SHIP Egypt

Session 09

Cooling

Wolfgang Glatzl | AEE INTEC
Josef Buchinger | ConPlusUltra

Why this topic in the training?

- Relevance for the food and drinks sector:
  - ⇨ In the food and drinks (F&D) sector, on average 30% of the electricity used in production and distribution is for refrigeration
  - ⇨ Importance of refrigeration related electricity use:

Subsector	% of electricity used for refrigeration
Liquid milk processing	25
Breweries	35
Confectionery	40
Chilled ready meals	50
Frozen food	60
Meat processing	70
Cold storage	85

Sources:
- Presentation „Kältesystemleitfaden“, Konstantin Kulterer, Austrian Energy Agency, Vienna, klima:aktiv Kälteworkshop, 4.4.2014 (Quoted as „Kulterer, 2014“);
- Carbon Trust & Food and Drink Association, Food & Drink Industry Refrigeration Efficiency Initiative - Guide 5, 2007 (See Reference Materials)

What induces the cooling load in buildings

- Heat flux through the envelope
- Direct irradiation
- Air leakage / ventilation (natural/forced)
- Human waste heat: 70W/Person @ 25°C
- Waste heat of
  - Lighting
  - Machines
  - Appliances
  - Data servers

Overview of contents

- A) Compression chillers: Basic information and potentials for optimisation
- B) Absorption chillers
- C) Measures to reduce energy consumption for refrigeration and to improve system efficiency

Remark:

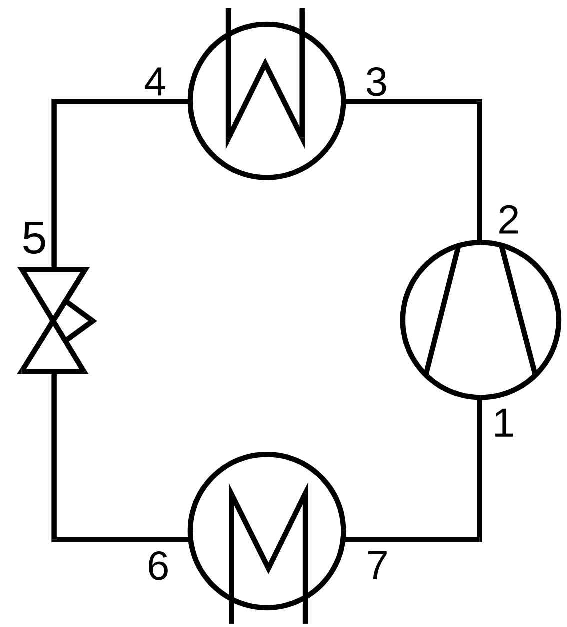
If not otherwise indicated, the following slides are based on the presentation „Energieverfahrenstechnik – Kältetechnik“ by Bettina Muster and Christoph Brunner (both @ www.aee-intec.at)

A) COMPRESSION COOLING

- Compression cooling in short:
  - ⇨ Absorption of „heat“ at a low temperature level
    = extracting heat from the environment
    = cooling
  - ⇨ Rejection of the heat at a higher temperature level
  - ⇨ Refrigerant (R) moves in refrigeration cycle
    - Gaseous R is compressed in the compressor
    - R liquefies in the condenser (heat exchanger)
    - R is expanded via the expansion device
    - R absorbs heat in the evaporator (heat exchanger) at a low temperature level and evaporates (boiling cooling)

Refrigeration cycle

- 1 Compressor inlet
- 2 Compressor outlet
- 3 Condenser inlet
- 4 Condenser outlet
- 5 Expansion valve inlet
- 6 Evaporator inlet
- 7 Evaporator outlet



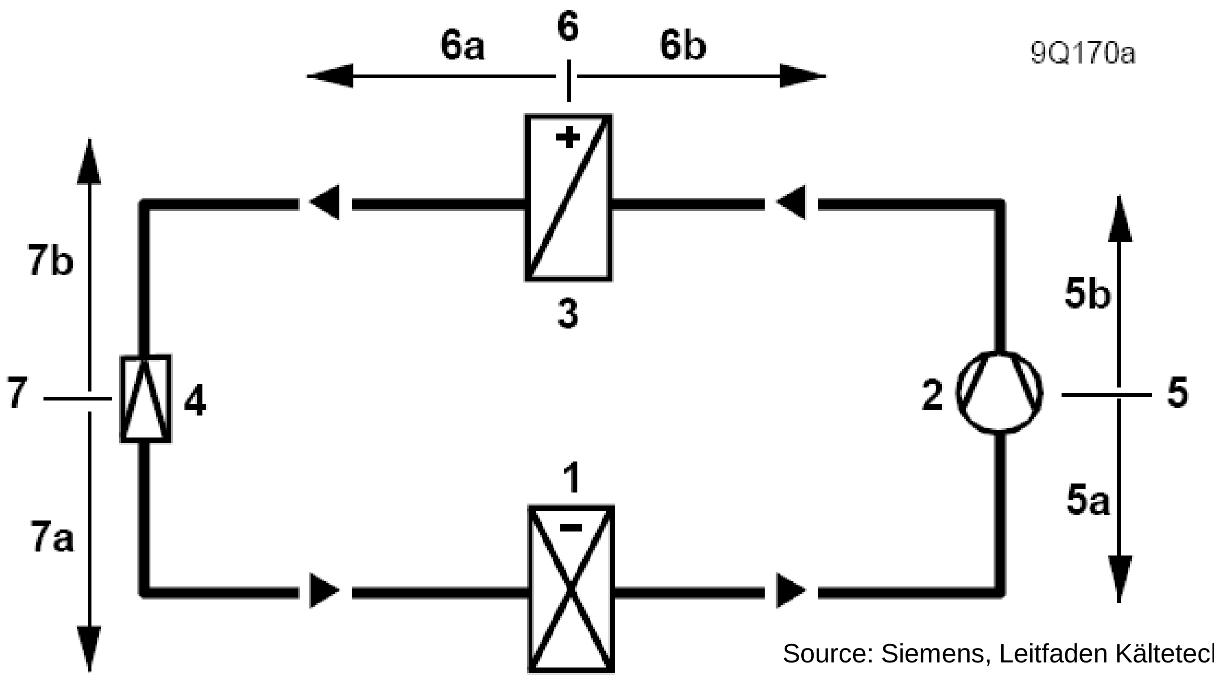
Refrigeration cycle components (1)

- Evaporator: liquid refrigerant evaporates at low pressure and low temperature. The heat necessary for evaporation is being removed from the medium to be cooled (air, water).
- Compressor: the gaseous refrigerant is pulled into the compressor via the suction line. The gas is compressed and leaves the compressor at a high pressure and in a superheated state (approx. 60 - 120 °C). It is still gaseous, and arrives via the pressure line at the condenser.

Refrigeration cycle components (2)

- Condenser: The heat of the hot gas is transferred to the coolant (air, water, etc.) and the gas condenses. Both the latent heat of evaporation and the work of the compressor (also converted to heat) have to be rejected here. The liquid refrigerant is then usually directed to a liquid receiver.
- Expansion valve: It reduces the high pressure of the liquid refrigerant to the low pressure prevalent inside the evaporator. It also controls the degree of filling of the evaporator according to the different loads. This is done by controlling the degree of superheating of the gas measured at the evaporator outlet.

Refrigeration cycle

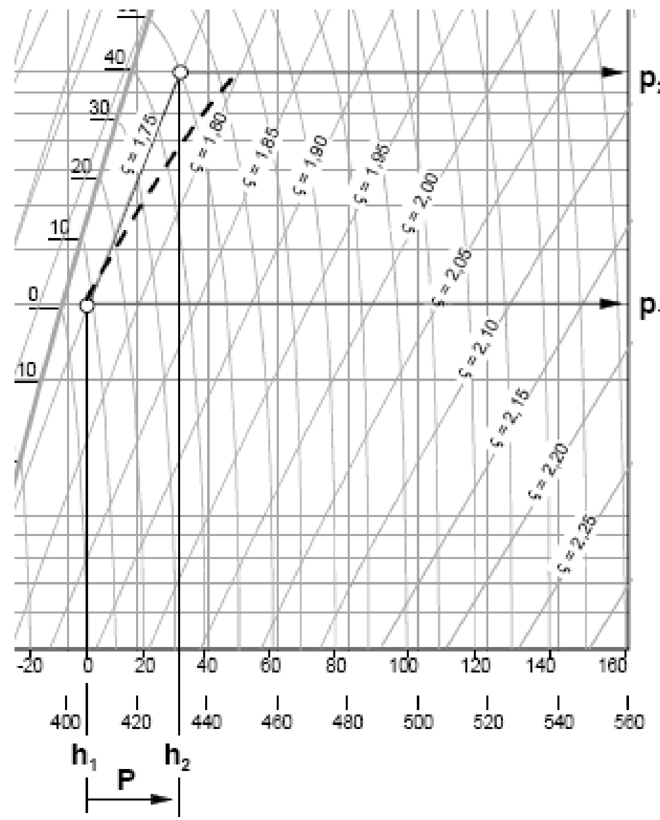


Source: Siemens, Leitfaden Kältetechnik

1 Evaporator
2 Compressor
3 Condenser
4 Expansion valve
5 Temperature: **5a low , 5b high**
6 State: **6a liquid, 6b gaseous**
7 Pressure: **7a low pressure, 7b high pressure**

Isentrops in refrigeration technology

- Isentrops are relevant for refrigeration as regards superheated gas
- Compression in an ideal compressor is along isentrops
- Ideal compression work can be calculated with the help of isentrops (comparing enthalpy in the beginning and in the end)
- How close the real values are to the isentrop = efficiency



Example: Compession work

- Refrigerant R134a

Point in the process (values for an example)		t °C	p kPa	v m³/kg	h kJ/kg	s kJ/(kgK)
1	**Compressor inlet**	-10,00	200,6	0,099571	392,57	1,7330
2s	**Compressour outlet, isentropic**	40,20	886,8	0,023831	423,42	1,7330
2	**Compressor outlet**	52,56	886,8	0,025594	436,64	1,7744

⇨ Δh [kJ/kg] = $h_{2s} - h_1$

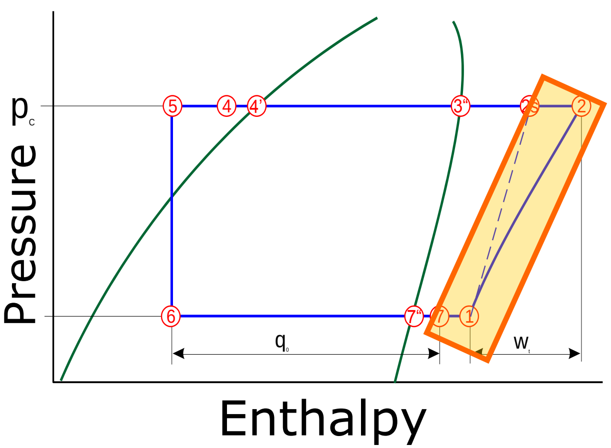
⇨ P [kW] = m [kg/s]* Δh [kJ/kg]

⇨ Compressor: efficiency $\eta = 0{,}7$

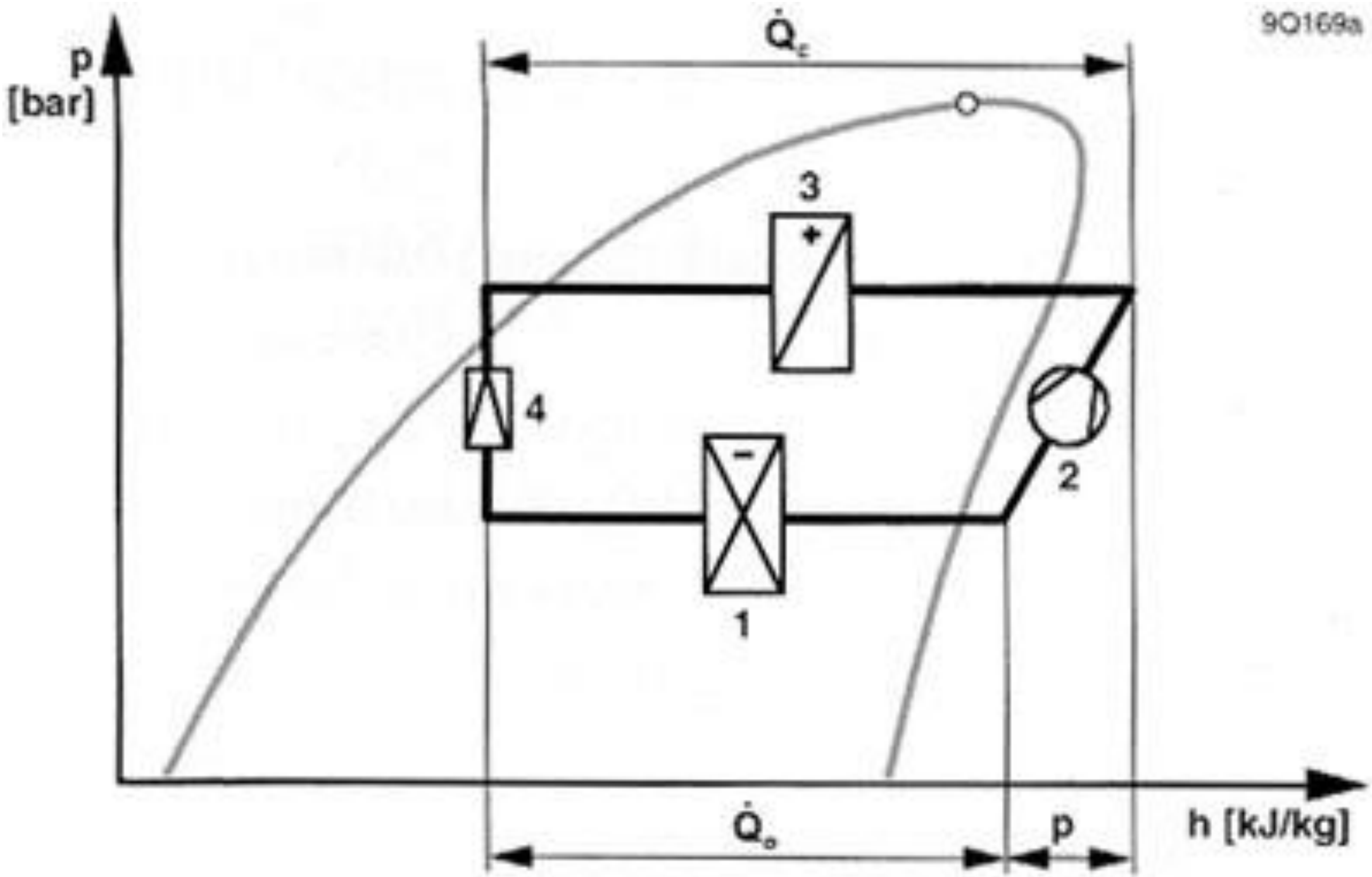
⇨ $h_2 = h_1 + (h_{2s} - h_1)/\ \eta$

⇨ Δh_{real} [kJ/kg] = $h_2 - h_1$

⇨ P_{real} [kW] = m [kg/s]* Δh_{real} [kJ/kg]



Refrigeration circuit in the Enthalpy-Pressure (h-lg p) Diagramme



Source: Siemens, Leitfaden Kältetechnik

Compressor

- Losses in a real compressor:

  We distinguish between

- Volumetric losses, caused by
  - Thermal expansion of the gas while flowing into the compressor, due to heating as it passes warmer surfaces (motor winding, piston, cylinder,...)
  - Leak between piston and cylinder
  - Leaks of valves
  - The „not usable“ room in the cylinder that remains filled with gas, which expands again during the suction stroke and thus reduces the amount of refrigerant that can be drawn in
- Mechanical losses, caused by
  - Friction between the moving parts
  - Additional work performed (eg. of the oil pump)

Compressor

- Calculation:
- State at the compressor outlet, if isentropic quality is not known, but system parameters are given:
  - ⇨ $P_{compressor}$ = 86 kW (example)
  - ⇨ Δh [kJ/kg] = P [kW] / m [kg/s]
  - ⇨ $h_{compressor\_outlet} = h_{compressor\_inlet} + \Delta h$ [kJ/kg]

Condenser (1)

- The refrigerant leaves the compressor in a highly superheated state (Point 2*) and arrives at the condenser via the pressure line. At the beginning of the condenser, the hot gas needs to be cooled down to the condensation temperature, which is determined by the pressure.
- The fans propel cooling air between the fine lamellae of the condenser, which have a large surface. This results in an intensive exchange of heat between the now condensing gas and the air. Towards the end oft the tubes, the refrigerant is completely liquid, and is then subcooled due to the temperature difference between cooling air and liquid refrigerant. The refrigerant flows back and into the receiver.

** Diagram in slide 5

Condenser (2)

- The three zones of the condensing process are visible in the h, log p diagramme** as follows:
  - 2-3 desuperheating,
  - 3-4 condensing,
  - 4–5 subcooling.
- The cooling of the condenser is usually controlled via the condensation pressure or the condensation temperature.

** Diagram in slide 10

Expansion valve (1)

- It controls the amount of refrigerant flowing into the evaporator and simultaneously reduces the pressure. Thus, this valve forms one of the boundaries between the high and low pressure sides of the system. (including pressure drop in the subsequent refrigerant distributor)
- In the h, log p-Diagramme**, the operating state after the expansion valve shifts vertically downwards, along the isenthalp 5-6. Point 6 marks the state after the expansion valve and after the distributor, at the evaporator inlet. Point 6 is characterised by the evaporating pressure p_o, the thermal content h_1 and the evaporating temperature t_o.

** Diagram in slide 10

Expansion valve (2)

- Point 6 also allows to determine the share of flash gas „x“. This share of the refrigerant evaporates already at expansion (without heat exchange), i.e. only e.g. 80% of the total latent heat of vaporzisation are being extracted from the medium to be cooled. This is why one tries to ensure that point 5 is located as much to the left as possible in the „liquid“ area, i.e. to subcool the refrigerant as much as possible.

Evaporator (1)

- The refrigerant distributor supplies the tubes of the evaporator, which are connected in parallel, thus ensuring each receives an equal flow of refrigerant. The continuous change of state takes place in these tubes. The share of gas increases until all liquid has evaporated.
- The saturated steam generated in the evaporator is marked in the diagramme with point 7‘‘. Point 7‘‘ in reality is at a pressure somewhat lower than at point 6, due to loss of pressure in the evaporator.

Evaporator (2)

- The heat absorbed by the refrigerant in the evaporator is slightly higher than the energy necessary to achieve saturated steam. Thus the refrigerant at the end of the evaporator is superheated by about 5 to 8 K. In the h, log p-diagramme, the end point of this superheating is marked with 7. The superheating is necessary to avoid droplets of liquid refrigerant getting into the compressor and causing damage there (liquid slugging).

Evaporator control

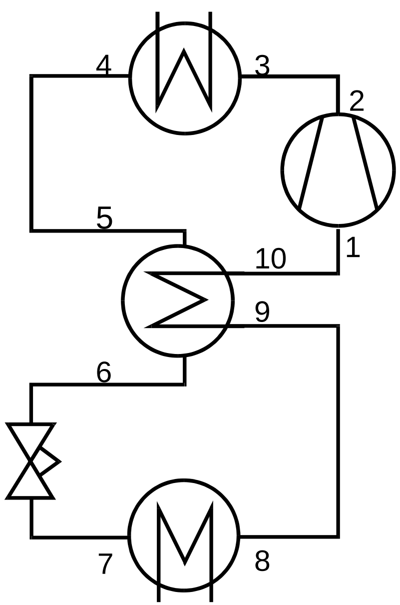
- The sensing liquid measures superheating via the change in pressure (evaporation of sensing liquid)
- In a state of equilibrium, the refrigerant injected into the condenser can evaporate (7‘‘) and superheat in addition (7). If the load is reduced (e.g. due to a lower temperature of the air entering the evaporator), the point where full evaporation of the refrigerant is achieved 7‘‘ approaches the evaporator outlet and superheating is reduced.
- As a consequence the bulb pressure lowers, so the diaphragm valve closes and reduces the filling level in the evaporator, until a new state of equilibrium occurs. In order to ensure that pressure decreases in the distributor and the evaporator do not affect superheating too much, the pressure at the evaporator outlet is measured and fed back to the valve.

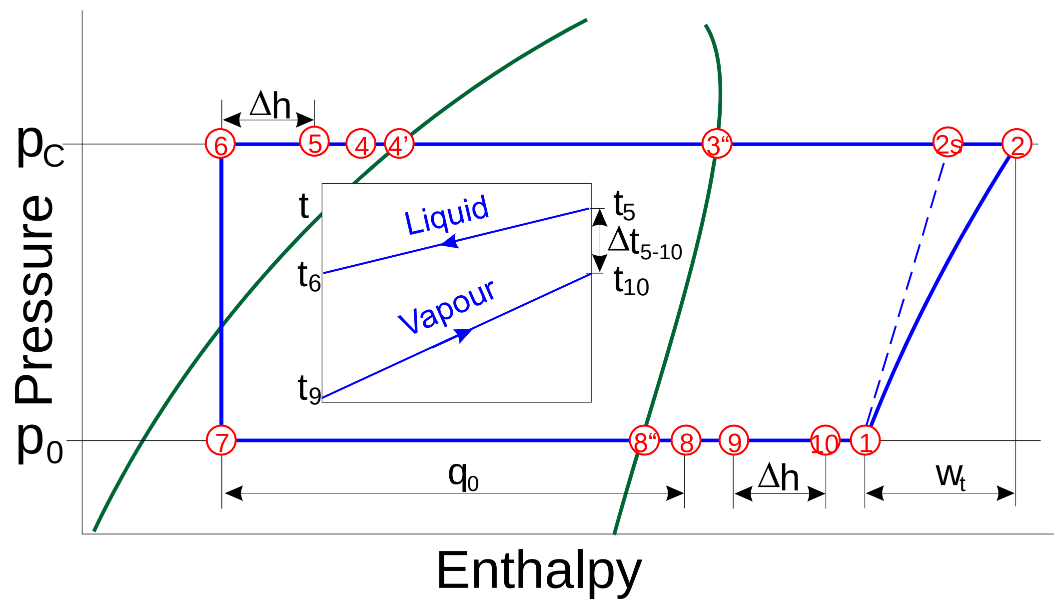
Possibilities for optimisation

- Internal heat exchanger
- Two stage compressor with interstage cooler

Refrigeration circuit with internal heat exchanger

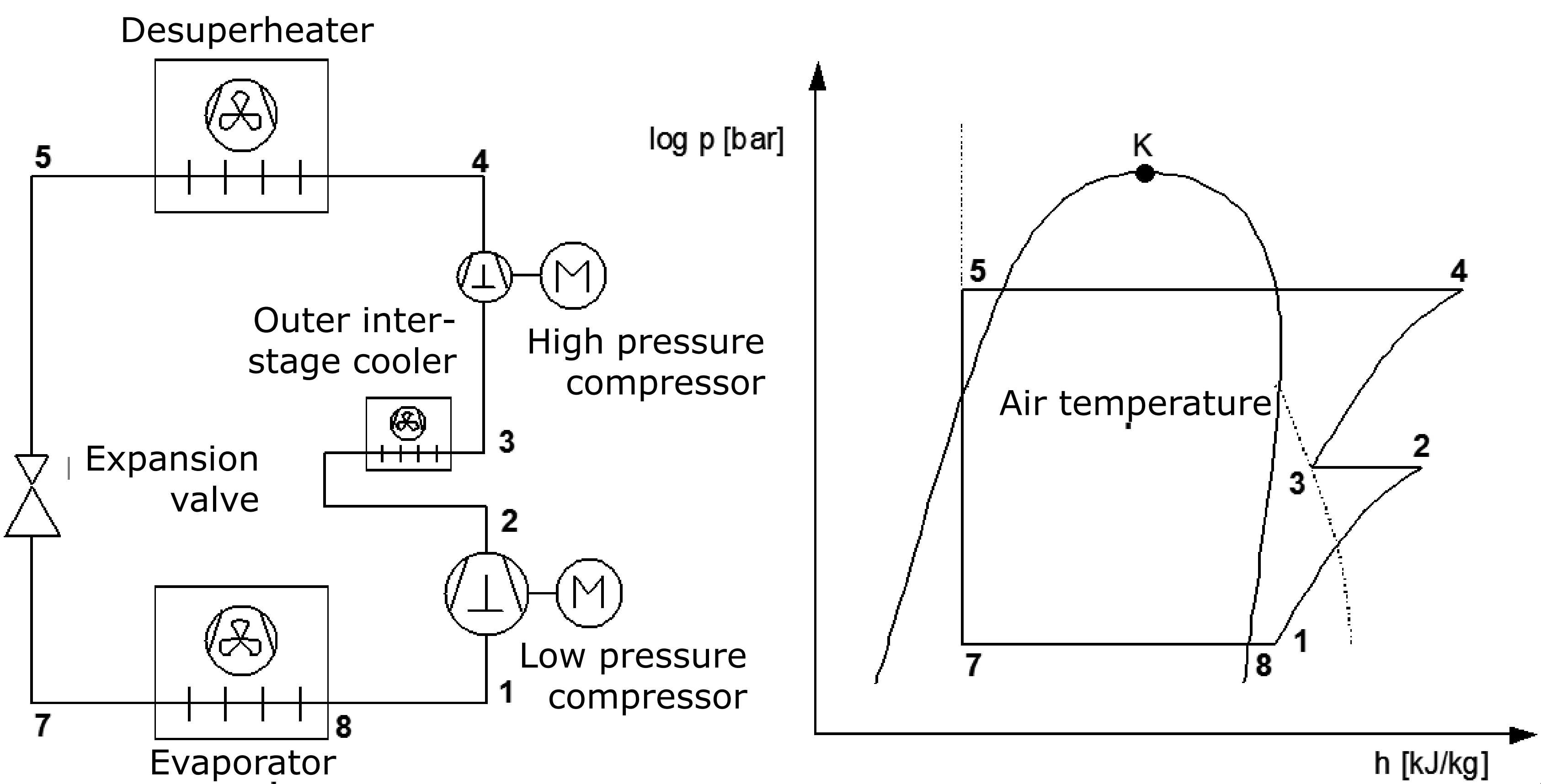
- Further subcooling of refrigerant (after condenser) and heating of suction gas (after evaporator)
  - ⇨ Especially for refrigerants that compress nearly isentropically, to achieve superheating.





Refrigeration circuit with interstage cooler

- Interstage cooling, in order not to exceed maximum permissible final temperature after compressor



Energy balance of refrigeration circuit

- Enthalpies are shown in h-lg p diagramme
  - ⇨ $\dot{Q} = \dot{m} \cdot \Delta h$
- Heat output at evaporation = refrigeration output
  - ⇨ $Q_K = m \cdot (h_7 - h_6)$
- Compressor power
  - ⇨ $P_{eff} = m \cdot (h_2 - h_1)$
- Condenser heat load
  - ⇨ $Q_C = m \cdot (h_2 - h_4)$

⇨ $Q_C = Q_K + P_{eff}$

⇨ $\mathrm{COP} = Q_K / P_{eff}$

⇨ But also think about primary energy use of P_{eff} when comparing!

Calculation of refrigerant amount

- Refrigeration output is given:
- Q_K = 200 [kW]
- At given evaporating and condensing temperatures, enthalpies can be determined from h-lg p diagramme

- Mass flow m [kg/s] = Q_K / (h_7-h_6)

Refrigerants

- Refrigerants are the working fluid of the cooling process

- Technical parameter are:
  - ⇨ Performance factor
  - ⇨ Volumentric cooling power
  - ⇨ Thermal stability
  - ⇨ Condensation pressure
  - ⇨ Evaporation pressure
  - ⇨ Pressure ratio
  - ⇨ Compression end temperature
  - ⇨ Oil mixing factor

+ safety: flammable, explosive, toxic?
+ Cost, availability
+ Reliability, experience

Issues of refrigerants

+ Environmental issues
  - **O**zone **D**epletion **P**otential (ODP)
  - **G**lobal **W**arming Potential (GWP),
  - **T**otal **E**quivalent **W**arming Impact (TEWI)
+ Substitutes for H(FCKW)
  - synthetic alternatives: R134a, R404A, R407C,…)
  - Ecological alternatives (NH3, CO2, Butan, Propan,…)

Refrigerant	Code	ODP	GWP100	Boiling temp, °C
Ammoniac	R717 (NH_3)	0	0	-33.6
Propane	R290 ($CH_3CH_2CH_3$)	0	3	-42
Isobutane	R600a (C_4H_{10})	0	3	-11.9
Carbondioxide	R744 (CO_2)	0	1	-78.4
Water	R718 (H_2O)	0	0	100

System components - Refrigerants (R)

- Choice of suitable refrigerant
  - ⇨ Type of R can change total system efficiency by up to 10%
  - ⇨ Effect of R on efficiency depends on compressor and operating conditions
  - ⇨ Correct amount of R is decisive for efficiency. Too much as well as too little has adverse effects.
  - ⇨ Leakages (= too little R) lead to overheating in the evaporator, this reduces suction pressure and makes the necessary pressure increase higher.
  - ⇨ Air in the R reduces performance
    - Substitution of the refrigerant should only be carried out with the help of an expert!

Source: „klima:aktiv Kälteleitfaden", Kulterer, K, Mair, O. , Austrian Energy Agency, developed as part of programme klima:aktiv of the ministry of environment, Vienna 2012 (Quoted as „klima:aktiv Kälteleitfaden 2012")

System components - Refrigerants (R)

- Pros and cons of selected refrigerants (1)
  - R404A, R507A (boiling point -47 °C)
    - +: Chlorine-free substitutes for R502, R22; suitable for low temperature freezing applications and commercial refrigeration; cover wide range of evaporating temperatures
    - -: Global warming potential GWP_{100} quite high (~3,800)
  - R410A (boiling point -51 °C)
    - +: Substitute for R22; broad range of applications, from air conditioning to commercial low temperature; High heat transfer coefficient in evaporator and condenser.
    - -: High condensing pressure required (25 bar at condensing temperature of 41 °C); GWP_{100} medium (1980)

Source: klima:aktiv Kälteleitfaden 2012

System components - Refrigerants (R)

- Pros and cons of selected refrigerants (2)
  - R290 = Propane (boiling point -42 °C)
    - +: Substitute for R22 and others; low GWP_{100} (3), no ozone depletion potential
    - -: Flammable, therefore to date rather rare in bigger installations due to required explosion prevention measures
  - R717 = Ammonia = NH_3 (boiling pont -33 °C)
    - +: Substitute for R22; low cost; energetically advantageous, hardly flammable, no GWP,
    - -: Should not be used directly for cooling foods (heat transfer via brine circuit is necessary); toxic, but distinctive odour, thus can be recognised even in case of a small leak; cannot be used with non-ferrous metals (e.g. Cu);
    - Often used with flooded evaporator. For big industrial installations, cold storage plants, rather not for small applications. Be sure system is designed to work with ammonia – careful with retrofits!

Sources: klima:aktiv Kälteleitfaden 2012; http://de.wikipedia.org/wiki/Kältemittel

System components - Refrigerants (R)

- Pros and cons of selected refrigerants (3)
  - R744 = CO_2 (boiling point -57 °C)
    - +: Substitute for several refrigerants; chemically inactive, not flammable, not toxic, negligible GWP_{100} (1); very high refrigerating effect per unit of swept volume, very high heat transfer coefficient.
    - -: Low critical temperature (74 bar), i.e. transcritical operation mode for chilling needs pressure of 80-90 bar.
    - Suitable for industrial/commercial refrigeration systems as secondary fluid in a cascade systems. For applications from -10 to -50 °C (=low temperature), pressure at approx. 30 bar.
    - Difference betw. flow and return temp. should be at least 50°C
- Info on working fluid pairs NH_3 /H_2O and LiBr/H_2O is on slides 43-44

Source: klima:aktiv – Kälteleitfaden 2012

System components - Compressors

- Reciprocating piston compressors (1)
  - Open
    - +: motor can easily be exchanged or repaired
    - -: sealing of shaft feedthrough, friction and power transmission losses
    - Application: from 0-1 MW, less suitable for air conditioning
  - Semi hermetic
    - +: Despite sealed construction repair of motor is easily possible. Shaft feedthrough sealing problem does not apply.
    - -: Sensitive to dirt: there must not be any humidity or dirt in the system. Total system has to be evacuated before starting operation.
    - Application: suitable for about 3-500 kW, broad range of application in air conditioning

System components - Compressors

- Reciprocating piston compressors (2)
  - Fully hermetic
    - +: compact design and cheap. Often already delivered complete with evaporator and condenser. Protected against dirt, mass production: high precision means long useful life
    - -: no possibility to repair, check oil, or change valves
    - Application: lower output range; refrigeration units, small air conditioners.
- Rotary compressors
  - Screw compressor
  - Scroll compressor
  - Cellular wheel compressor
  - Turbo compressor
  - Advantage compared to piston compressor: only rotating movement, no valves, continuous speed variation.

System components - Compressors

- Power ranges of compression and absorption machines for use in refrigeration, airconditioning and heat pumps

Type	Power range at $t_0 \varnothing$ 0°C
Fully hermetic compressor (usually reciprocating type, but also rolling piston or rotary, and special types)	>0 – 50,000 W
Semi hermetic reciprocating piston compressor	> 0 – 300,000 W
Open reciprocating piston compressor	> 0 - 1 MW
Screw compressor	0.2 – 5 MW
Absorption machine	0.35 – 6 MW
Hermetic turbo-compressor	0.35 – 6 MW
Open turbo-compressor	0.35 – 30 MW

System components - Condensers

- Condenser
  - Purpose: reject heat that has been added in evaporator and compressor
  - Possibility to use ejected heat (heat recovery)

  - Types
    - Water cooled (usually shell and tube heat exchanger or plate heat exchanger)
    - Air cooled (usually finned condenser)
    - Evaporative

System components - Condensers

- Water-cooled condensers and heat recovery from condensing
  - Single stage or two-stage possible
  - For systems with higher capacity and high discharge temperature installing a desuperheater is reasonable (if heat can be used efficiently)
  - Two-stage process
    - Desuperheater (~ sensible heat is recovered)
    - Condenser (~ latent heat is recovered)
  - Designed as
    - Plate heat exchanger
    - Shell and tube heat exchanger (usually water in tubes and refrigerant outside)
    - Coaxial heat exchanger

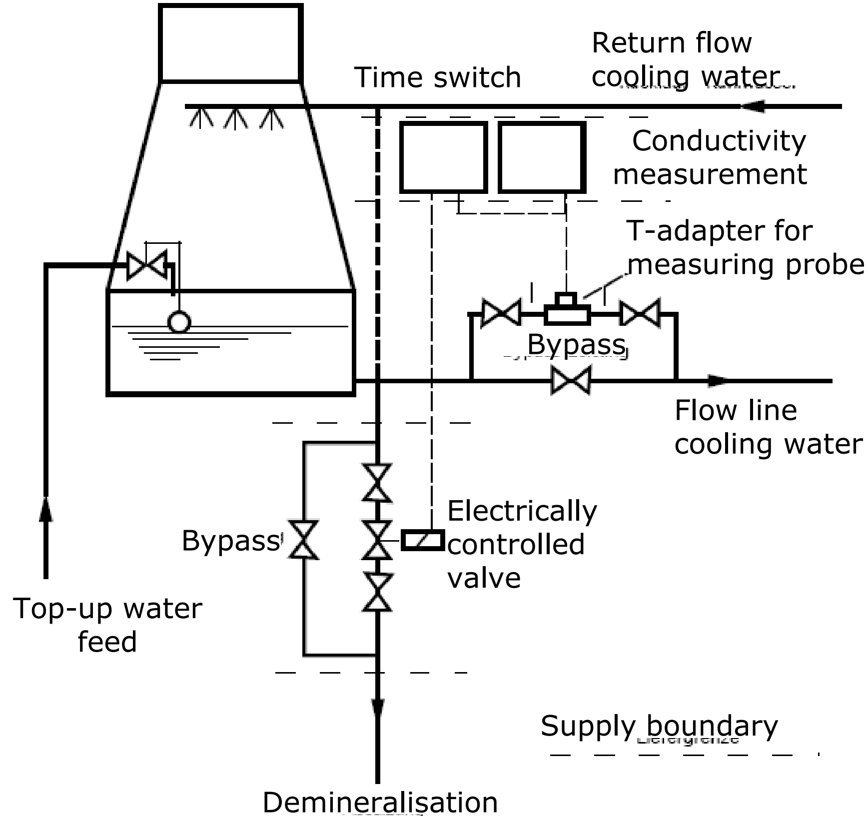
System components - Condensers

- Finned condenser
  - Advantages compared to water-cooled condensers:
    - Maintenance-free operation, easy cleaning
    - Water too expensive, aggressive, unclean
    - No accumulation of ice
  - Disadvantage: no efficient heat recovery possible
  - Design:
    - Usually finned-tube heat exchanger with finned copper tubes

Evaporative cooler (Cooling tower)

- Water is circulated in addition to air
- Water evaporates due to heat pickup and is being carried out by the stream of air (high energy due to evaporation of water)
- Water treatment required

Source: www.rehsler.de

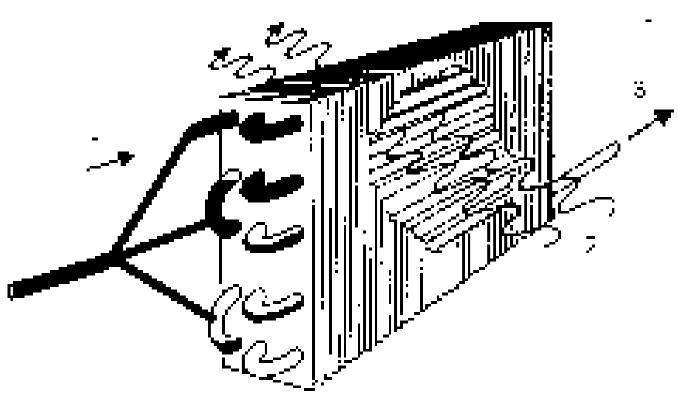


Source: www.wernerwasser.ch

System components

- Evaporator

Direct expansion cooling	Indirect expansion cooling
Lower initial investment	Easy planning, installation, operation
Higher refrigerant temperatures	Easy control at consumer
Smaller compressors	Better part load characteristics
Lower energy cost	Leaks are less critical
Only appropriate for use with single or few evaporators	No problems with oil return
	Refrigeration machine and ancillary equipment located in central machine room; This facilitates maintenance
	Cooling and heating possible
	Best solution for complex installations with large network



Source: Siemens, Leitfaden Kältetechnik

Evaporators

- Plate evaporators
  - ⇨ For smaller loads
- Tube bundle evaporator
  - ⇨ Refrigerant inside tubes
- Coaxial evaporator
  - ⇨ Refrigerant inside tubes

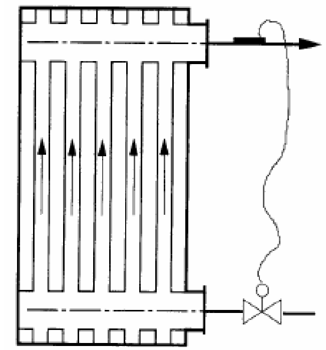
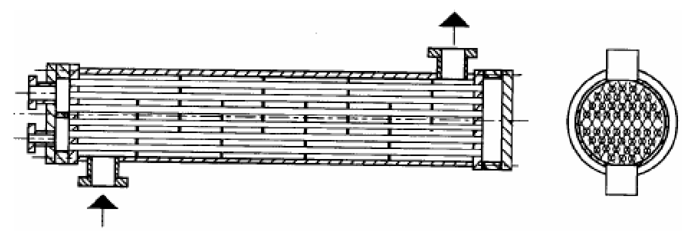
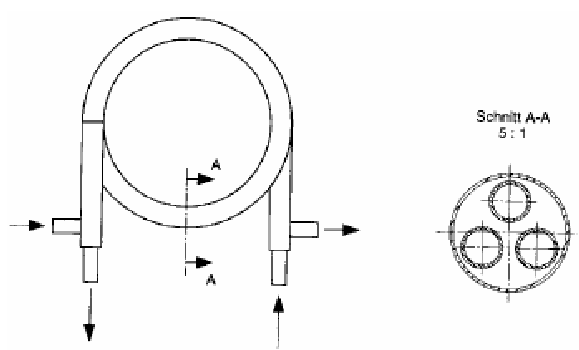


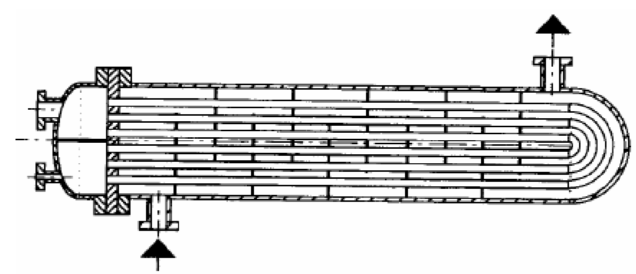
Plate evaporator



Tube bundle evaporator



Coaxial evaporator



U-shaped tube bundle evaporator

B) ABSORPTION CHILLERS

- Absorption: Gas particles enter into liquids or solids
  - Absorption of gases at low temperature and low pressure, absorption heat is released
  - Desorption (after heat has been supplied externally) at high pressure and high temperature
  - → can be operated as a circular process = thermal compressor

Absorption chillers

- Working principle – circular process
  - ⇨ 1 Thermochemical compressor
  - ⇨ 2 Condenser
  - ⇨ 3 Restrictor /Dosage instrument
  - ⇨ 4 Evaporator
  - ⇨ *5 Use as heat pump*
  - ⇨ *6 Use as refrigeration machine/chiller*

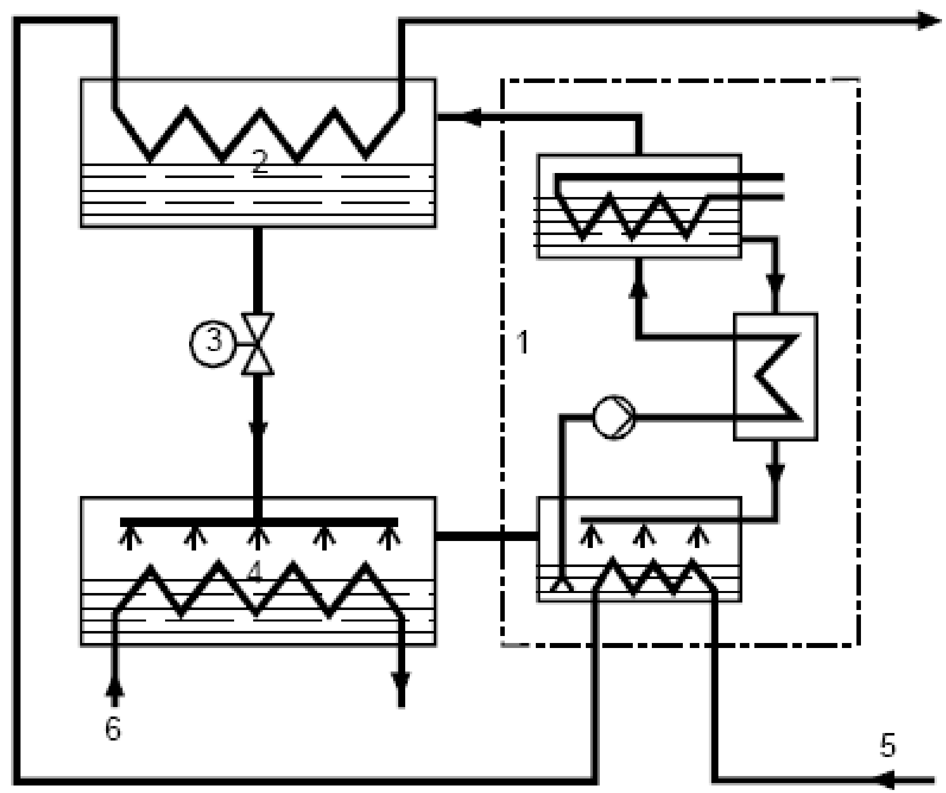
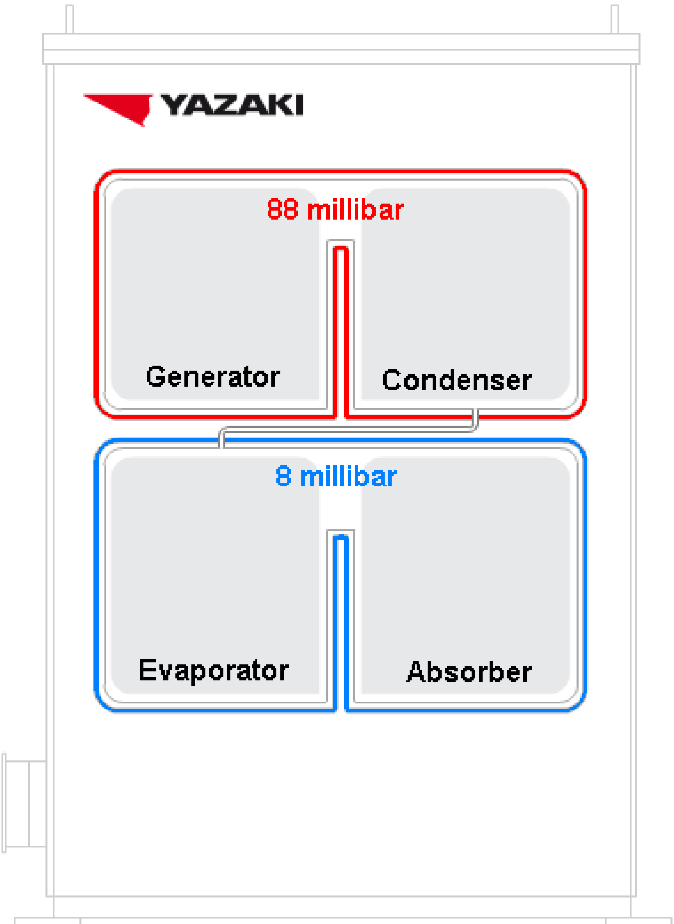


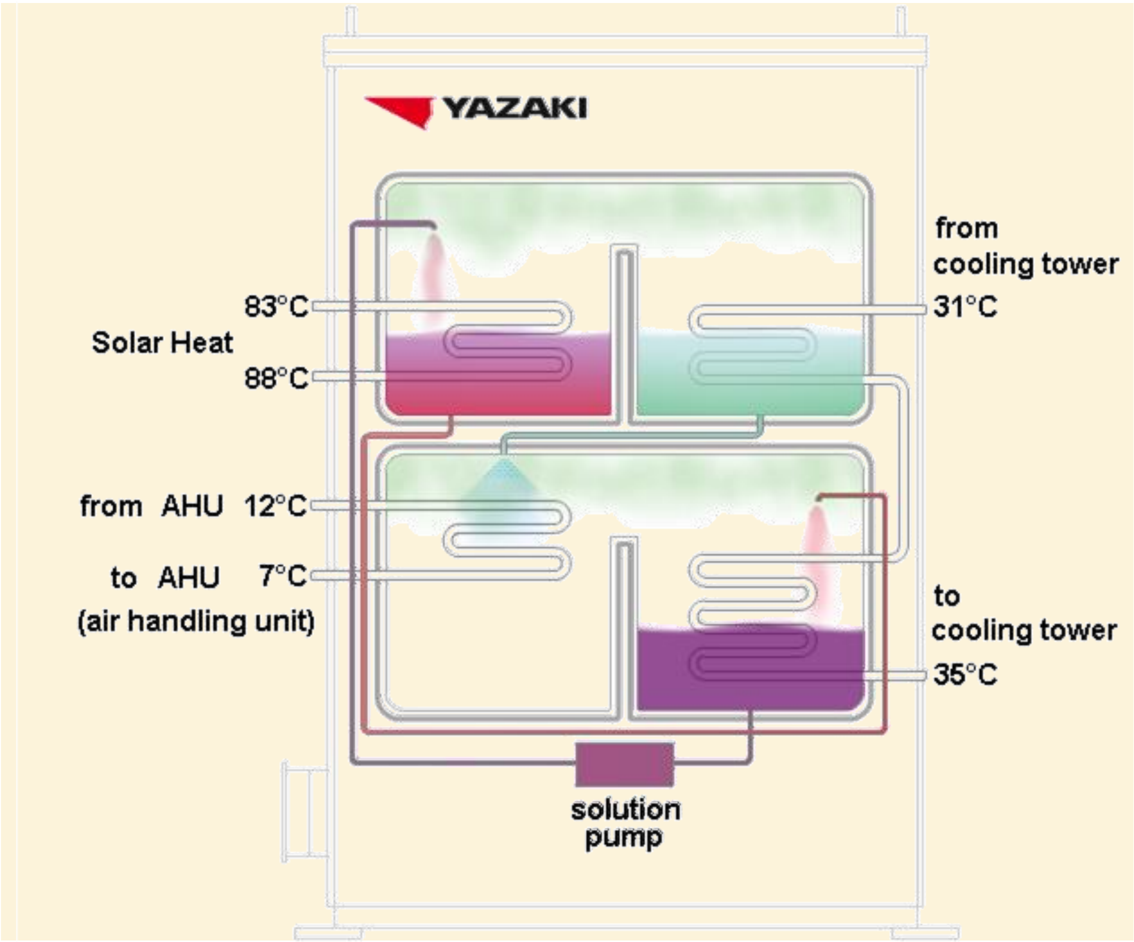
Fig. 50

Source: Siemens, Leitfaden Kältetechnik

2 chambers at different pressure levels



Flows and temperatures



Long lasting technology

Long lifetime of absorption chillers. No mowing parts.
This one is > 70 years old !

Thermal compressor

- Instead of mechanical energy for compression (like in compression chillers) thermal energy must be supplied to the system for the functioning of absorption chillers
- Economical, if (waste) heat is available
  - ⇨ Hot gases from processes / combustion processes
    - Heating of generator with low-pressure steam from a turbine, condensate is then recirculated to steam boiler
  - ⇨ Solar energy

Thermal compressor

- Absorption of low pressure refrigerant vapour by an appropriate liquid solvent / working fluid pair in the absorber (This corresponds to the suction process in the compressor.)
- The refrigerant-saturated solvent is being transported to the generator. There, heat is supplied externally. Temperature and pressure of the solution increase, the refrigerant evaporates and reaches the condenser via the pressure line of the refrigerant circuit. (This corresponds to the compression and ejection of the compressed, hot refrigerant gas from the compressor.)

Working fluid pairs

- Most well-known working fluid pairs:
- Ammonia/Water
  - Refrigerant = Ammonia
  - Evaporating temperatures 0 to -60°C
  - Rectification (multistage distillation process via rectifying column) necessary
- Lithium bromide/Water
  - Refrigerant = Water
  - Mainly for air conditioning, evaporating temperature > 0°C
  - Operation below atmospheric pressure
    - Evaporator pressure 0.008 bar / Condenser pressure 0.1 bar
    - Design suitable for vacuum

Comparison of working fluid pairs

NH_3/Water	Water/Lithium bromide
Operative range at pressure ranges much higher than amospheric	Operative range very low (high vacuum) pressures
Useful cooling also < 0°C	Useful cooling min. 5°C
Heat ratio (one-stage) 0.6	Heat ratio (one-stage) 0.75 (no rectification necessary)
Energy consumption of solvent pump 2-6%	Energy consumption of solvent pump <1%
Materials: no copper or brass	Higher risk of corrosion, inhibitors necessary, no aluminium
Characteristics: Toxic, flammable, but easily recognizable, safety requirements	Not toxic, higher evaporating enthalpy of refrigerant
Rectification necssary (= more complicated equipment), lower heat ratio	No rectification necessary, lower investment cost
High vapour pressure → high requirements regarding materials and construction	Operation at vacuum → also high requirements regarding construction, problem of leakages
Much operating experience already exists	

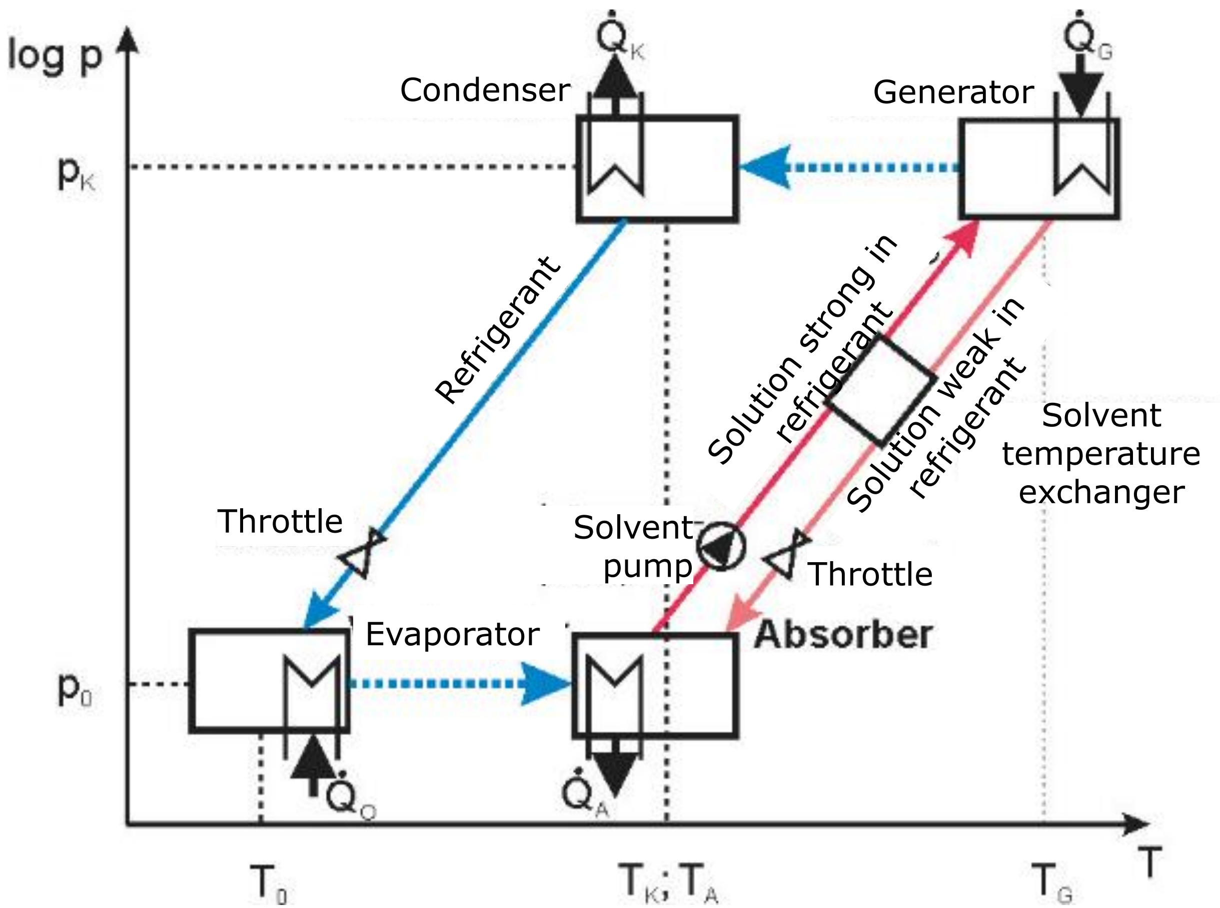
Refrigerant circuit

- Warm refrigerant vapour at condensing pressure moves from generator to condenser
- In the condenser, vapour cools down (heat is extracted via the coolant)
- Liquid refrigerant is expanded to low pressure in the restrictor/throttle
- In the evaporator, refrigerant is sprayed over tube bundles, necessary evaporating heat is extracted from cold water circuit. (Cooling of the cold water = useful cooling/cooling output)

Solvent circuit

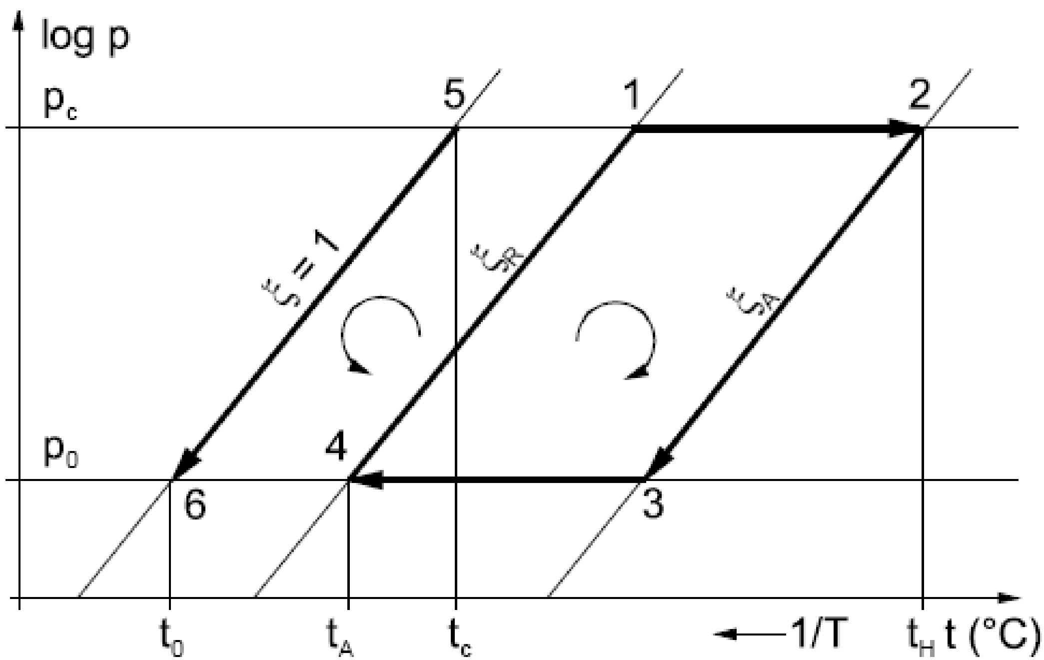
- In the absorber, vapour with a high concentration of solvent is being sprayed
- Refrigerant vapour comes into contact with this spray and is absorbed
- Absorption heat is released, which has to be ejected. This is done via cooling tubes in the absorber containing the same coolant as those in the condenser of the refrigerant circuit.
- The solvent, which is now diluted with refrigerant, is pumped to the generator by the solvent pump.
- In the generator, heat is supplied → Refrigerant evaporates, necessary increase in pressure and temperature
- Refrigerant moves to condenser, solvent moves via temperature exchanger to absorber
- Temperature exchanger: warm solvent from generator pre-warms cold solvent from absorber

Circular process of absorption chiller



Circular process of absorption chiller

- For absorption cooling processes: lg p, 1/T Diagram
- Concentration is important factor for absorption

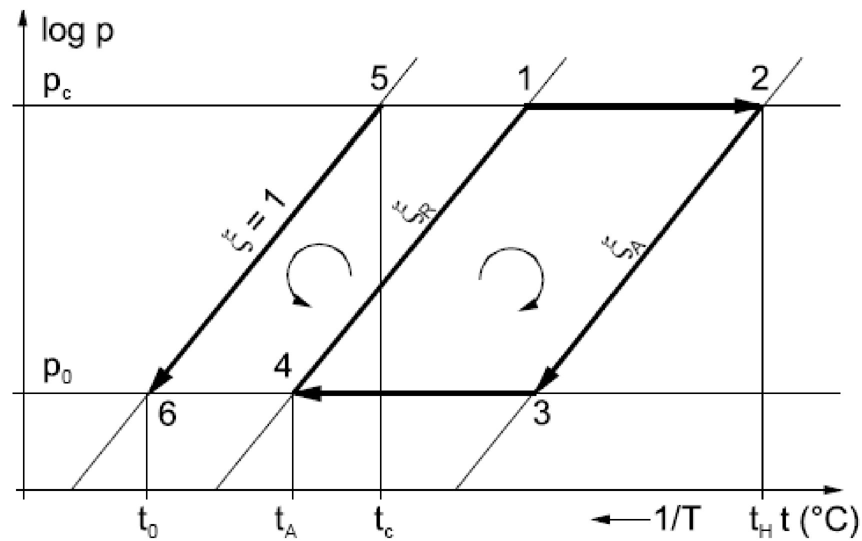


Source: Siemens, Leitfaden Kältetechnik

t_A	Absorption temperature
t_H	Generator temperature
ξ	Concentration
t_c	Condensing temperature
t_0	Evaporating temperature
4-1	Pump
1-2	Generator
3-4	Absorber
6-4	Evaporator
1-5	Condenser
5-6	Restrictor/Throttle (refrigerant is expanded)

Circular process of absorption chiller

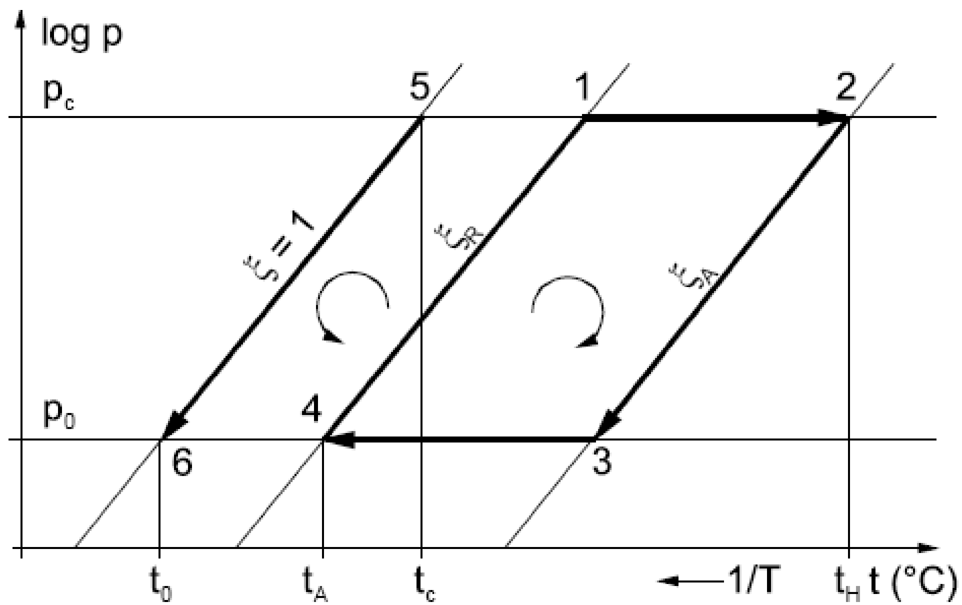
- The solution strong in refrigerant with concentration ξ_R enters the generator (point 1).
- Heating up to process temperature t_H (point 2): refrigerant is generated; concentration reduces to ξ_A (weak in refrigerant).
- The generated refrigerant (vapour) reaches a concentration of ξ= 1 and is liquefied at process temperature t_c (point 5).



Source: Siemens, Leitfaden Kältetechnik

Circular process of absorption chiller

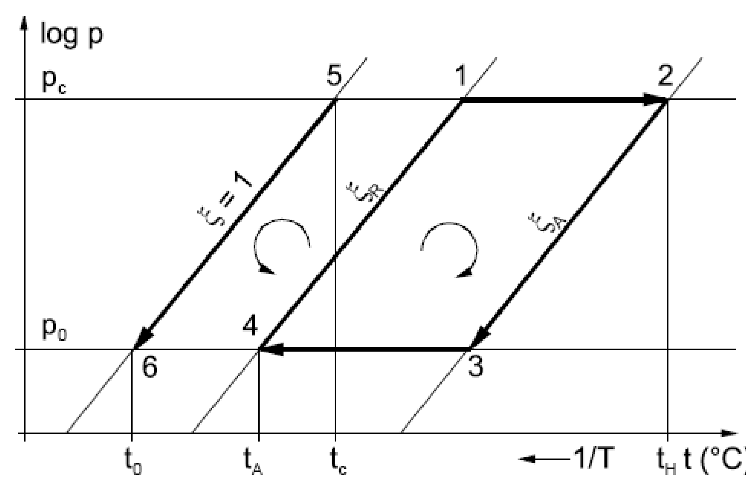
- The intersection of t_c with the line $\xi = 1$ determines pressure p_c on the warm side of the process. The refrigerant is then expanded via an expansion device from this pressure p_c to p_0, which is determined by the desired process temperature t_0 on the cold side (point 6).



Source: Siemens, Leitfaden Kältetechnik

Circular process of absorption chiller

- The weak solution is also expanded to pressure p_0 and enters the absorber (point 3).
- Due to the absorption of refrigerant vapour into the weak solution, heat of condensation and heat of solution is rejected. By cooling down to the process temperature t_A (point 4), the absorption capacity of the solution is increased up to concentration ξ_R, so that the refrigerant vapour coming from the evaporator (point 6) can be fully absorbed. The pump brings the solution strong in refrigerant up to p_c (point 1).



Source: Siemens, Leitfaden Kältetechnik

Degassing range

- Difference ξ_R - ξ_A = degassing range
- Determined by the available or permissible generator temperature t_H and the achievable ultimate absorption temperature t_A
- The smaller the degassing range, the more solvent is required per kg refrigerant.
- At a given difference $t_H - t_A$:
  - ⇨ Degassing range becomes smaller, the smaller the difference (t_c - t_0) gets
  - ⇨ For higher temperature differences t_c - t_0 two- or multi-step processes are required, as is the case with compression chillers.

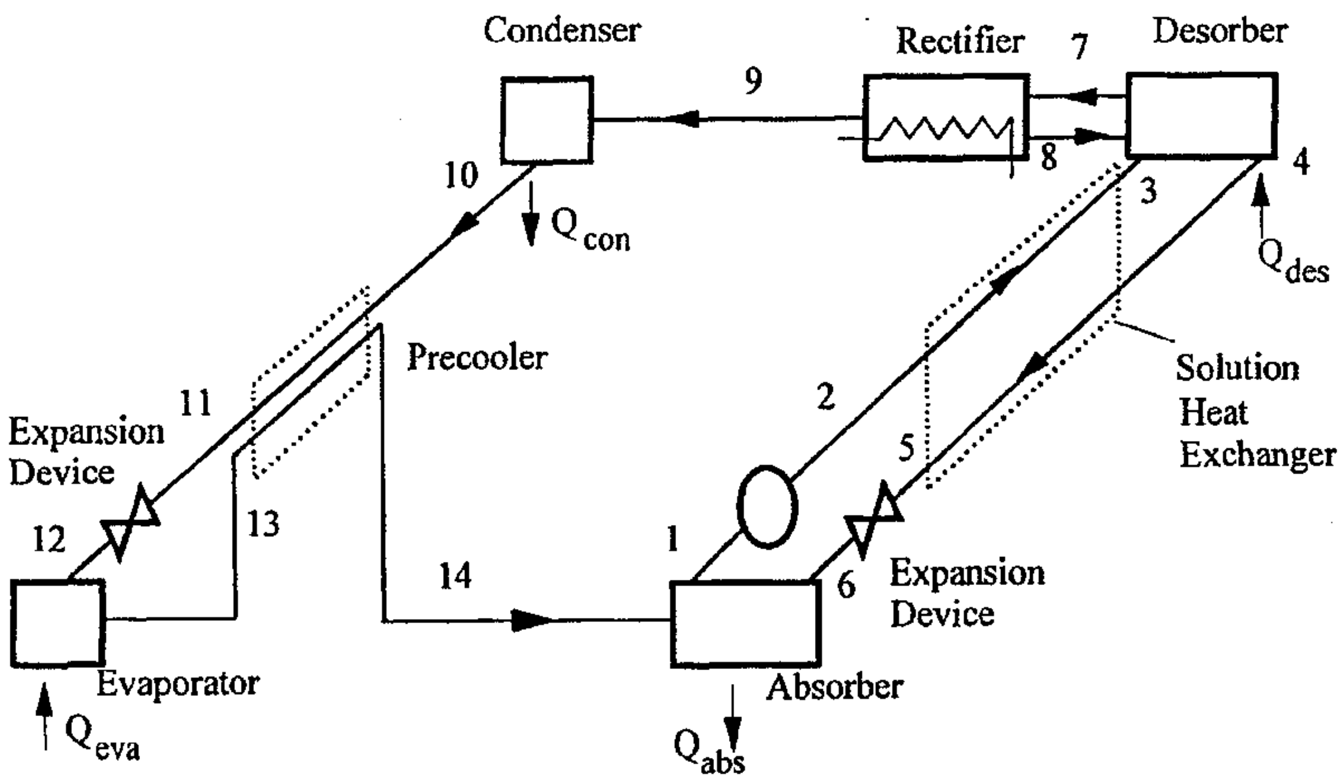
ζ of the absorption chiller

- Heat ratio
  - $\zeta = Q_K / Q_H$ = cooling power/heat supplied

- **Different absorption technologies and their COP**

Absorption technologies	Single stage	Two stage	Single stage
Refrigerant	Water	Water	Ammonia
Solvent	LiBr	LiBr	Water
Coolant	Water	Water	Water-Glycol
Cooling temp. range [°C]	6 to 20	6 to 20	-30 to +20
Heating temp. range [°C]	70 to 90	130 to 160	80 to 180
Temp. of cooling water [°C]	25 to 40	25 to 40	25 to 50
Cooling capacity [kW]	5 to 20,500	170 to 23,300	10 – 1,000
COP	0.6 to 0.7	1.1 to 1.4	0.5 to 0.6

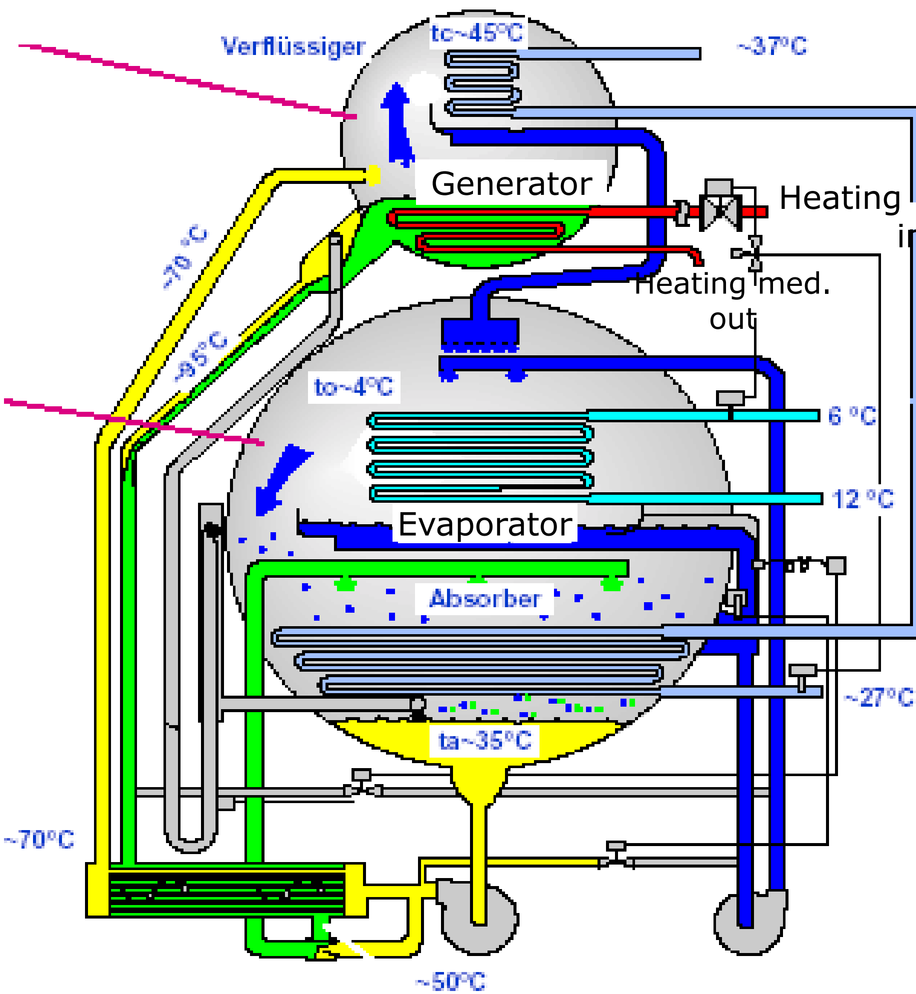
Circular process for NH3/Water chiller



Lithium bromide/Water Chiller

Pressure
approx.
60 Torr
60 mm Hg
80 mbar
8 kPa

Circular process



Pressure
approx.
6.2 Torr
6.2 mm Hg
8.2 mbar
0.83 kPa

Cooling water out

Steam or hot water

Cold water

Cooling water in

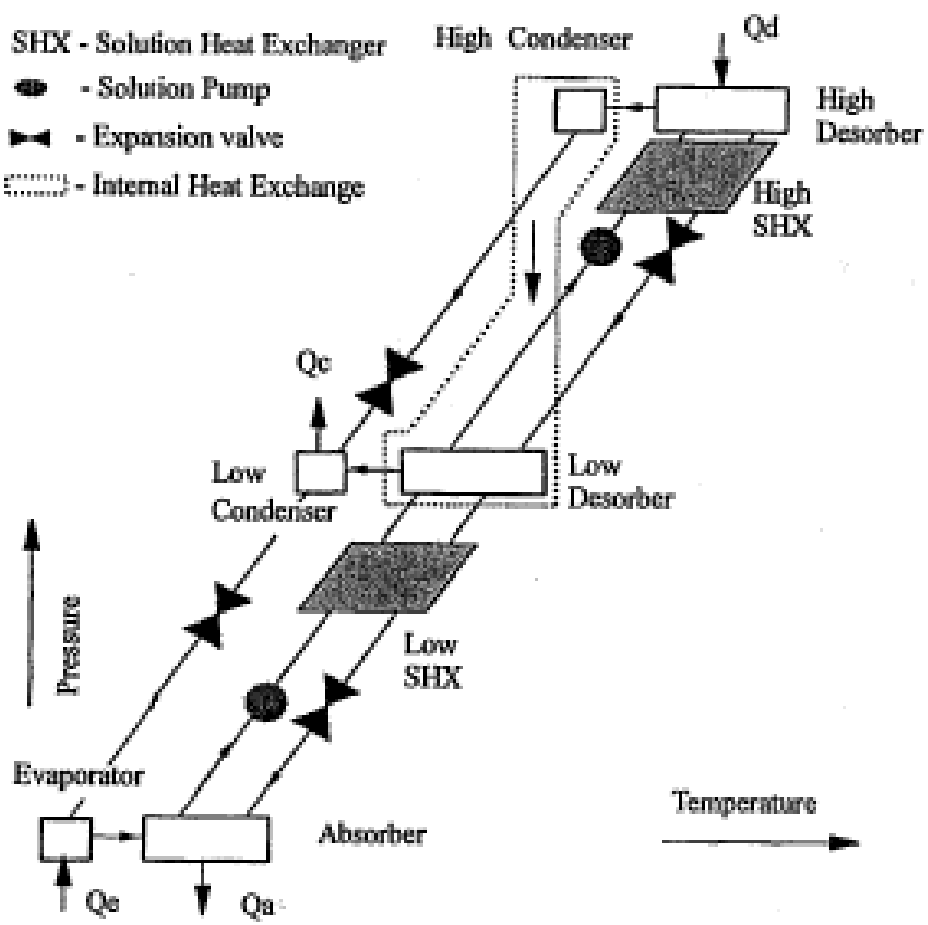
- Cold water
- Refrigerant (Water)
- Strong solution (LiBr)
- Weak solution (LiBr)
- Steam or hot water
- Cooling water

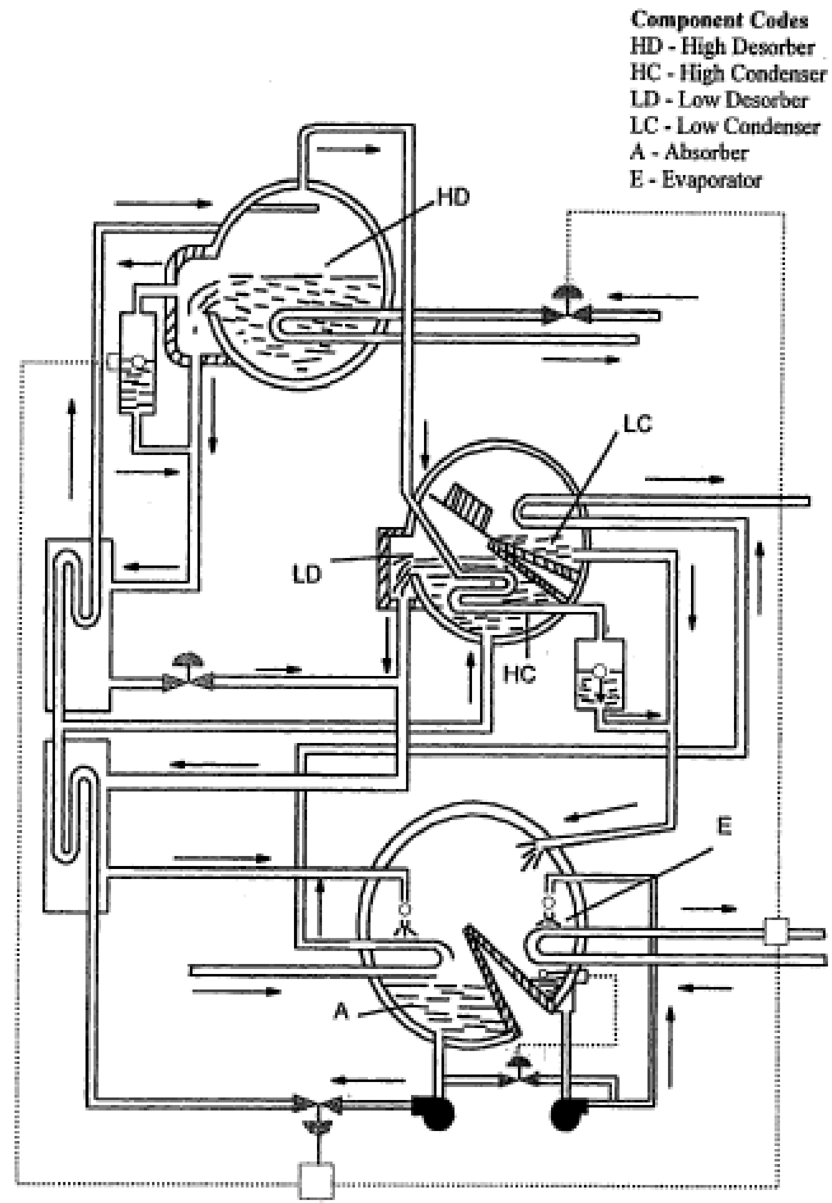
Lithium bromide/Water Chiller

- Single-stage process
  - ⇨ Heat ratio of approx. 0.7 can be achieved
  - ⇨ Input temperature 70 – 90°C

- Two-stage process
  - ⇨ Two generators at different temperature levels
  - ⇨ Heat ratio of up to 1.1 – 1.5 can be achieved
  - ⇨ Higher input temperatures

Two Stage LiBr/Water Chiller





Comparison

	Compression	Absorption with NH_3	Absorption with LiBr
Compression	mechanical	thermal	
Heat supply, typical temperature	„highly valuable" from an exergy perspective (electricity)	„less valuable", e.g. waste heat (therefore: *!) 85…120…180 °C	70…180°C
Cooling temperature	-50…15°C	-50…-10…5°C	5…15 ° C
Cooling capacity	50… 5,000kW	150…1,100…5,500 kW	15…400…5,000 kW
Specific primary energy consumption	1.3…1.65	0.6…1.0	
*For the comparison between thermally and electrically driven chillers, the primary energy ratio should be used, not just the COP!			
COP (Coefficient of performance)	3…5	0.3…0.55…0.7	0.6 – 0.75 (1-stage) 1.0 – 1.5 (2-stage)
Waste heat	1.2…1.3	1.9…2.7	
Advantages	Compact design, lower investment cost, less waste heat, dynamic	Low cost for heat supply, lower maintenance cost, reliability, part load performance, little noise and vibration	

Main source: BEZ, Armin, 2012: Kälte durch Wärme erzeugen, Bachelorthesis

C) Measures to reduce energy use for refrigeration and to improve system efficiency

- Overview
  - Reduce heat loads
  - Raise evaporating temperature + Optimise evaporator
  - Lower condensing tepmerature
  - Optimise condenser control
  - Efficiency and control of fans
  - Use of waste heat – heat recovery
  - Avoid and repair leakages
  - Storage of (heat and) cold
  - Energy efficient (heat and) cold distribution
  - Trigeneration
  - Other approaches

Source: Project Einstein, Slides of Cooling Module

Optimisation approaches

- Age of system (10 years for small AC)
- Filling level of refrigerant

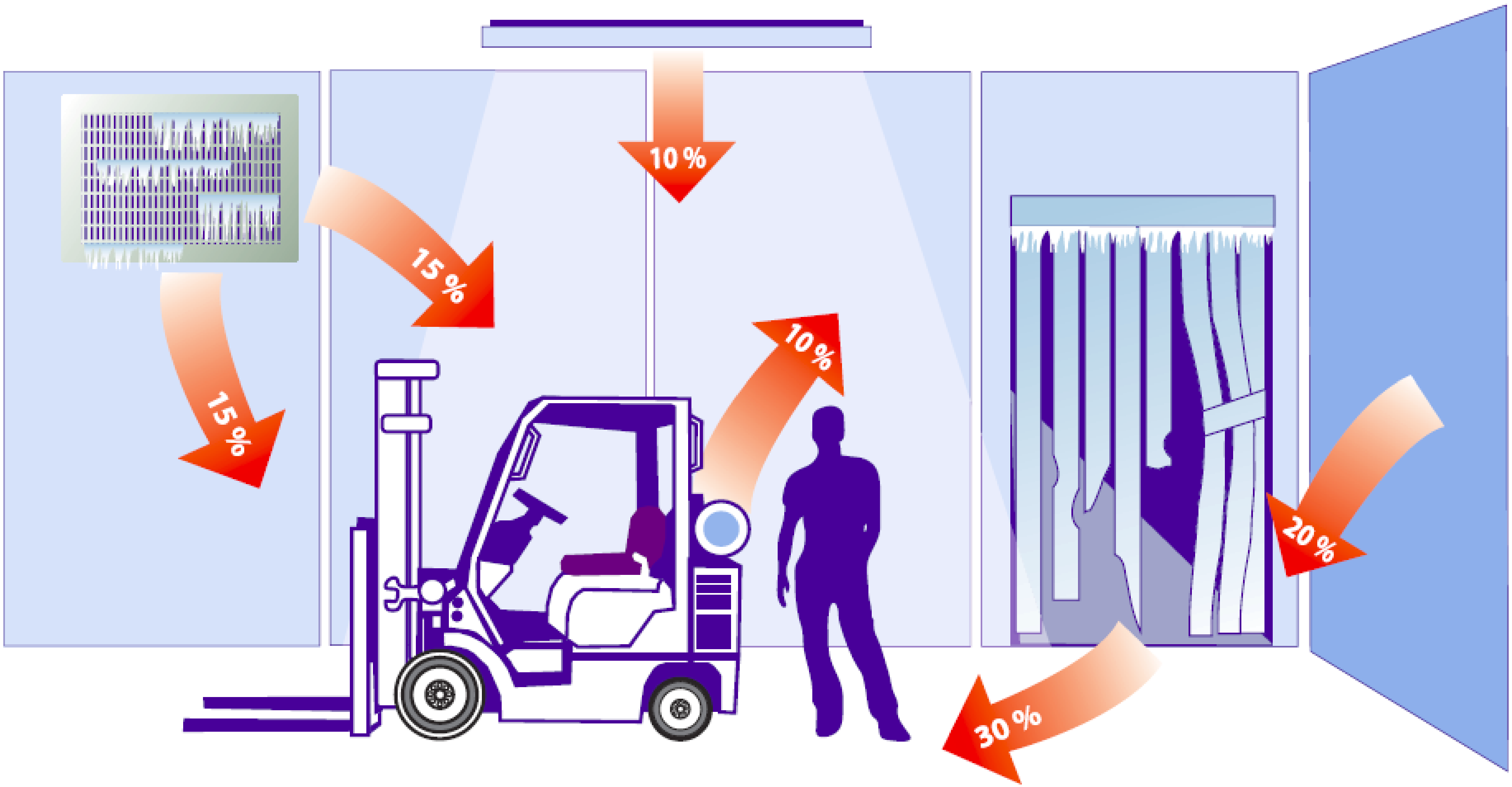
- Free cooling
- Night cooling

- Set point temperatures
- Operating times (programmable controllers)

- Recooling tower maintenance (filter, water, fans,..)
- Evaporater maintenance (filter, ..)
- Proper insulation of distribution pipes

Reduce heat loads

➢ *Cold Room Heat Gains (Source: Carbon Trust)*



Reduce heat loads (1)

- General formula to evaluate / quantify savings:

$$\text{Savings} = (Q_{\text{old}} - Q_{\text{new}}) \times \frac{1}{\text{COP}} \times \text{FLH}$$

- ⇨ Q — Heat load before and after implementation of measures [kW]
- ⇨ COP — Average COP during the year (or during plant operation times)
- ⇨ FLH — full load hours [h/a]

Source: Kulterer, 2014

Reduce heat loads (2)

- Switch off unused chill rooms, increase temperature in unused cold storage rooms from e.g.-18°C to -5°C
- Evaluate possibilities to increase process and storage temperatures
  - Check recommended temperatures
  - Which factors determine maximum value?
  - Compare required temperatures with current situation
- Cold storage: avoid temperature increase before storage
  - Avoid interruption of cold chain
  - Seal passage from truck to cold storage
  - Do not temporarily store cooled products in warm rooms
  - In store: air should flow over goods to be cooled, circulation of air should not be obstructed.

Source: Kulterer, 2014

Reduce heat loads (3)

- Reduce heat load caused by product temperature or activity of storing
  - Process free cooling: explore opportunities to pass heat from one stream that needs cooling to another stream that needs to be heated
  - Ambient free cooling: e.g. reduce blast freezing by letting hot product cool at ambient air first followed by blast chilling stage, then move into blast freezer (if compatible with hygiene standards)

Heat gain sources for cold rooms	%
Heat gained through insulated walls, ceiling and floor	20%
Warm air, moisture leaking in through doors and gaps	30%
Evaporator fans	15%
Evaporator defrost	15%
Lights	10%
Occupants and associated equipment	10%

Source: Kulterer, 2014

Source: Carbon Trust, CTL 137

Reduce heat loads (4)

- Reduce heat gain via door (1)

- Signs that actions may be needed:
  - Open doors or cooling positions without doors
  - Chill or cold room where door often remains open
  - Formation of ice on ceiling, floor or wall of chill or cold room (due to humidity of air getting in)
  - In cold rooms with low temperatures also when there are automatic doors and the room is frequently entered into

Source: Kulterer, 2014

Reduce heat loads (5)

- Reduce heat gain via door (2)
  - User behaviour: Keep doors of chill/cold rooms closed as much as possible
  - Install alarm that sounds if doors remain open a certain time
  - Repair doors that do not close well
  - Check, clean, repair or regularly change door seals
  - Doors with inflatable PVC or PU seals
  - Install strip curtains
  - Automatic door closing mechanism for cold rooms (Cost approx. 120 EUR)
  - Install rapid action door and optimise opening times

Source: Kulterer, 2014

Reduce heat loads (6)

- Insulation
  - Heat Tranfer Coefficients (U)
    - Recommendations: approx. from 0.3 for normal temperature cooling to 0.14 for low temperature cooling.
      This corresponds to approx. 80 mm to 170 mm PUR
    - New implementation regulation for 2009/125 (EC) foresees: 0.35 for walls and 0.2 for ceilings of walk-in refigerators
  - Regular thermography check to identify and remove thermal bridges
  - Avoid penetration by cable or ventilation ducts

Source: Kulterer, 2014

Reduce heat loads (7)

- Reduce heat gain from lighting
  - Light bulbs used in cold rooms can be replaced by LEDs (with E27 socket)
  - Install ballasts outside chill room (in case of chiller cabinets also the lamps)
  - Adjust illumination level to actual need
  - Reduce times lighting remaines switched on, use door contacts, presense or motion detectors
  - Use reflectors
  - T8 lamps have a very bad luminous efficacy at low temperatures

Source: Kulterer, 2014

Reduce heat loads (8)

- Defrost when required instead of periodically
  - Savings of about 2-3% can be achieved by defrosting when needed (different technologies are available for that) compared to defrosting scheduled at regular intervals

Source: Kulterer, 2014

Increase evaporating temperature (1)

- Step 1: Check evaporating temperature
  - ⇨ First check if evaporating temperatures are set as high as possible for the different uses.

- **Step 2: Determine design conditions**
  - ⇨ Temperature differences (TD) at evaporator

Possible TD	Can be optimised	Poor
Air cooled heat exchangers		
Finned heat exchanger, dry evaporator type	TEV: 6 K possible EEV: 4 K possible	TEV: more than 10 K EEV: more than 7 to 10 K
Finned heat exchanger, flooded evaporator type	2K possible	Higher than 8 K
Water cooled heat exchangers		
Plate heat exchanger	2-6 K	Higher than 6 K
Shell and tube heat exchanger	3-5 K	Higher than 5 K*

Source: Campaign „effiziente Kälte 2011", Discussions with experts;
TEV= thermostatic expansion valve, EEV=electronic expansion valve

Source: Kulterer, 2014

Additional info:
Temperature levels of different applications

	Evaporating temperatures t_o	Cooling temperatures	Condensing temperatures t_c
Air conditioning	+5°C	+15°C	30-45°C
Chilling	-5°C	+5°C	30-45°C
Medium temperature refrigeration	-10°C	0°C	30-45°C
Low temperature freezing	-30°C	-20°C	30-45°C
Quick-Freezing	<-45°C	-35°C to -50°C	30-45°C

Source: Kulterer, 2014

Increase evaporating temperature (2)

- Step 3: Evaluate/implement optimisation measures
  - Avoid too low evaporating temperature, due to unfavourable circulation of air in the room (how goods are stacked, mould in chill room)
  - Clean dirty heat exchangers
  - Straighten bent lamellae/fins with comb (Air circulation in heat exchanger should be unobstructed)
  - Build-up of ice on heat exchanger is an indication for savings potential
  - Ventilators/blades in bad condition, ventilator defective
  - Correct settings (at EEV or TEV) if super-heating is too high
  - Use an electronic expansion valve (EEV)

Source: Kulterer, 2014

Increase evaporating temperature (3)

- Step 4: Quantitative estimation of results
  - An increase in evaporating temperature of 1 Kelvin can improve the COP by up to 3%.

  - Calculation:
  - $ES_{max} = EC_{old} \times (3\% \times \Delta T_{incr\_to})$

    - ES_{max} Maximum achievable energy savings
    - E_{Cold} Energy consumption before measures
    - ΔT_{incr_to} Kelvin by which measure increases evaporating temp

Source: Kulterer, 2014

Reduce condensing temperature (1)

- Size of heat exchanger and k-value influence minimum temperature difference necessary

⇨ $\boldsymbol{Q_C = A * k * \Delta T}$

- Q_C Liquefaction capacity in [W]
- A Surface of heat exchanger [m²]
- k k-Value [W/m²K]
- ΔT Temperature difference [K]

Source: Kulterer, 2014

Reduce condensing temperature (CT) (2)

- Step 1: Determine minimum condenser temperature difference
  - ⇨ By determining design conditions, or estimate using guidance values:

Type of condenser	Guidance values for CT
Remote air cooled condensers	10 - 12 °C above dry bulb ambient temp.
Evaporative condensers	10 °C above wet bulb ambient temp.
Air cooled condensing units	15 - 20 °C above dry bulb ambient temp.
If you are specifying new systems: • try to avoid air cooled condensing units (a multi compressor central plant system plus remote air cooled or evaporative condenser will have up to 40% lower running cost than typical individual units); • use evaporative condensers when heat rejection load is above 250kW, as CT will be up to 5 ° lower than with air cooled condensers; • ensure such condenser position that cooling air flow is not restricted and not warmer than necessary	

(Source: Food & Drink Industry Refrigeration Efficiency Initiative, Guide 5, p-14)

Reduce condensing temperature (CT) (3)

- Step 2: Compare minimum temperature difference
  - Measure current CT or determine temperature from steam tables using saturated vapour pressure (depending on the refrigerant). Head pressure can be measured anywhere between compressor outlet and expansion valve.
  - Measure ambient temperature and temperatures at condenser inlet/outlet.
  - If temperature difference or expected CT higher than determined in step 1 or than shown in table on next slide*, the system is probably running inefficiently.

  - *Attention: Temperature difference is defined a bit differently there

Source: Kulterer, 2014

Reduce condensing temperature (4)

- Temperature Differences
  - ⇨ Between condenser outlet and condensing temperature

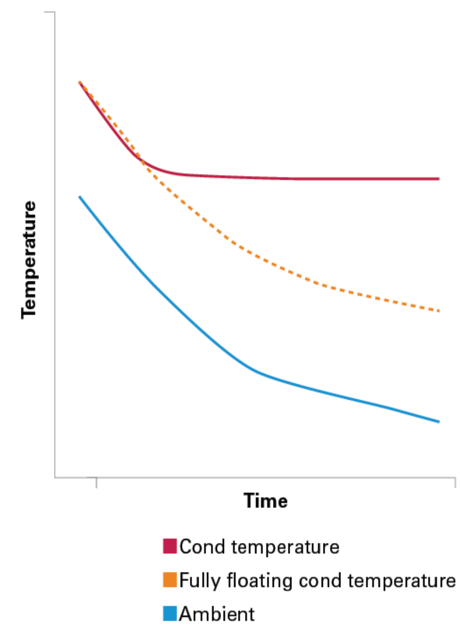
	Recommended	Can be optimised	Poor
Air cooled condensers			
Finned heat exchanger	10 K	10-13 K	Above 13 K
Condenser with heat carrier			
Plate heat exchanger*	2-3 K	3-6 K	Above 6 K
Tube bundle heat exchanger**	5 K	5 K	Above 5 K

Source: Campaign „effiziente Kälte“, 2011; *,** discussions with experts from Danfoss, Cofely

Source: Kulterer, 2014

Reduce condensing temperature (CT) (5)

- Step 3: Reasons for higher CT & measures (1)
  - ⇨ Too high minimum CT
  - ⇨ If system works at a fixed minimum CT of 40 to 45°C, controls of CT should be checked. Target value can probably be reduced.
  - ⇨ Constant CT
  - ⇨ Even if the system operates at floating CT, often a minimum is set, below which temperature does not fall, despite falling ambient temperature. In such cases also check if reduction is possible.
- Attention: ensure that other important parameters, such as minimum head pressure required by some technologies (expansion devices, hot gas defrost etc.) are still met!



Source: Kulterer, 2014

Source: Carbon Trust 136, How to minimize head pressure

Reduce condensing temperature (6)

- Reasons for higher CT & measures (2)
  - ⇨ Heat exchanger design too small

	Maximum ambient temperature (summer)	CT	ΔT
Old systems	32°C (30°C)	45 °C	K 13 (K 15)
New systems	35°C	45 °C	K 10
Optimum	35 °C	43 °C	K 8
Design data for air cooled condensers (Source: discussions with experts, 2012)			

  - ⇨ Heat exchanger dirty or corroded/damaged, ventilation defective
  - ⇨ Location (restricted air flow, proximity to other condensers)
  - ⇨ Housing does not fit closely, permits air to re-circulate around condenser
  - ⇨ Non condensable gas in the system

Source: Food & Drink Industry Refrigeration Initiative, Guide 5

Source: Kulterer, 2014

Reduce condensing temperature (CT) (7)

- Step 4: Calculation of savings
  - If actual CT is above the one necessary, a decrease in CT of 1 Kelvin can improve the COP by up to 3% (in reality often around 2%)
  - Static Calculation: $ES_{max} = EC_{old} \times (3\% \times \Delta T_c)$
    - ES_{max} maximum achievable energy savings
    - EC_{old} energy consumption before measures
    - ΔT_c Kelvin by which measure decreases condensation temp
  - Dynamic Calculation: Example: Calculation of new COP and of savings due to lowered CT

Hours	T_{amb} (ambient)	T_c old	COP old	T_c new	COP new	Savings [kWh_{el}]
176	> 32°C	45°C	3.04	= $T_{c,old}$	= COP_{old}	0
72	26°C < T < 32°C	45°C	3.04	= $T_{c,old}$	= COP_{old}	0
92	24°C < T < 26°C	45°C	3.04	40°C	3.41	169
3,457	< 20°C	45°C	3.04	35°C	3.9	6,328
Assumptions: operating hours: 16h/d and 5d/week, constant cooling load 100 kW, constant CT 0°C						

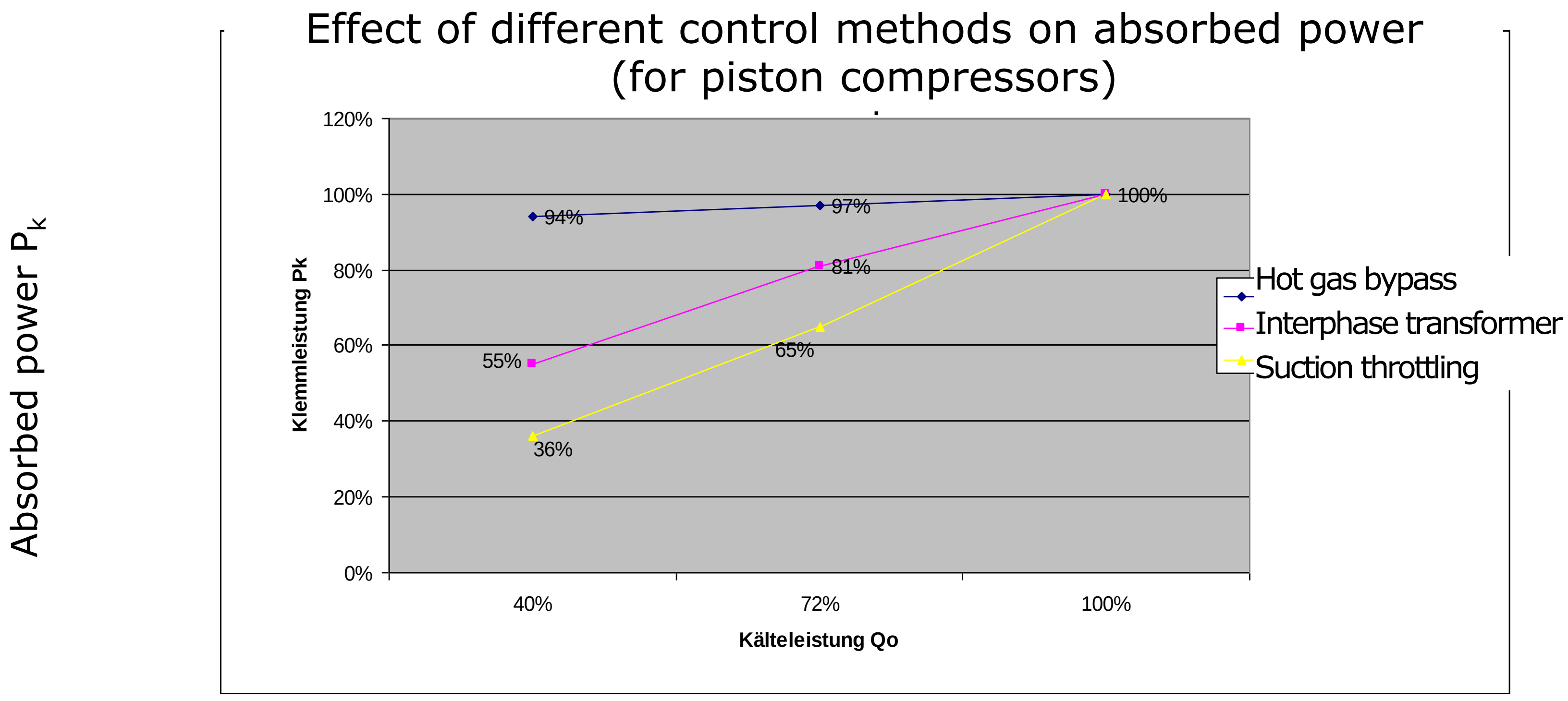
Source: Kulterer, 2014

Optimise compressor control (1)

- Compressor capacity control is important for efficient part load operation (systems rarely run at full load!)
- Savings potentials exist very probably, if:
  - One big compressor serves several small users
  - Screw compressor is controlled with a hot gas bypass
  - Compressor cycles more often than 6 times per hour
- Step 1: Determine current settings
- Step 2: Estimate load profile
- Step 3: Estimate options for improvement
  - What control types are useful?
  - Can frequency converters be used?
  - Combination of several compressors instead of one large possible?
  - Install refrigeration controllers

Source: Kulterer, 2014

Optimise compressor control (2)



Source AEA, Info-Tour, 2003, Slide 60

Cooling output Q_o

Source: Kulterer, 2014

Optimise compressor control (3)

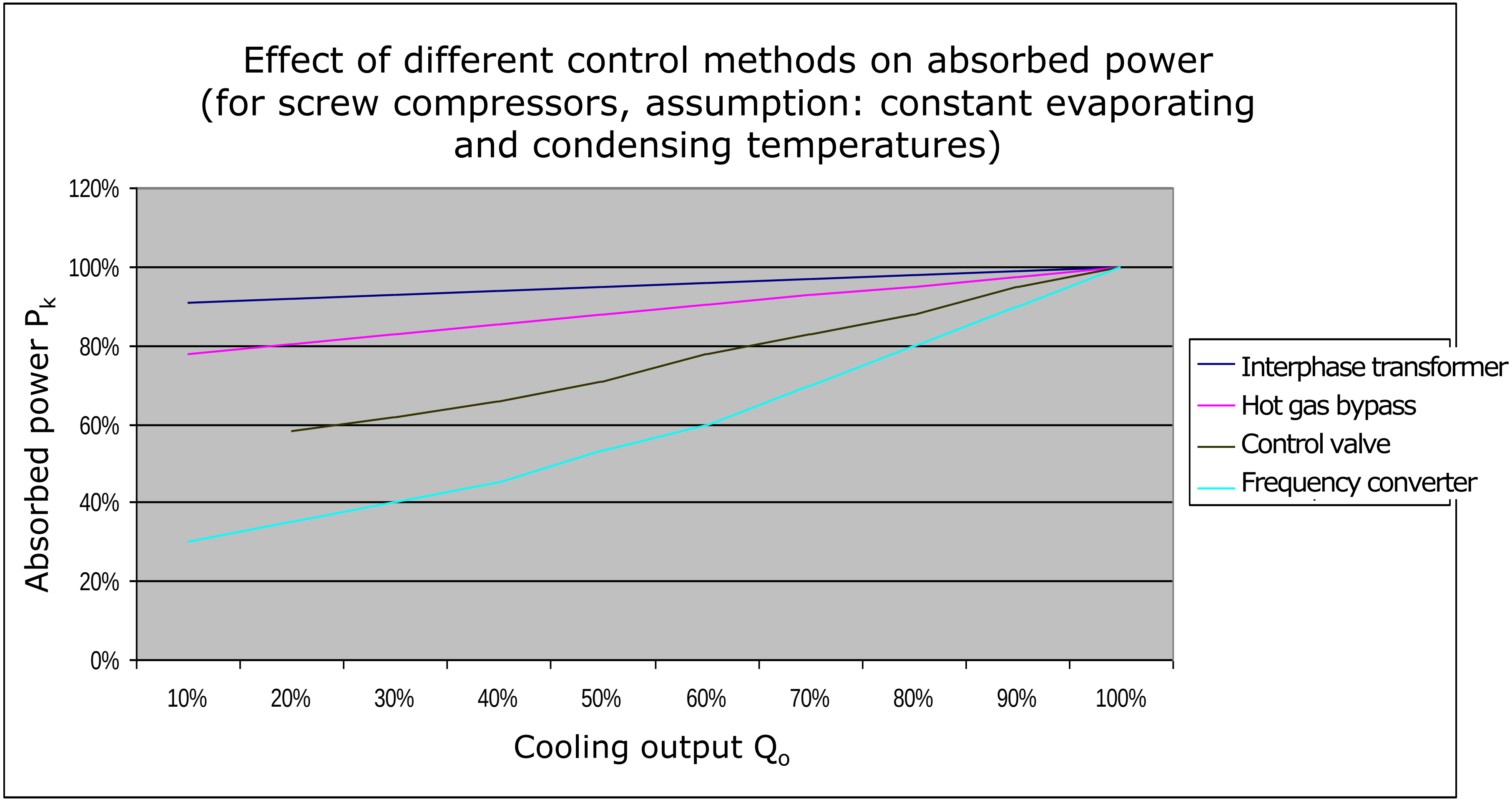


Diagram by AEA, based on Cascade Energy Engineering, 2004

Source: Kulterer, 2014

Fan efficiency and control (1)

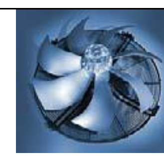
- The following savings potentials are common with fans in refrigeration systems
  - Use of a fan and/or motor with higher efficiency (are often installed as a unit)
  - Reduction of operating hours
  - Capacity control

- More details about these measures are presented on the following slides.

Source: Kulterer, 2014

Fan efficiency and control (2)

- **Efficiency of different fan types**

Axial fans	**Efficiency**	
Fan with simple blades		0,5-0,6
Fan with profiled blades		0,6-0,7
Fan with profiled, sickle-shaped blades		0,7-0,75
Fan with air-flow optimised blades		0,75-0,8

Source: AEA, Handout 4th Info-Tour Slide 52

Source: Kulterer, 2014

Fan efficiency and control (3)

- Efficiency of electric motors (up to 1.5 kW)
  - ⇨ Especially for smaller power ranges (below 1 kW) permanent magnet motors have significantly better efficiency than asynchronous motors

	125 W	250 W	500 W	750 W	1.5 kW
Permanent magnet motor (PM)	0.65	0.75	0.8-0.85	0.85	Up to 0.88
AC motor (IE2)	0.4	0.55	0.7	0.77	0.85
AC (IE2) motor with frequency converter	0.33	0.5	0.65	0.73	0.82
Standard motor (IE1) (approx.)	?	?	?	0.7	0.77

Source: Lindegger, M.: Permanent Magnetisiert, Faktor, Heft 28, Zürich 2010, for IE1: Estimate AEA

Source: Kulterer, 2014

Fan efficiency and control (4)

- Reduction of operating hours

- Possible measures for evaporator fans:
  - Switch off, when cooled area is not in use or when no cooling is needed/required temperature is reached.
  - Install door contact switch: if door is open, cooling is being interrupted in order to avoid cold air seeping out.
  - Switch off evaporator fans when defrosting (if electric or with hot gas)
  - Switch of manually (seasonal)
  - Switch off, when refrigerant flow stops

Source: Kulterer, 2014

Fan efficiency and control (5)

- Control of evaporator fans
  - Use multipolar motors (step-by-step coupling). Two fans at half speed consume less energy than one at full load. (e.g. at night or during weekends)
  - Infinitely variable thermostatic control: can reduce load by on average 20% (rough estimate)

Source: Kulterer, 2014

Fan efficiency and control (6)

➢ Load reduction depending on type of control and rotational speed

Power consumption in W in % Rotational speed	Voltage control with silencer	Frequency converter with all pole sine-wave filter	Fan with EC-Technology (integrated frequency converter)
40%	25% - 35%	12% - 17,5%	8% -9%
50%	35% - 46%	17% - 25%	12% - 15%
60%	57% - 64%	25% - 35%	18% - 24%
70%	60%- 65%	36% - 48%	28% - 35%
80%	75%	52% - 66%	40% - 52%

Power consumption of fans depending on control type and rotational speed (and thus volume flow rate)
Source: Info-Tour 2003: Leistungsregelung an Kälte- und Klimaanlagen. Folie 92, Gorbach, 2011

Source: Kulterer, 2014

Fan efficiency and control (7)

- Evaporator fan:
  Calculation/Estimation of energy savings
  - Formula for calculation of energy savings of fans due to frequency converter for condenser
  - Electricity consumption of fan motor AND compressor is reduced, due to lower cooling load
  - $Energy\ saving = P_{fan} \times t \times load\ recduction \times \left(1 + \frac{1}{COP}\right) \times d$
    - P_{fan} absorbed power of fan $[kW]$
    - t fan operating hours / day
    - d operating hours/ day (not of the compressor!)
    - load reduction average load reduction due to the variable speed control (assumption 20%, or as shown in previous slide)

Source: Kulterer, 2014

Fan efficiency and control (7)

- Condenser fan – Savings opportunities:
- Control of condenser fans should be examined, especially if:
  - ⇨ Power absorbed by condenser fans is too high compared to electrical compressor output!
  - ⇨ I.e. especially industrial plants, where centrifugal fans are installed (due to acoustic properties).

Source: Kulterer, 2014

Waste heat recovery* - Estimation

- A) Demand for heat below condensing temperature
  - ⇨ If heat below the condensing temperature can be used (e.g. 25-35 °C), the total waste heat of the refrigeration plant (heat extracted from cooled product/stream + from electrical power used by compressor) can be used: „full condensation".

Waste heat capacity at full condensation	Amount of waste heat
Formula: $Q_{WH} = (Q_O + P_e) \times \eta \times COI$	Formula: $WH = Q_{WH} \times OT$
Q_{WH} Waste heat [kW] Q_O Refrigeration capacity [kW] Pe Absorbed power [kW] η Plant efficiency (heat loss), can be estimated at 0.8 COI Factor of coincidence, depending on number of cooling points	WH Waste heat [kWh] OT Assumption about plant operating time; on average 10h/day [h] x days

*For more information on heat recovery see Module 08 of the GREENFOODS-Training!

Source: Kulterer, 2014

Waste heat recovery - Estimation

- B) Demand for heat above condensing temperature
  - ⇨ If heat above the condensing temperature is needed (e.g. 45-65 °C water temperature), only the waste heat from desuperheating – about 15% of condenser capacity - can be used. (B is already included in A)
  - ⇨ *Formula:* $Q_{SH} = (Q_O + P_e) \times \eta \times \frac{Q_e}{Q}$
    - Q_{SH} Waste heat from superheating [kW]
    - Q_O Refrigeration capacity [kW]
    - P_e Absorbed power [kW]
    - η Plant efficiency (heat loss), can be estimated at 0.8
    - Q_e Desuperheating capacity
    - Q Total heat output (Condenser capacity)
    - (Q_e/Q can be estimated as 15-20%)

Source: Kulterer, 2014

Avoidance and repair of leakages

- There is a legal obligation to detect and repair leakages at regular intervals
  - For plants with more than 3 kg of HFKW refrigerant
- Determine annual amount and type of refrigerant added
  - Refrigerant GWP (CO_2e)
  - Annually added amount / Total amount of refrigerant in %
- In reality, this is on average 5-10%, sometimes (e.g. in supermarkets) up to 20%
- Target values for new plants are very low

Source: Kulterer, 2014

Storage of heat and cold

- Reduces peak load:
  - ⇨ Increases share of base load
  - ⇨ Enables higher portion of demand to be covered by energy efficient equipment, which will have higher operating hours
- Enables generation of needed heat or cold from waste heat or solar thermal heat
  - ⇨ even if supply and demand do not occur simultaneously

Source: Project Einstein, Slides for Module „Design and Optimisation of Heat and Cold Supply“

Energy efficient heat and cold distribution

- A suitable H/C distribution system can often contribute to reducing energy consumption
- Reduction of temperature level
  - Can reduce losses in pipework and storage
  - Can be necessary precondition for using efficient technologies such as CHP, heat pumps, solar thermal energy

Source: Project Einstein, Slides for Module „Design and Optimisation of Heat and Cold Supply“

Combined Heat and Power & Trigeneration

- CHP enables highly efficient conversion of fuel into power and heat
  - ⇨ Conversion losses of 10-25% compared to at least 45% for power generation only
- CHP can also cover heat demand (Trigeneration = Power + Heat + Cold)
  - ⇨ Use of absorption coolers
- Maximise energy savings:
  - ⇨ CHP should deliver also heat to own location
  - ⇨ Feed surplus electricity into public grid

Source: Project Einstein, Slides for Module „Design and Optimisation of Heat and Cold Supply“

Measures to reduce energy demand for cooling – additional approaches

- Use free cooling, where possible
- Use cascade plants, where appropriate
- Aim at achieving as low a temperature for recooling water supply as possible
- Reduce part load operation of refrigeration plant
- In case of designing a new system, take into consideration the whole set of technology options:

Source: Project Einstein, Slides for Module Cooling

Measures to reduce energy demand for cooling – additional approaches

- Types of cooling systems, incl. „alternative“ ones
  - ⇨ Vapour-Compression-Refrigeration (see above)
  - ⇨ Thermally driven chillers (often well suited for trigeneration or integration in solar cooling concepts!)
    - Absorption chiller – described in detail above;
      also models with more than 2 steps available („triple effect“ etc.); multi-step models increase COP, as available heat of higher temperature can be used, but equipment is soon getting very complex)
    - Adsorption and steam jet refrigerating machines (see next slide)
  - ⇨ Cooling towers (“free cooling”)
    - open/closed, wet (evaporative) /dry/hybrid
    - Electrical power level typically between 10 and 23 kWel/MWth
  - ⇨ Other types: diffusion absorption refrigeration system, Linde-process, magnetic cooling, pulse tube refrigerator, Peltier element

Source: Project Einstein, Slides for Module Cooling

Measures to reduce energy demand for cooling – additional approaches

- Types of cooling systems (2)
  - Steam jet refrigeration machines
  - Water vapour as expanding agent, refrigerant and cooling medium.
  - Expansion of a jet of water vapour using a steam ejector generates a vacuum, and water vapour is being drawn in from an evaporator. Due to the evaporation, the remaining water in the evaporator is cooled and can thus be used as a cooling medium.
  - Characteristics: Water as a refrigerant, good dynamic properties in part load operation and a COP that is independent of pressure. This cooling process is mainly used for product cooling in industrial processes, among others also in food industry.

Main source: http://de.wikipedia.org/wiki/Kältemaschine

Measures to reduce energy demand for cooling – additional approaches

- Types of cooling systems (3)
  - Adsorption chillers
  - Work with a solid adsorbent into and from which the refrigerant is adsorbed and desorbed. When heated up, the refrigerant desorbs from the adsorbent, and the heat is released again during adsorption. As the adsorbent is solid, the process works discontinuously. To achieve a continuous supply of cooling, there must be at least two adsorption pumps, where one is working while the other is regenerating (cycle of about 6-10 minutes). Then, heat supply is switched between the two pumps and adsorpation and desorption start anew.
  - Due to the low temperature level needed, adsorption chillers are well suited for use with solar heat. The efficiency of utilization of solar energy depends on the temperature level and is higher at lower temperatures.

Main source: http://de.wikipedia.org/wiki/Kältemaschine

Sources and Additional Information in German

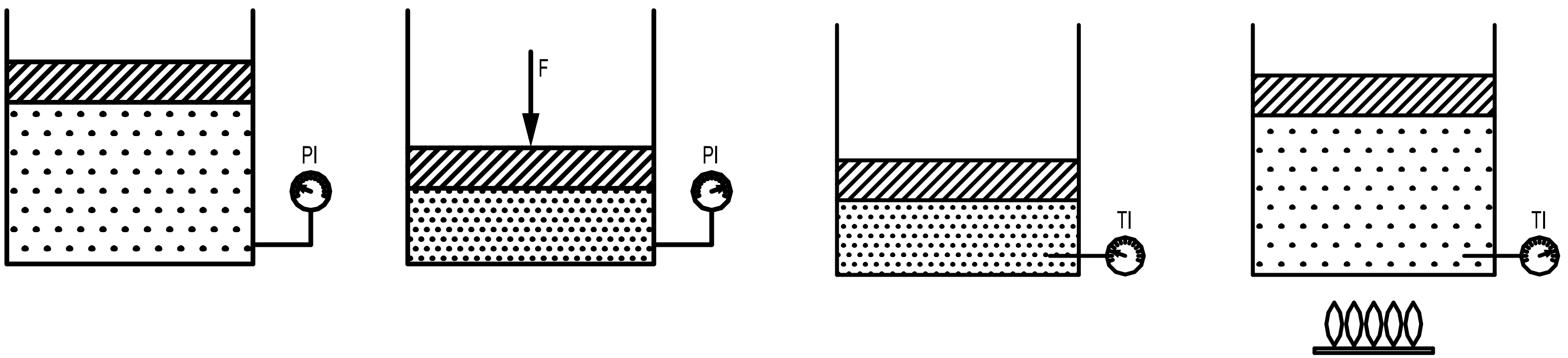
- klima:aktiv Kälteleitfaden, Kulterer, K, Mair, O. , Österreichische Energieagentur im Rahmen des Programms des Lebensministeriums, Wien 2012 & weitere Schulungsunterlagen, verfügbar unter: http://www.klimaaktiv.at/energiesparen/betriebe_prozesse/technologieschwerpunkte/kaeltesysteme.html
- „Kältetechnik“ Auszug aus Trainingsmodul "B08RF – Kältetechnik“, Siemens AG, Schweiz
- Arbeitsstoffkombinationen für Absorptions-wärmepumpen, Reinhard Radermacher, 1981
- Aserep Excel Kältemittelsimulationstool
- Wärmepumpen und Kältetechnik, Bauteile Stand 2007, Kunz Beratungen, Schweiz

Sources and Additional Information in English

- Aserep Excel Simulation Tool
- Absorption Chillers and Heat Pumps, Keith Herold, 1996
- Food & Drink Industry Refrigeration Efficiency Initiative - Guide 5, Carbon Trust & Food and Drink Association, 2007
  - For download at: http://www.ior.org.uk/VJEQN5TPAG
- Refrigeration guidance published by the Carbon Trust
  - Refrigeration systems technology guide (CTG046)
  - How to maintain refrigeration equipment (CTL135)
  - How to minimise head pressure in refrigeration (CTL136)
  - How to reduce heat gain in refrigeration (CTL137)
  - How to reduce heat load in refrigeration (CTL138)
  - How to add adiabatic cooling to your refrigeration plant (CTL139)
  - How to implement heat recovery in refrigeration (CTL056)
  - Refrigeration road map (CTG021)

Basics

Gas laws



Compression increases pressure

Heating increases volume

Gas Law

$$P \cdot V = R \cdot n \cdot T$$

p – pressure (Pa)

V – Volume (m^3)

T – absolute Temperature (K)

n - Mol amount

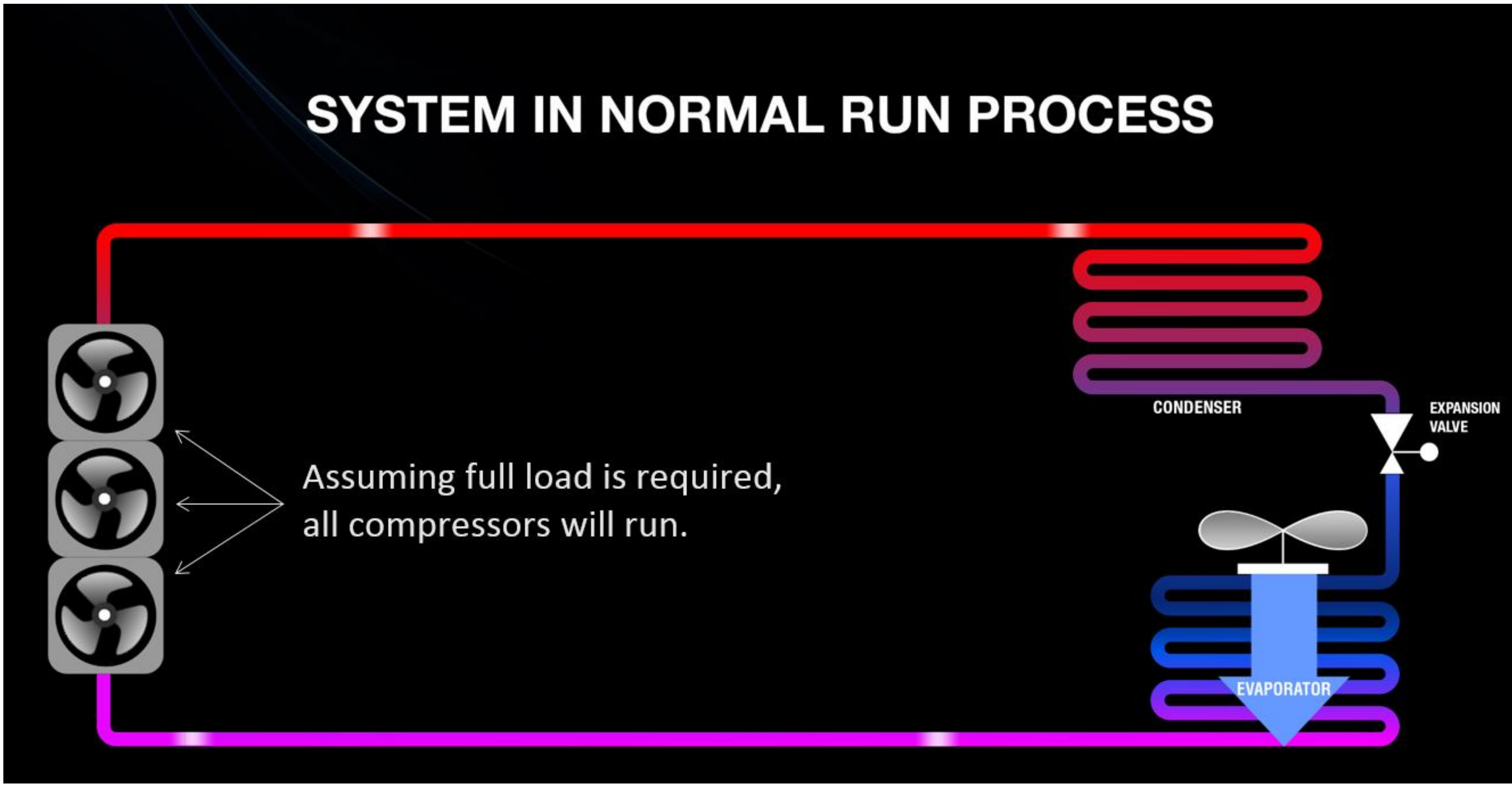
R – Gas constant for ideal gases

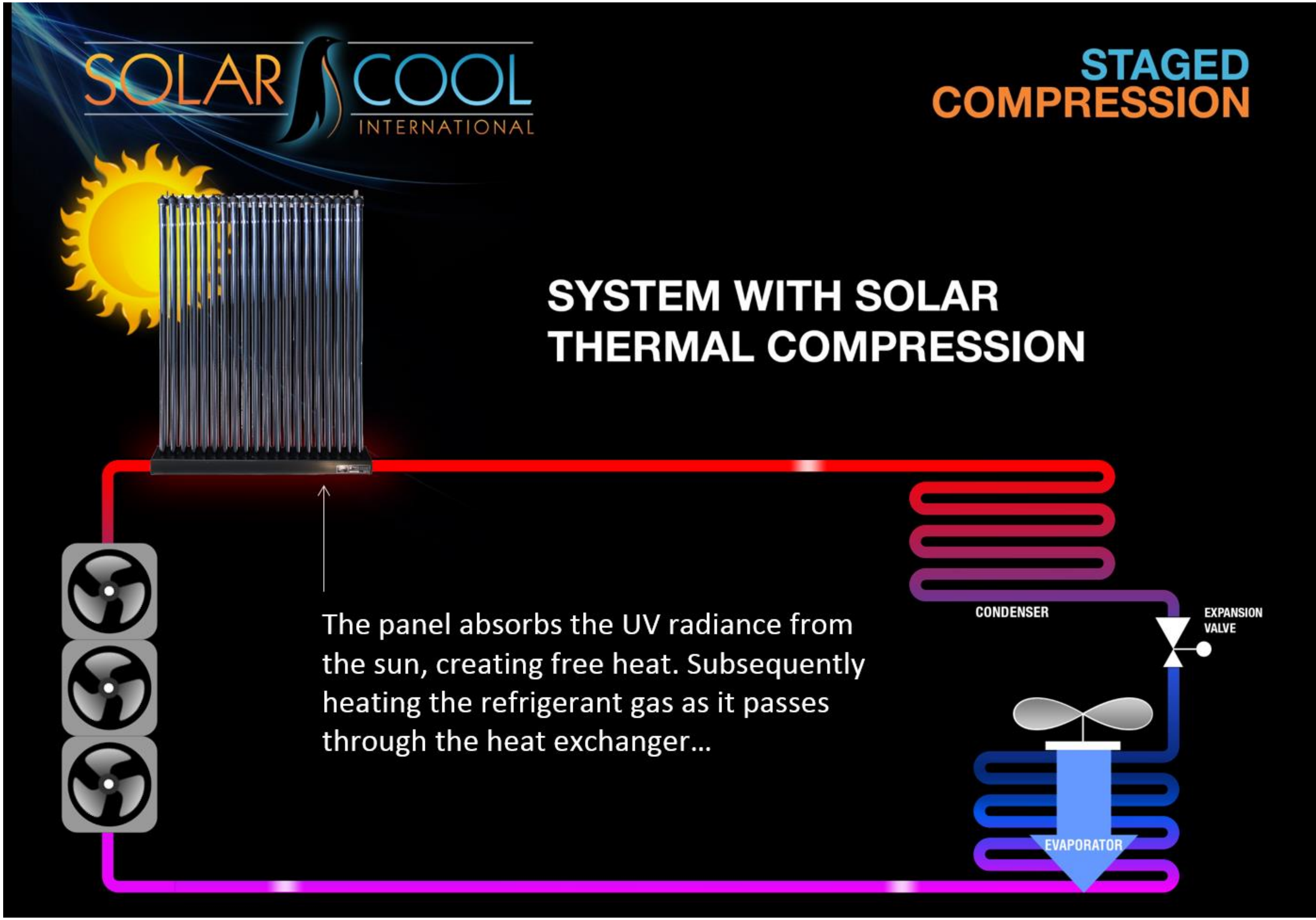
Basics

Gas law

$$V_c = V_m x \frac{p_m}{p_r} x \frac{T_r}{T_m}$$

Vc – Gas volume reference conditions (Nm^3)
Vm – Gas volume working conditions (m^3)
Pm – Working pressure (bar)
Pr – Reference pressure 1,033 bar
Tm – working temperature 273 K+t(ºC)
Tr – Reference temperature 273 K


SYSTEM IN NORMAL RUN PROCESS
CONDENSER
EXPANSION VALVE
Assuming full load is required,
all compressors will run.
EVAPORATOR

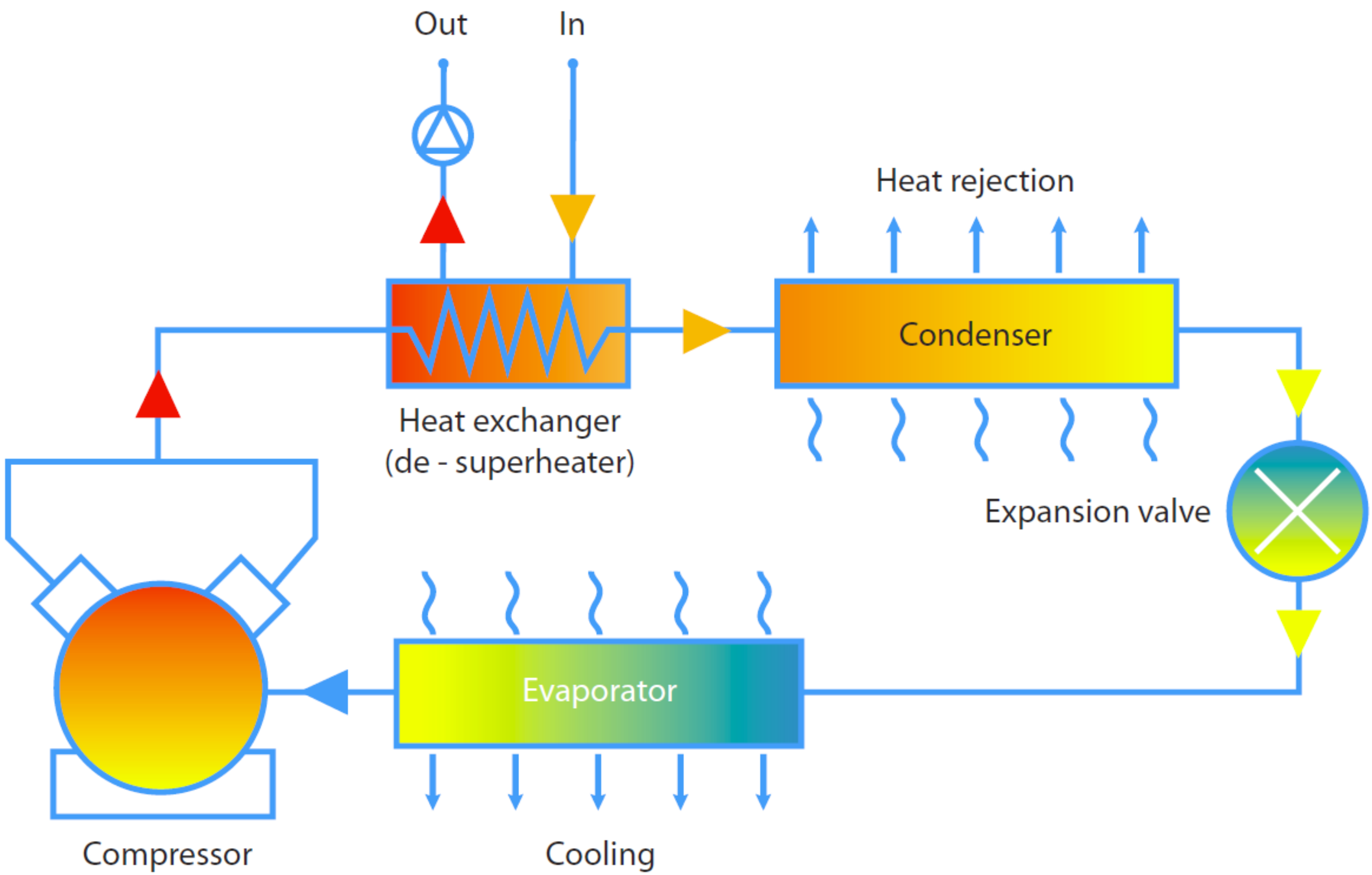

SOLAR COOL
INTERNATIONAL
STAGED
COMPRESSION
SYSTEM WITH SOLAR
THERMAL COMPRESSION
The panel absorbs the UV radiance from the sun, creating free heat. Subsequently heating the refrigerant gas as it passes through the heat exchanger…
CONDENSER
EXPANSION
VALVE
EVAPORATOR

Solar Cool

- Temperature = kinet. Energy on molecular level
- T rises → P rises but actually transforms into higher mass flow through the expansion valve
- higher ΔT leads to improved heat transfer in the condenser
- Higher kinetic energy on molecular level amplifies the heat transfer rate from the fluid to the tube surface

- With an adaptive controller overall the power and time of the compressor can be reduced

- http://solarcoolenergy.com/


Out
In
Heat rejection
Condenser
Heat exchanger
(de - superheater)
Expansion valve
Evaporator
Compressor
Cooling

SHIP Egypt

Session 09

Cooling

Wolfgang Glatzl | AEE INTEC
Josef Buchinger | ConPlusUltra