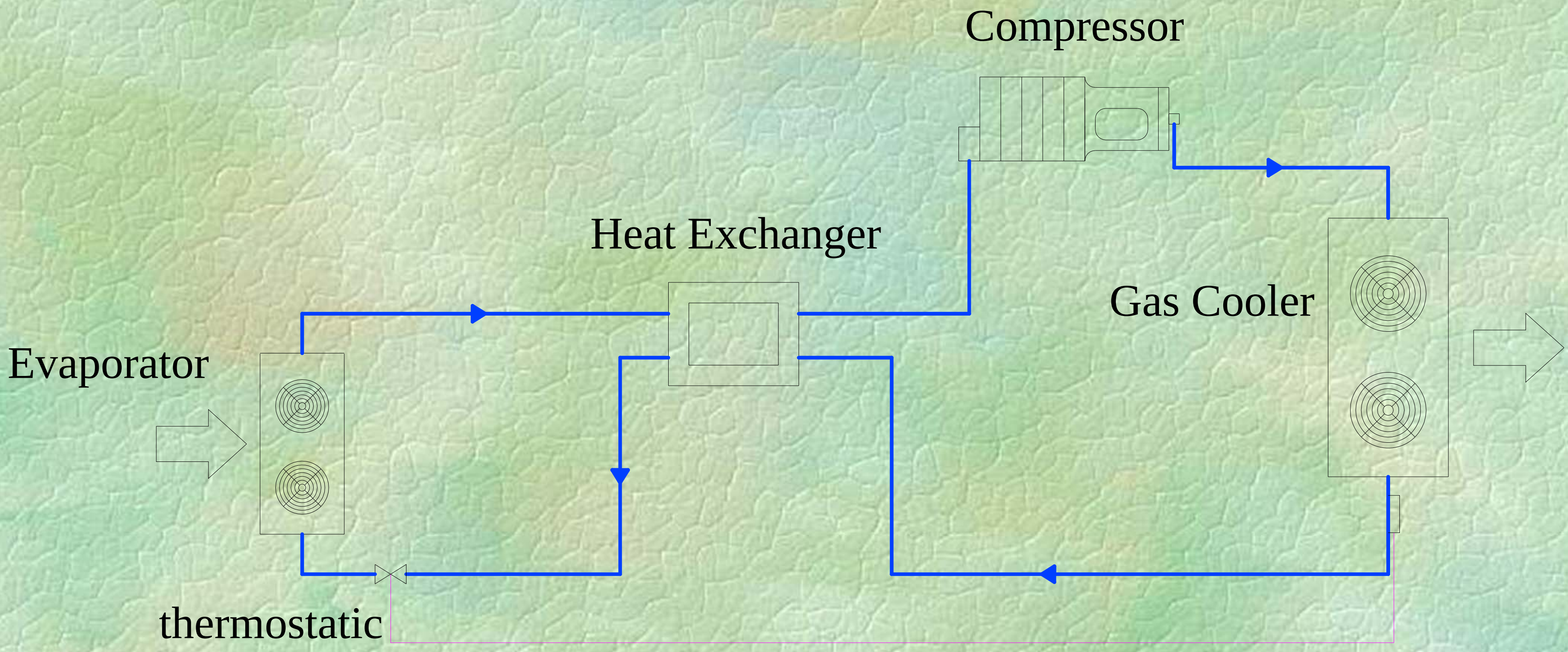
Transcritical Cycle
Simple System



Transcritical Cycle Simple System

- A thermostatic expansion valve can be used for systems that operate with large variations in ambient conditions and with requirements for capacity or efficiency at two or more rating points.
- If there is small variations in ambient temperature an automatic expansion valve can be used.

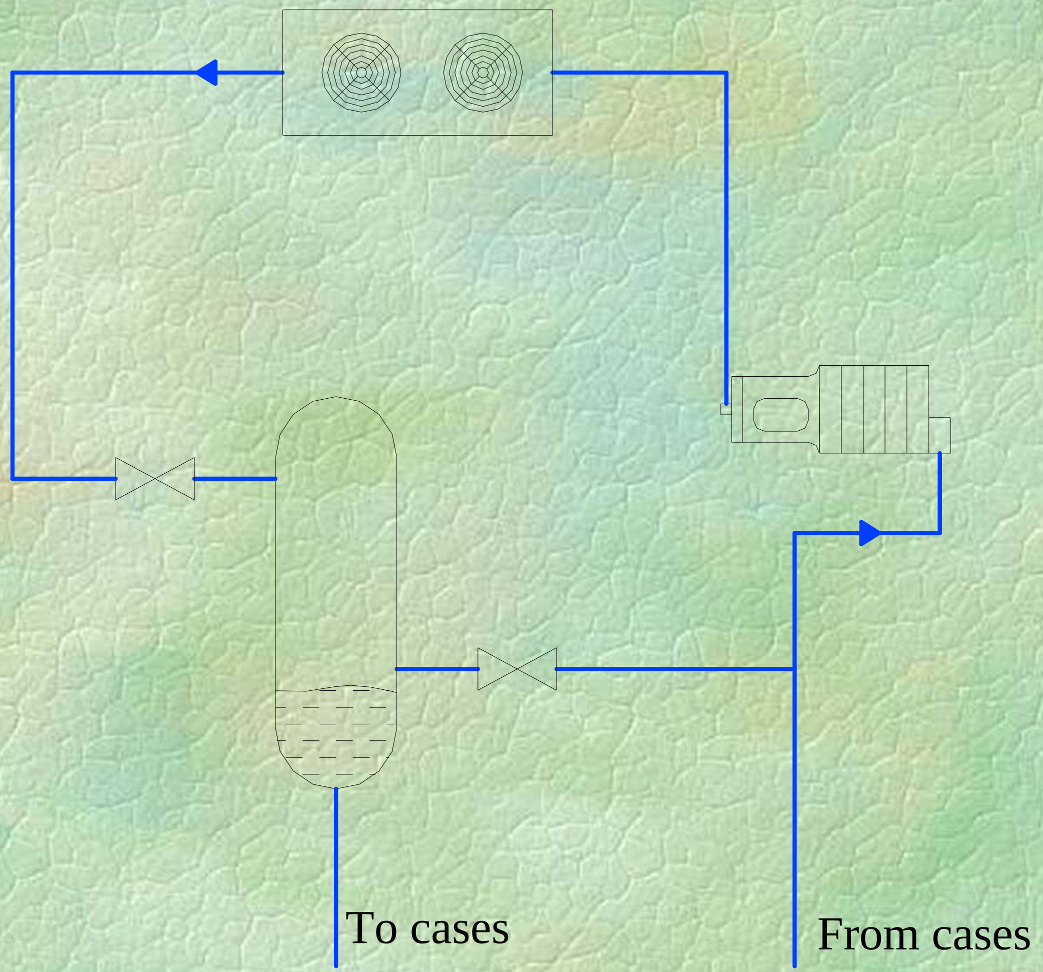
Transcritical Cycle
Simple System



Transcritical Cycle

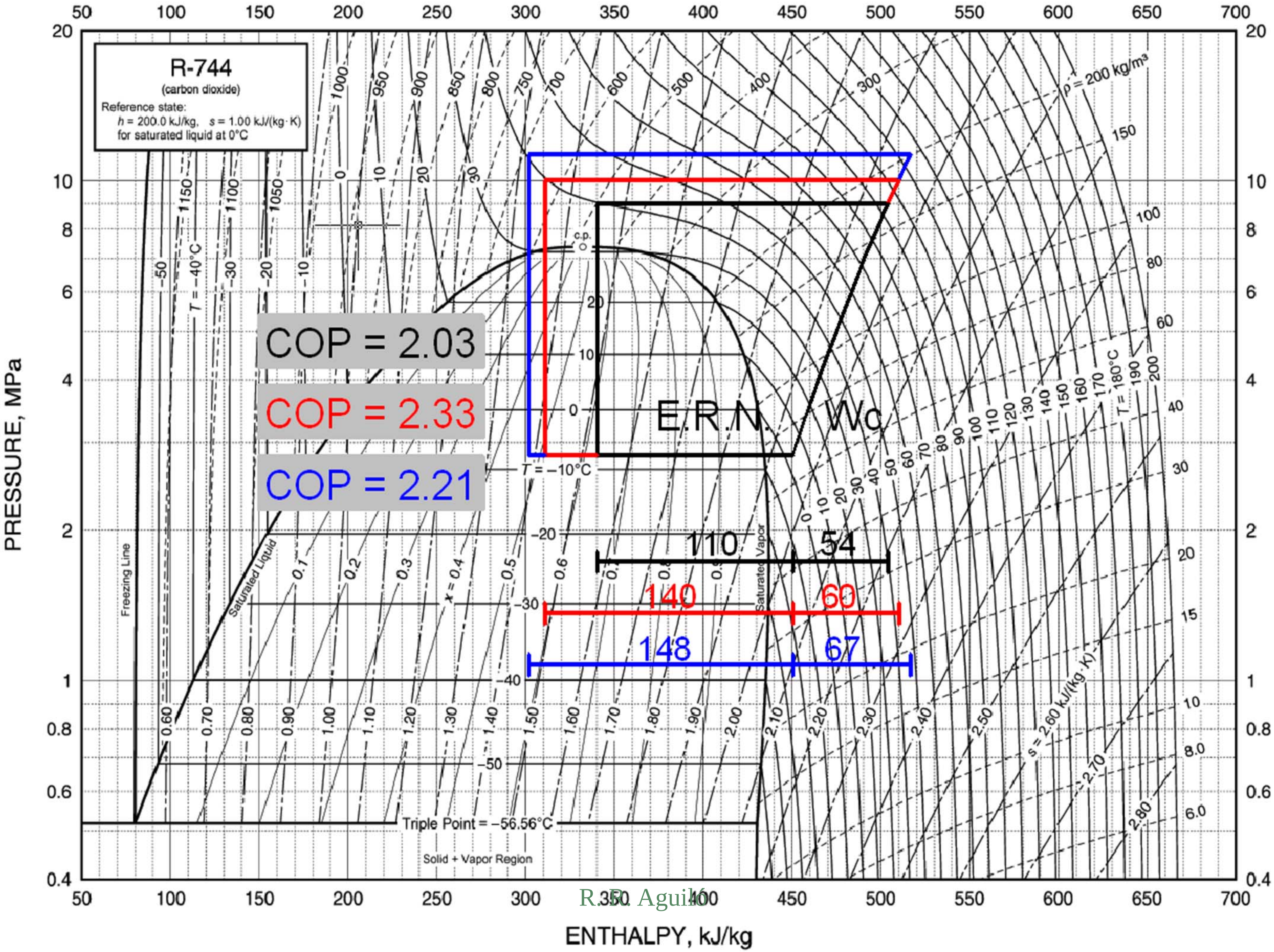
- Liquid refrigerant will appear in the expansion process when pressure is reduced and enter in the area under the saturation liquid line.
- In larger systems an expansion valve is mounted between the gas cooler and the liquid receiver.
- The liquid receiver also works as liquid separator.

Intermediate Pressure Control



Transcritical Cycle

- To reduce the pressure in distribution systems, the gas bypass is removed toward the compressor.
- After the high pressure expansion, the gas and liquid are separated and the gas is bypassed directly to the suction side of the compressor.
- The liquid is distributed to the evaporators and makes it possible to use standard pressure components


R-744
(carbon dioxide)
Reference state:
h = 200.0 kJ/kg, s = 1.00 kJ/(kg·K)
for saturated liquid at 0°C
COP = 2.03
COP = 2.33
COP = 2.21
E.R.N.
Wc
110
54
140
60
148
67
PRESSURE, MPa
ENTHALPY, kJ/kg
Freezing Line
Saturated Liquid
Saturated Vapor
Triple Point = −56.56°C
Solid + Vapor Region
T = −10°C
ρ = 200 kg/m³
s = 2.60 kJ/(kg·K)
T = 180°C
c.p.

Transcritical Cycle

- The optimum condition for refrigerating capacity is found for a higher gas cooler pressure than for the optimum condition for COP.
- For a system operating at conditions close to the optimum COP, the extra refrigerating capacity that can be obtained by increasing the gas cooler pressure is relatively small.

Transcritical Cycle

- Flash gas is discharged from the receiver to the compressor in a bypass.
- If the bypass is not installed it means that mass flow is doubled what makes difficult the design of suction lines and the oil return.

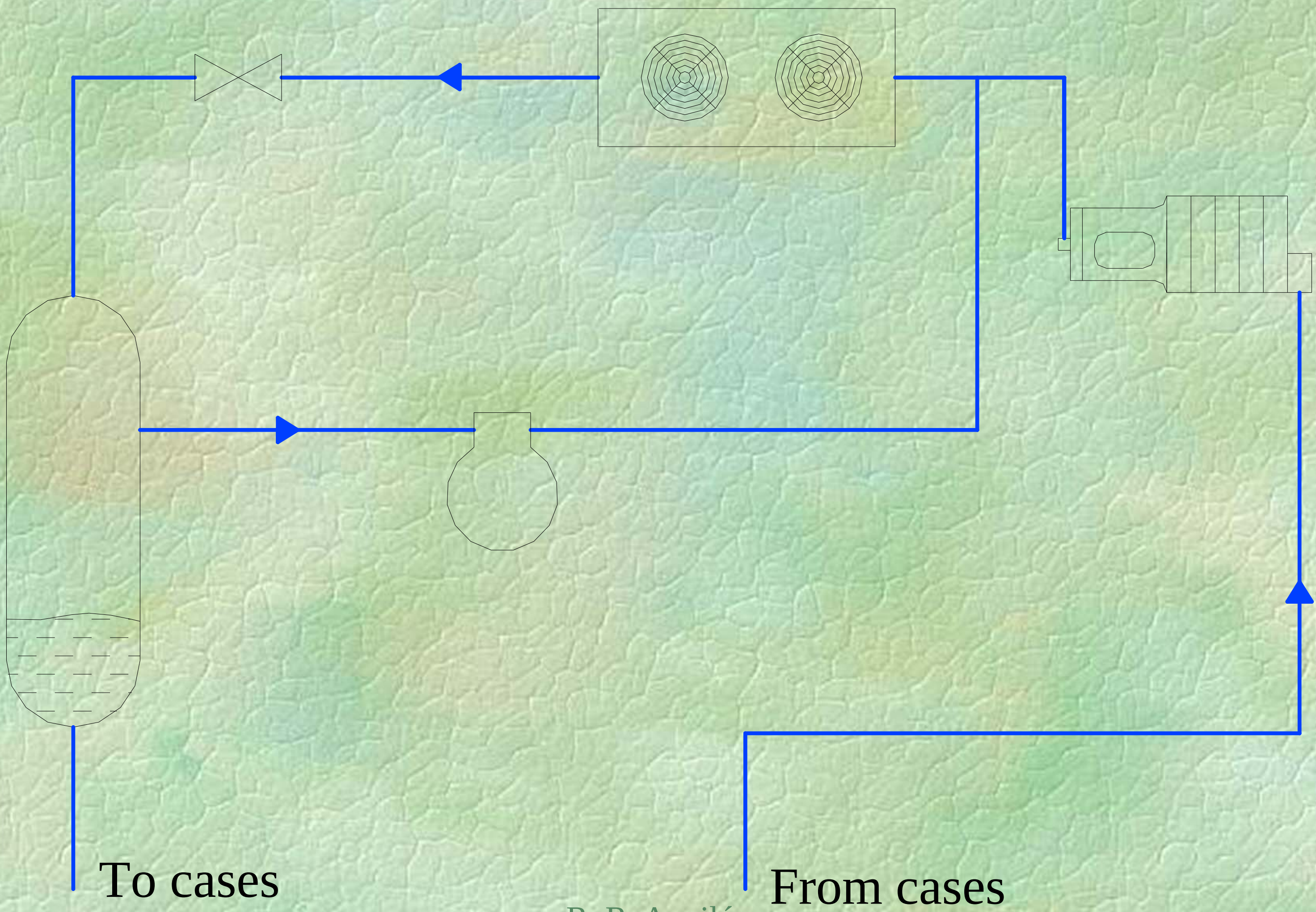
Intermediate Pressure Control

- Gas cooler pressure must be as low as possible to reduce the amount of liquid in the bypass line.
- Usually pressures between 30 to 35 bar / 435 to 500 psi (-8°C to -10°C / 18°F to 14°F) are chosen because liquid in the bypass is approximately between 1 a 2%.

Intermediate Pressure Control
Parallel Compression

- To lower the energy consumption, parallel compression is one of the technologies that is available.
- In this case, instead of bypassing the gas from the receiver, the gas is compressed directly

Intermediate Pressure Control



Gas Coolers

- It is the component that presents more differences with a normal one.
- The heat rejection for condensing refrigerants occurs at constant pressure and the condensing temperature is determined by the final temperature of the cooling media.

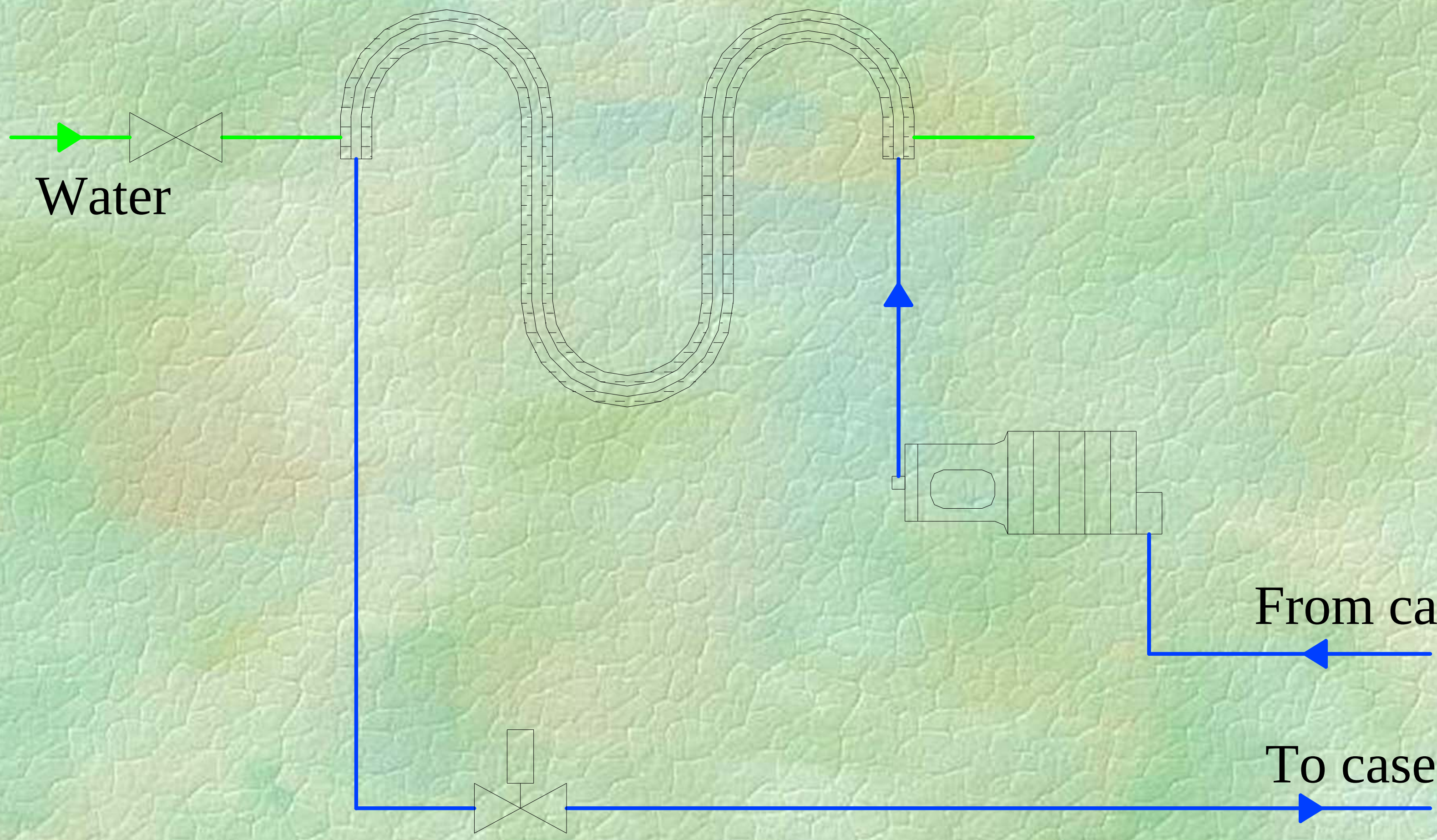
Gas Coolers

- In the transcritical cooling of CO_2 the minimum temperature difference between refrigerant and cooling media is not at the end of the cooler.
- To obtain the maximum cooler efficiency, it must work as counter flow.
- It must be designed to handle very high pressures.

Water Gas Coolers

- Characteristics of water gas coolers are great heat exchange in both sides and very compact size.
- Coaxial heat exchangers (tube in tube) are very good and commonly used.
- Internal volume is very small compared with its thermal capacities.

Water Gas Coolers



Water Gas Coolers

- Water flow in the system is controlled by a pressure operated water valve, which regulates according to the discharge temperature.
- CO_2 pressure is regulated by an electronic regulated valve and a controller taking an input from a temperature sensor and a pressure transmitter

Water Gas Coolers

- High temperatures of CO_2 create a problem with limestone that needs attention.
- The discharge gas of some systems are as high as 160°C (320°F) and together with the relatively high heat capacity and high heat transfer coefficient compared to other refrigerants, the wall temperature will be higher than that of other refrigerants.

Gas Air Coolers

- Gas air coolers have a lower heat transfer coefficient, therefore they are larger and have greater internal volume than water gas coolers.
- Pressure drops in the order of 0.5 to 1 bar (7 to 14 psi) are normal and do not affect the performance by enabling the use of small diameter pipe (5 / 16 "or 3 / 8").

Gas Air Coolers

- Gas air coolers do not have a perfect countercurrent flow and heat conduction in fins is a problem.
- Depending on their configuration there can be 100 ° C (180°F) difference between two pipes separated 20 to 25 mm. (3/4 to 1 inch)
- In this way the capacity can be reduced between 20 to 25%, but it can be improved by dividing the fins.

Compressors

- Hermetic or semi-hermetic compressors are commonly used.
- Open compressors have problems in the seals because of the high pressure.
- Usually works at 1450 rpm at 50 Hz (1750 rpm at 60 Hz).

Compressors

- With evaporating temperatures of -10°C (14°F), discharge temperatures of 200°C (390°F) can be given. Semi-hermetic compressors can not tolerate it. It must be ensured low superheating.
- It is advisable the use of two stages of compression when the evaporation temperature is below -25 °C (-13°F).

Compressors

- The specific volumetric capacity is 5 to 10 times larger, which means lower volumes displaced, but much higher strengths in the compressor.
- Thermal load is great and very high discharge temperature.

Compressors

- Poliolesters oils are highly miscible with CO_2 in transcritical conditions and significantly decreases the lubricating power.
- The compressor manufacturers recommend the use of oil coolers.

Liquid Separator

- A liquid separator is a vessel that, by gravity, separates liquid and gas and also contains a managed level of liquid which goes to the evaporators.
- The vessels have to be designed to meet the physical properties of the refrigerant.

Design Pressure

It depends on various parameters:

- Pressure during operation
- Pressure during stand still
- Temperature requirements for defrosting
- Pressure tolerances for safety valves (10-15%)

For CO_2 stand still pressure is the main limiting factor

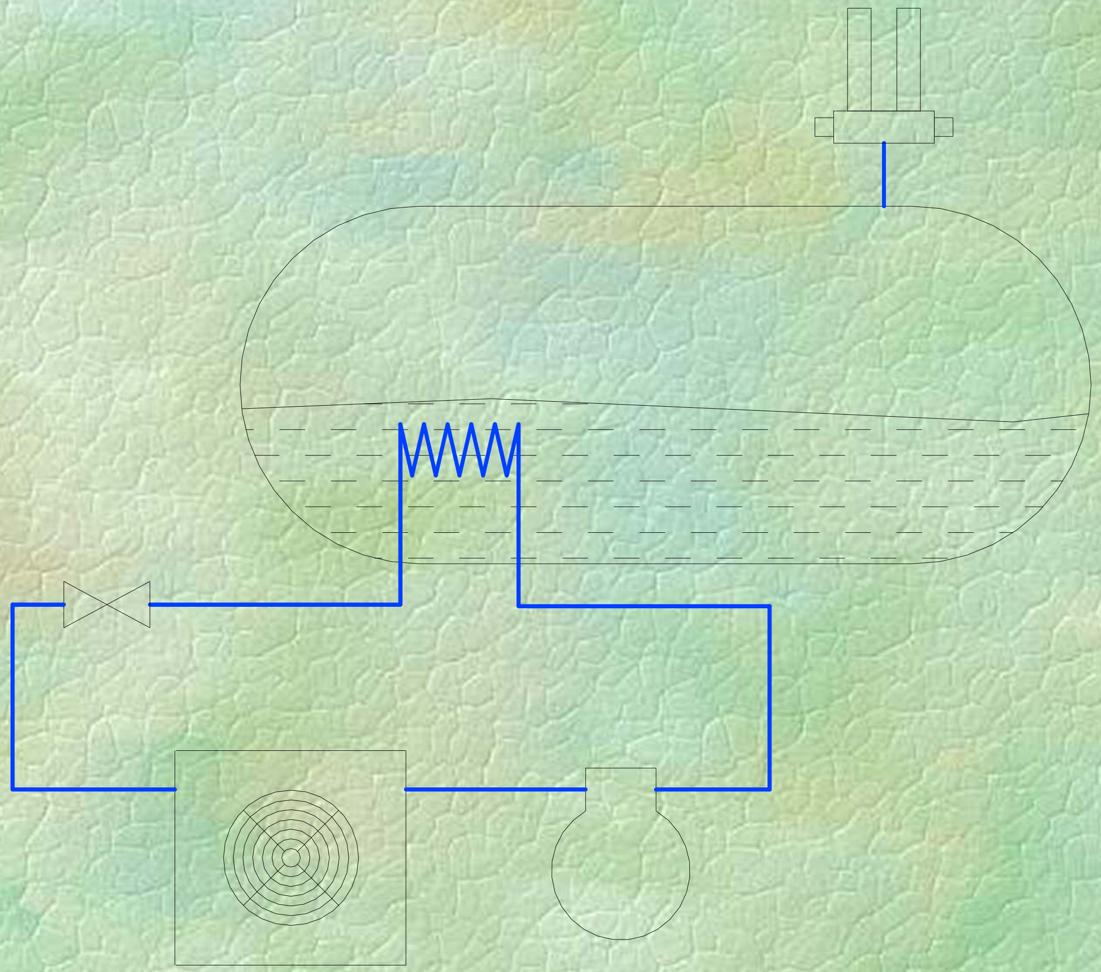
Design Pressure

- There are two major factors defining CO_2 pressure during standstill:
  - ambient temperature
  - the charge of the system
- As long as CO_2 is in liquid form, the pressure in the system is saturated and corresponds to the ambient pressure, e.g. ambient temperature 20ºC (68°F) corresponding to approx. 57 bar (826psi).

Separator Pressure Control

- To assure that liquid separator pressure remains in the specified values the following can be used:
  - Auxiliary refrigeration systems
  - CO_2 venting

Auxiliary Refrigeration System



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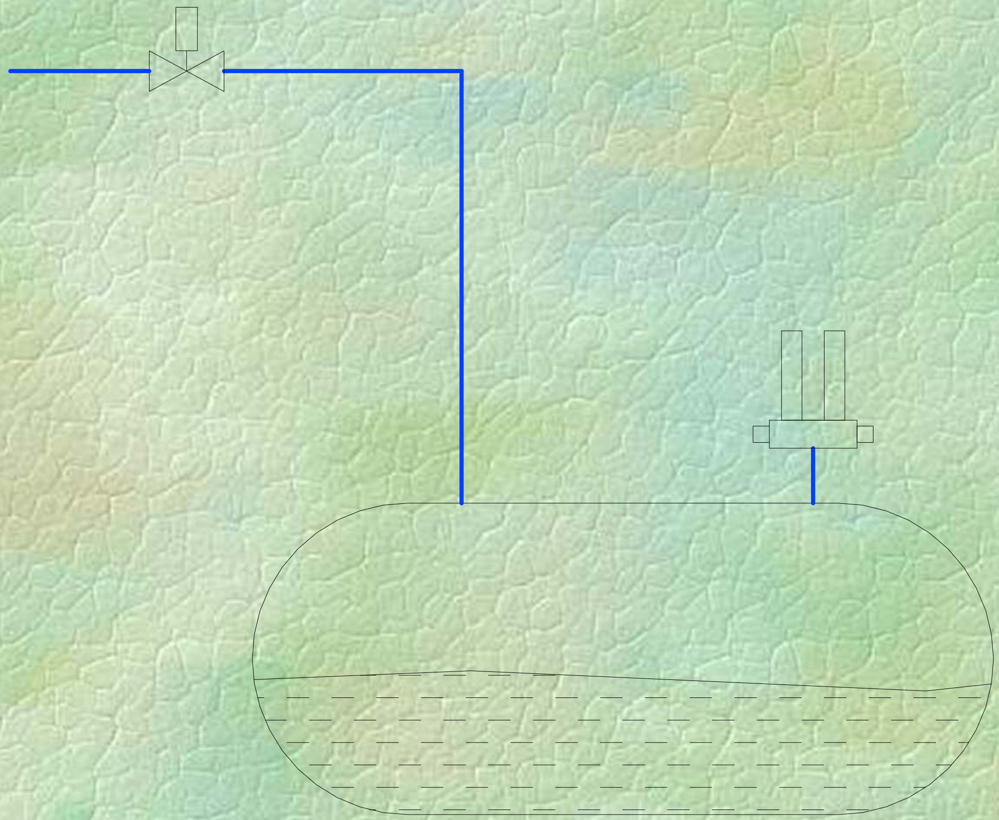
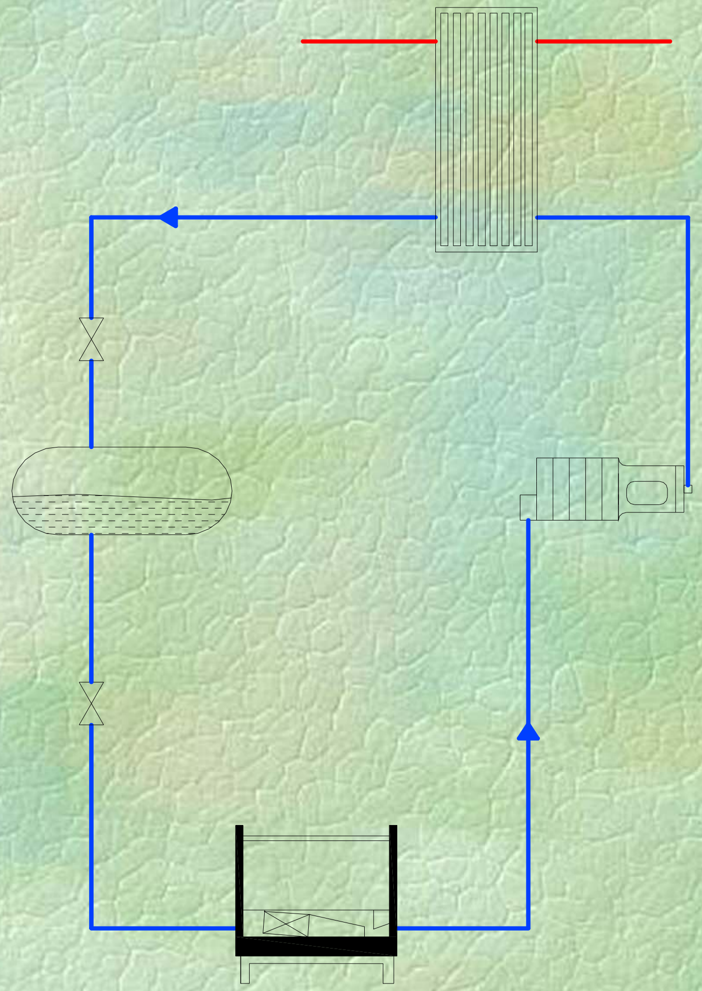
Venting System



Refrigerant Flow Control to Evaporators

- The flow control systems of the evaporators is just like with any other refrigerant:
  - Direct Expansion
  - Pump Recirculated Systems

Direct Expansion Systems



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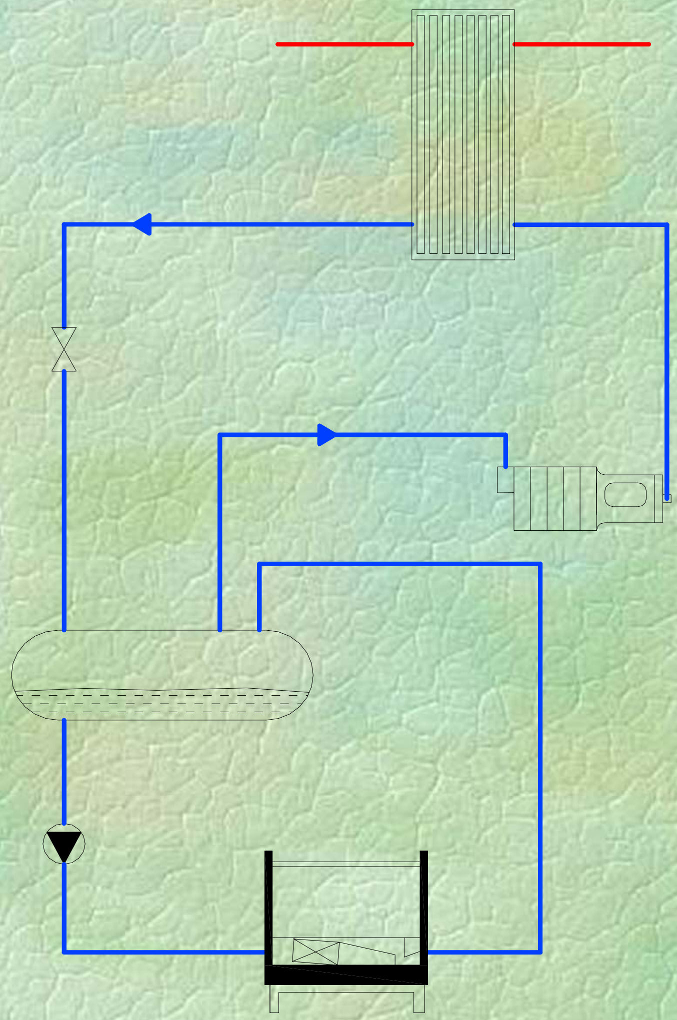
Direct Expansion Systems

- Smaller charged DX systems are less complex, as they do not require pumps or liquid level controls systems.
- A disadvantage of these systems is an efficiency penalty due to the higher superheat level.
- For this reason they would be typically used for smaller systems (e.g. discount stores or convenience store).

Recirculated Systems



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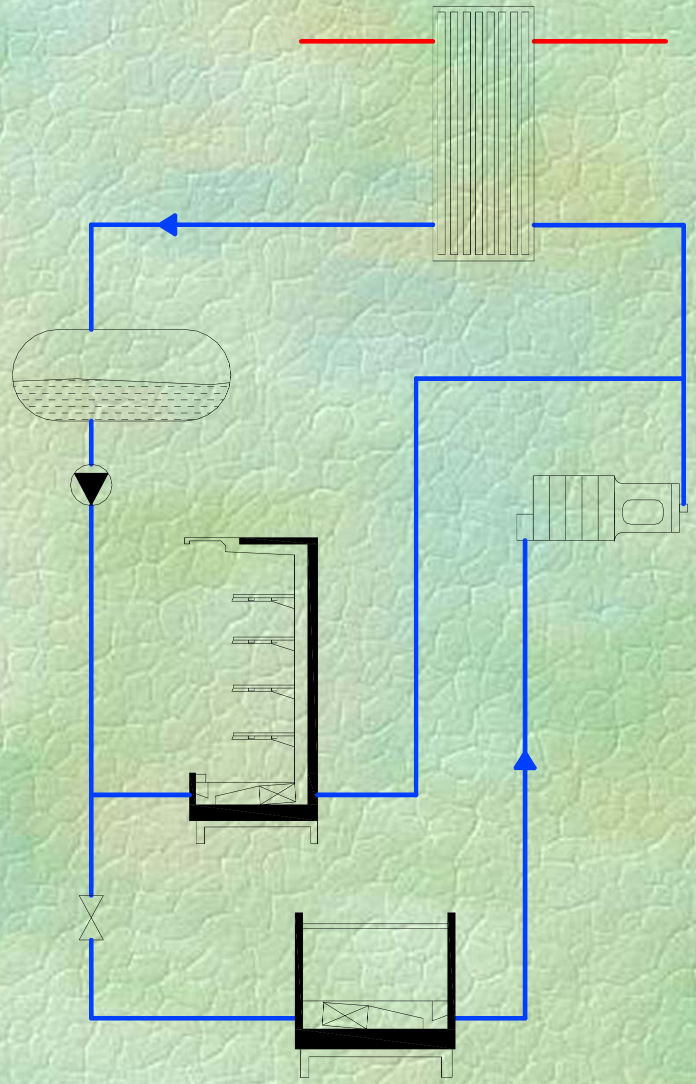
Combined Systems



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Recirculated Systems

- The recirculated rate for CO_2 is about 1.5 a 2.5.
- Refrigerant velocity in suction lines to pump must be between 0.3 a 0.5 m/s.
- It must be ensure a minimum flow in order to cool the motor winding in the low flow range of the pump. This is done with the use of a by-pass with Q-min orifice.

Recirculated Systems

- A variable speed drive could be successfully used for CO_2 pumps, as they are quite often oversized.
- A check valve typically has to be installed in a discharge line of a pump in order to prevent backflow during standstill and parallel operation.
- A typical minimum differential pressure over CO_2 pump lies between 15 and 45 psi.

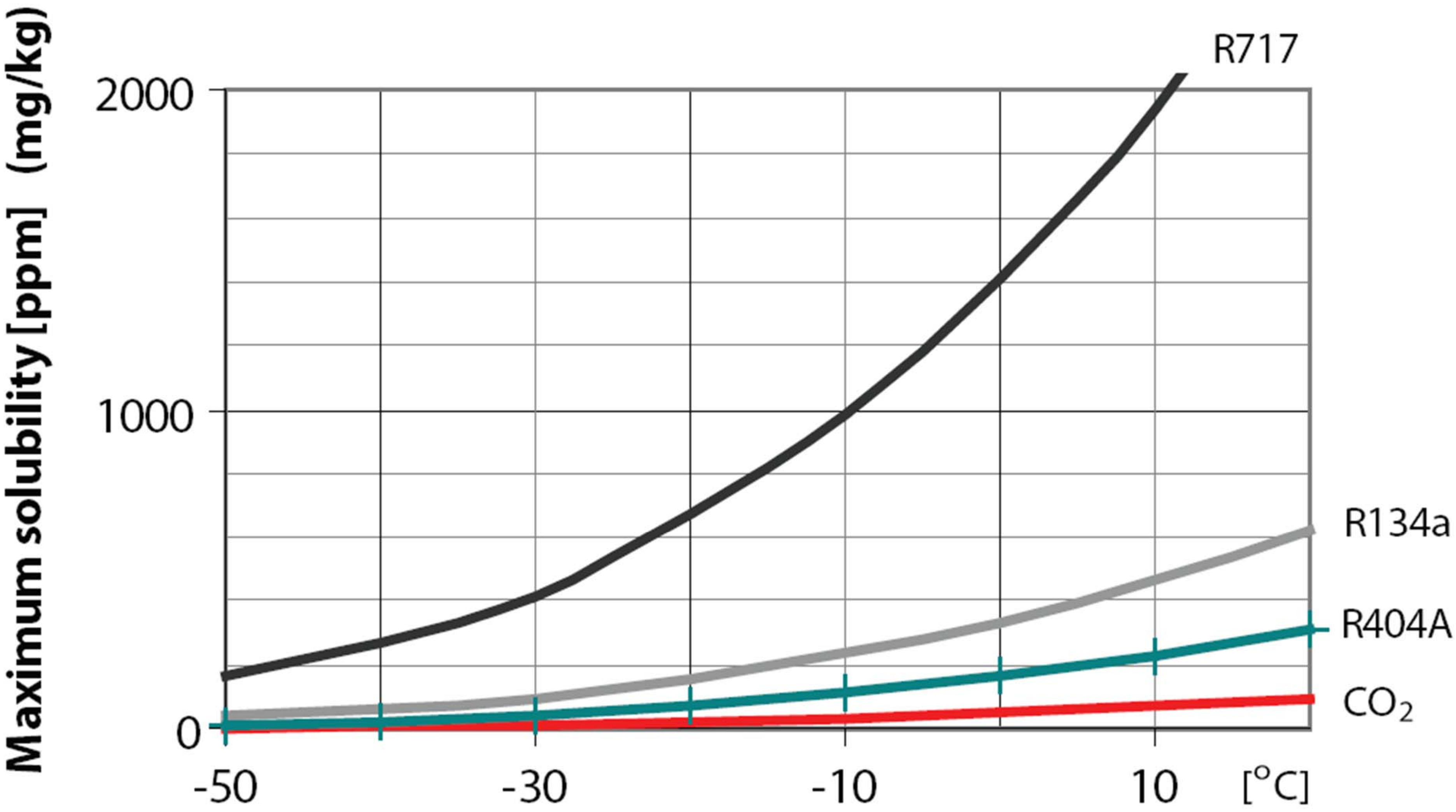
Recirculated Systems

- For CO_2 a pure molecular sieves insert should be used
- It is advisable to install a filter dryer in the pump discharge line or in a parallel line to reduce pressure loss in the evaporators line.

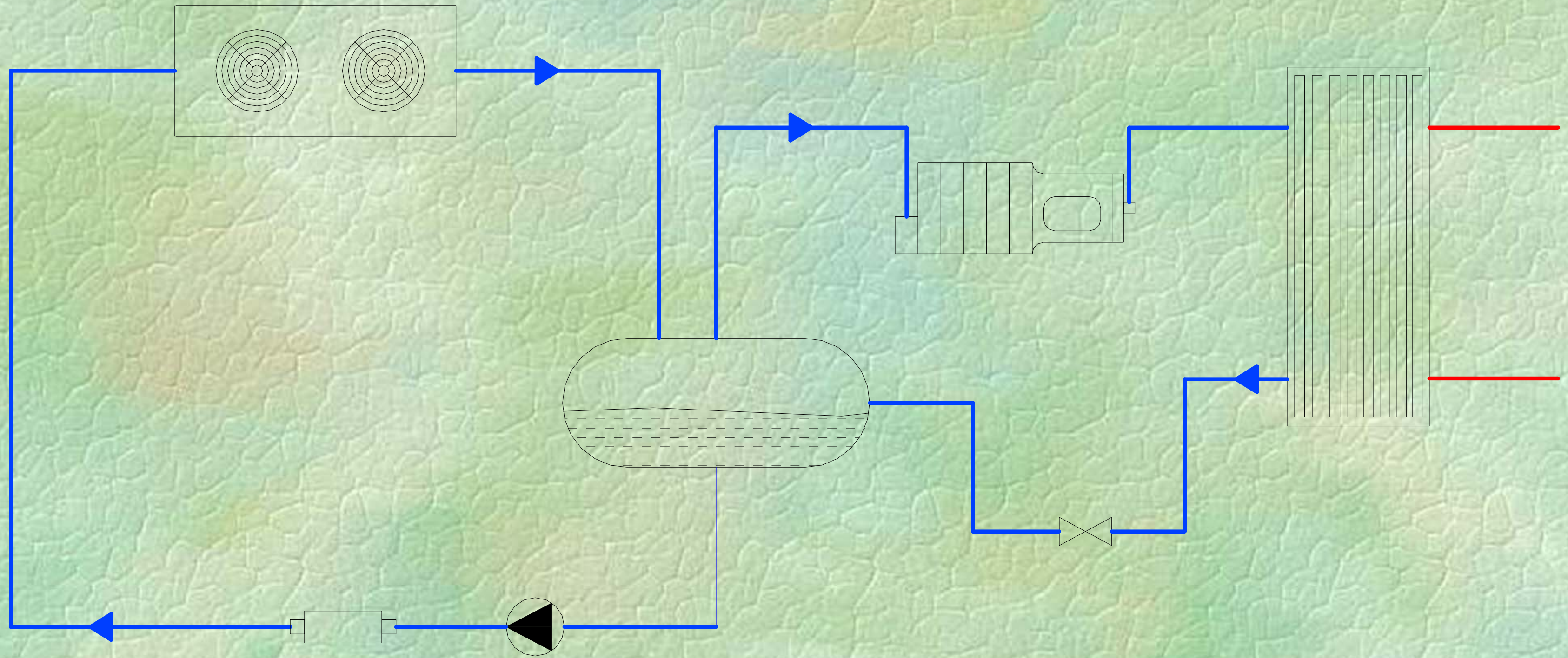
Evacuation and Charging

- Due to the low acceptable water concentration, the evacuation process of the system is very important.
- It is important to start up charging with CO_2 in the vapor phase and continue until the pressure has reached approximately 5 bars (72 psi).
- The system will exhibit low temperatures until the pressure is sufficiently raised.

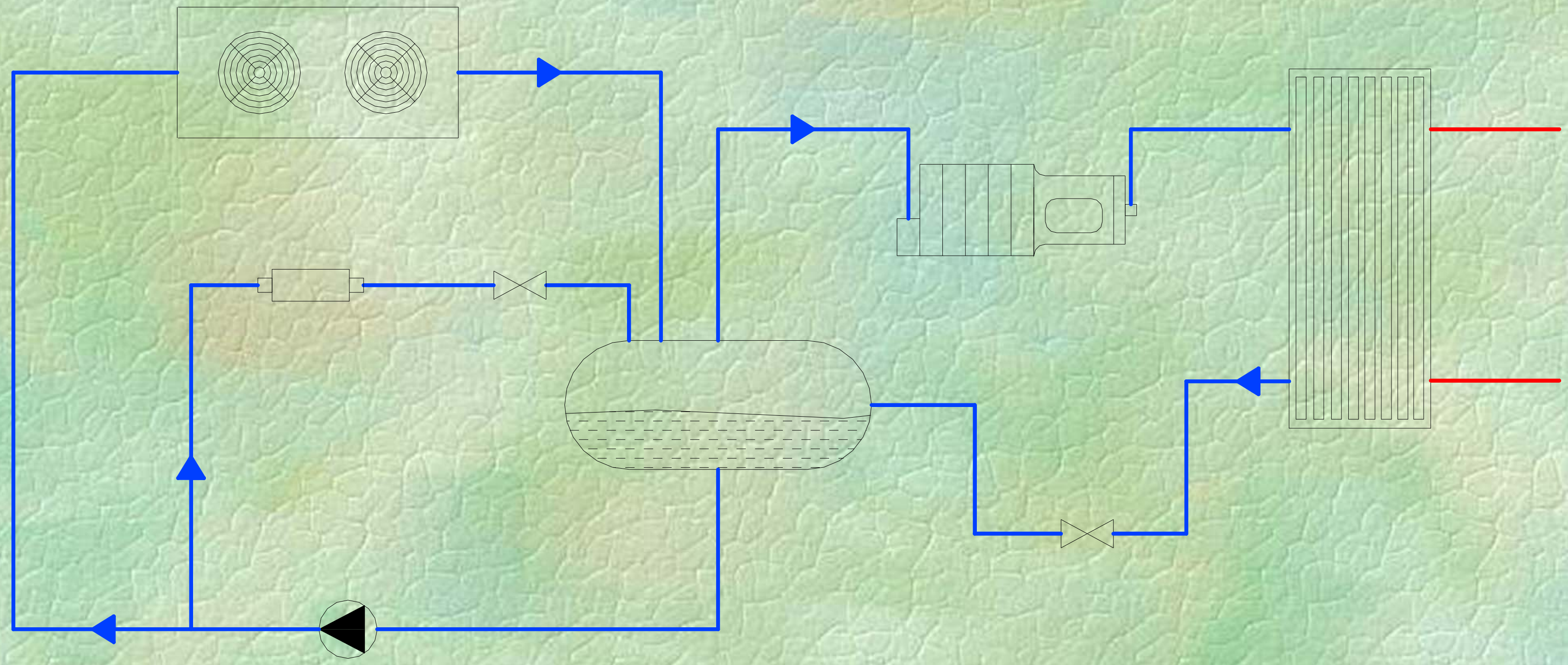
Water solubility in various refrigerants in vapour phase



Installation of Filter Drier



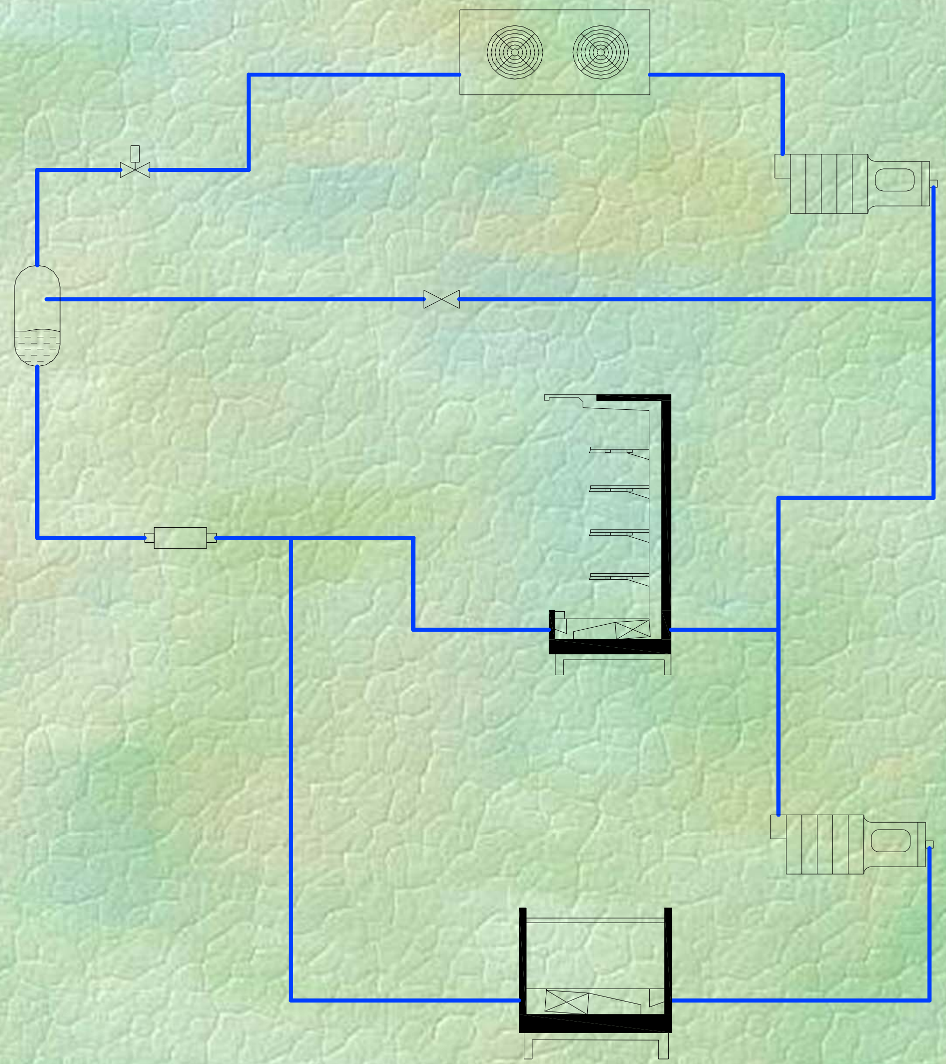
Installation of Filter Drier



Heat Recovery

- It is commonly known that heat recovery with CO_2 works perfectly in transcritical mode.
- Even in subcritical mode, CO_2 heat recovery is still much more efficient than that of e.g. 134a and 404A.
- With a condensing temperature of +15°C (59°F), about 30% of the energy can be reclaimed at approx. +60°C (140°F).

Booster Double Stage Systems



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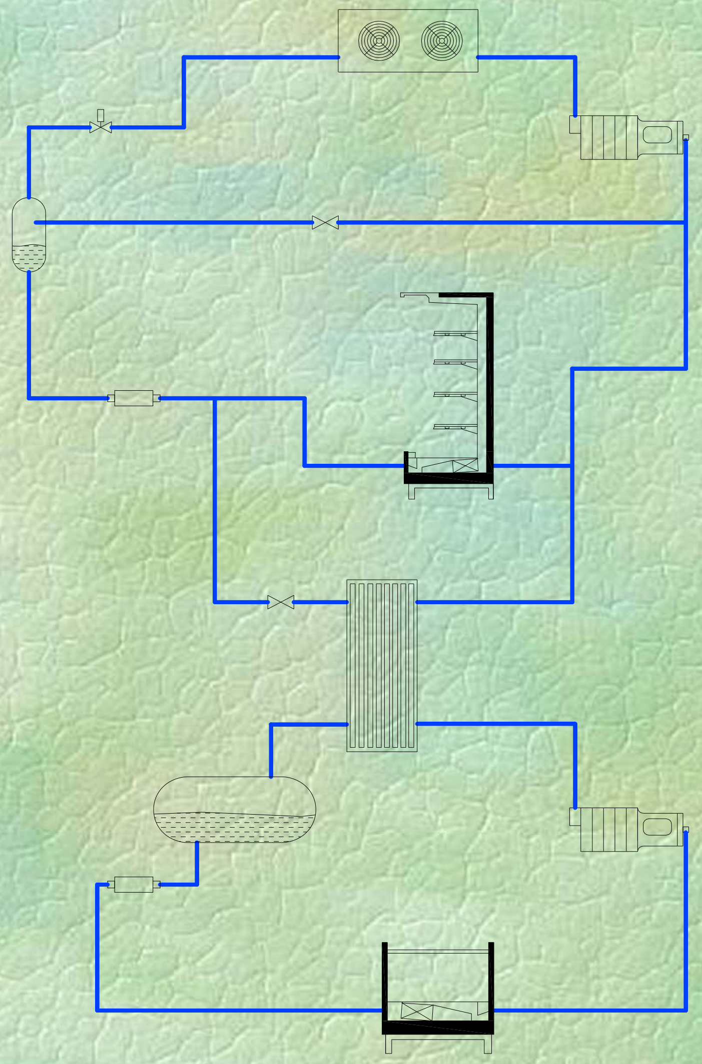
Cascade Double Stage Systems



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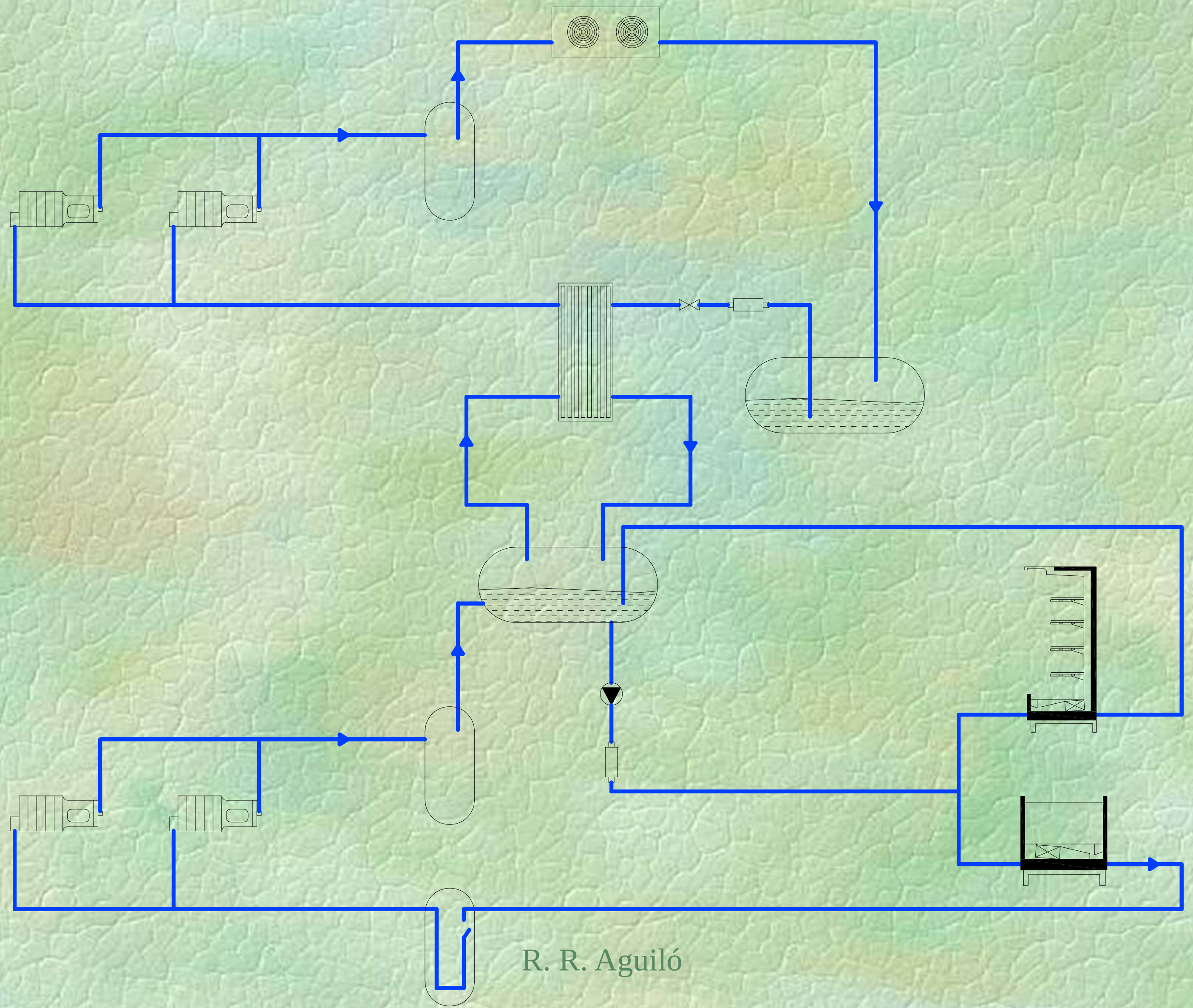
Cascade Double Stage Systems



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Conclusions

- CO_2 is a valid choice to be used as refrigerant.
- It is necessary to adequately design the systems for very high working pressures and the low critical point.