Class 13
Refrigeration and Heat Pumps

While heating is an ancient technology, the widespread application of cooling technologies occurred only after a firm understanding of thermodynamic cycles was established.

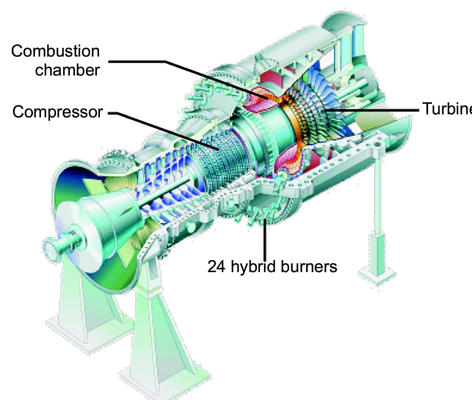
Recap: What is Eng. Thermodynamics?

- **Engineering Thermodynamics:** application of thermodynamics to solve technological problems that engineers face

- Analysis of transport and conversion of various forms of energy:
  work ↔ electricity ↔ heat ↔ cold

- **The objectives are:**
  1. Conversion of heat (fuel) into work / electricity (heat engine)
  2. Transportation of heat using work / electricity (cooling / heat pump)


Heat converted into work (electricity) [1]



Heat converted into work to generate power [1]


Work (electricity) converted into cold [2]

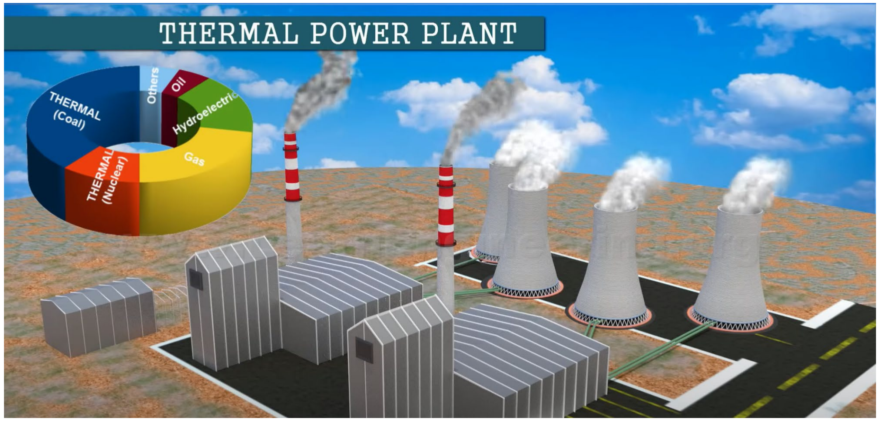
Recap: Eng. Thermodynamics – Heat engine

1. **Convert fuel / heat in work (heat engine)**
   - What do you want to know?
     - How much net work / electricity (power) is produced
     - How much heat (energy / fuel) do you have to put in
     - What is the efficiency

Recap: Examples – Heat engine

- Installations or machines that convert fuel or heat to work or electricity (power) using water / steam as working fluid

How does a thermal power plant work?
https://www.youtube.com/watch?v=IdPTuwKEfmA



Recap: Examples – Heat engine

- Installations or machines that convert fuel or heat to work or electricity (power) using hot and compressed air as working fluid

How do jet engines work?
https://www.youtube.com/watch?v=eA699AKxT7s

Recap: Eng. Thermodynamics - Cooling

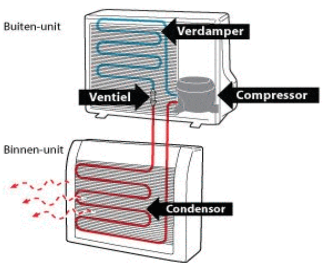
2. **Transportation of heat using work / electricity (cooling / heat pump)**
   - What do you want to know?
     - What is the cooling capacity
     - How much electricity is required
     - What is the coefficient of performance (COP)

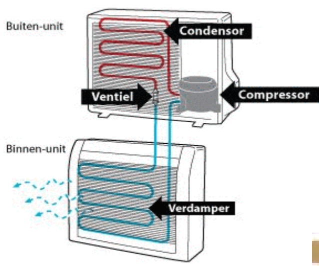
Recap: Examples – Cooling / Heat-pump

- Installations or machines that transport heat in the non-spontaneous direction (cold to hot) using work / electricity












Recapitulate Thermo 1 (class 1 – 11)

- Class 1 - 5 → Concepts, definitions, open – and closed systems energies, properties of water, 1 and 2 law of thermodynamics (energy conservation and entropy increase)

  → **all tools to make and analyze thermodynamic systems**

- Class 6 → A **thermodynamic cycle** is composed of a series of processes which return to the initial state
  - **Heat power cycles** produce power from heat
  - **Refrigeration / heat pump cycles** transport heat using power

- Class 7, 8 → Vapor cycles, cycles using a working medium that undergoes a phase change during the cycle to produce power
  - Steam engine, Rankine cycle (steam turbine cycle)
  - Combined heat and power (CHP) cycle (co-generation)

- Class 9 → Properties of gas (a missing tool)

- Class 10, 11 → Gas cycles, cycles using gas as working medium to produce power
  - Brayton cycle (gas turbine cycle, jet engine), combined cycles

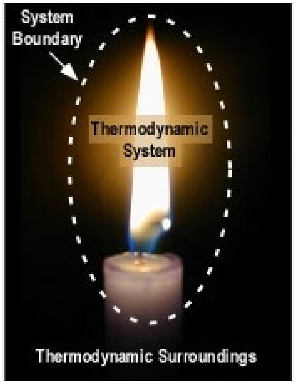
Content Engineering Thermodynamics 2

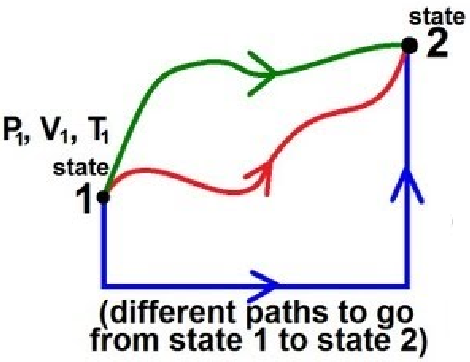
- Engineering Thermodynamics 2 is a follow – up of Thermo 1
- Class 13 → Refrigeration and heat pumps cycles, cycles that transport heat in the non-spontaneous direction using work (instead of using heat to produce power as in heat engines like gas- and steam turbines) This one
- Class 14 → Internal combustion engines like, Stirling, Otto and Diesel engines, another type of cycle using gas as working fluid
  These cycles don't use a gas turbine, as we studied before, to convert heat into work, but they use a piston cylinder device
- Class 15, 16, 17 → Theory behind thermodynamic diagrams, formulas, ….
  - This is the Mathematical background of Engineering Thermodynamics (in Dutch: Wiskunde achtergrond Technische Thermodynamica, abbreviated to WaTT, which is so nice that I kept the abbreviation to denote this part of the course)
  - There is a separate reader, that also contains the assignments for this WaTT part

Refresh: Roadmap Engineering Thermodynamics 1

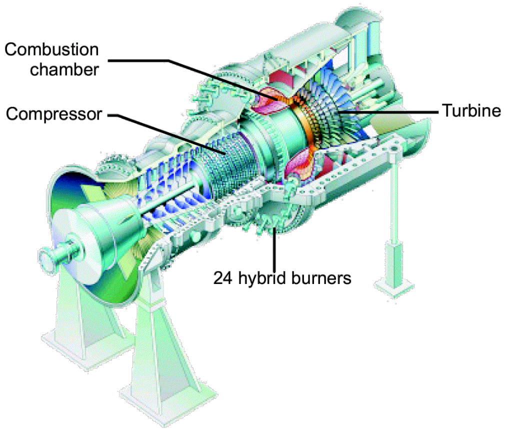
- Using thermodynamics for practical applications requires knowledge of:

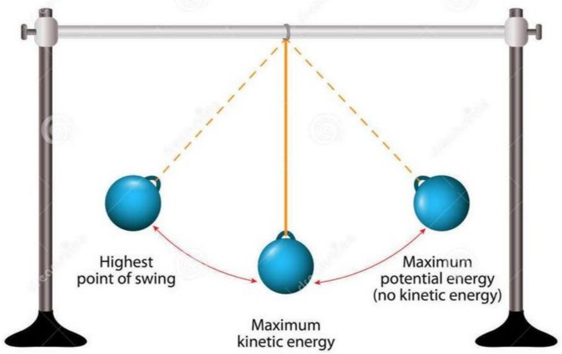
Concepts and definitions (Class 1) → Various forms of energy (Class 2)

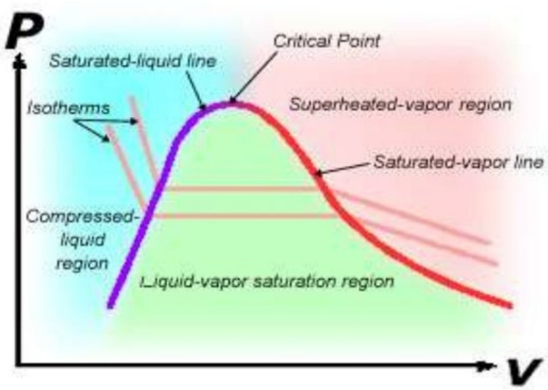




Power cycles (Class 6 – 11) ← Laws of Thermo (Class 4 and 5) ← Properties of Substances (Class 3, 9)

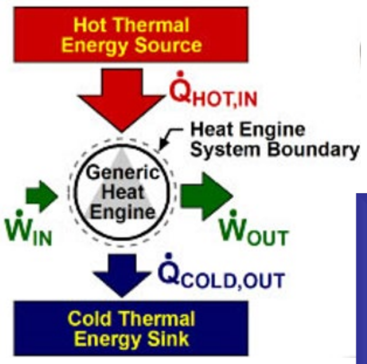




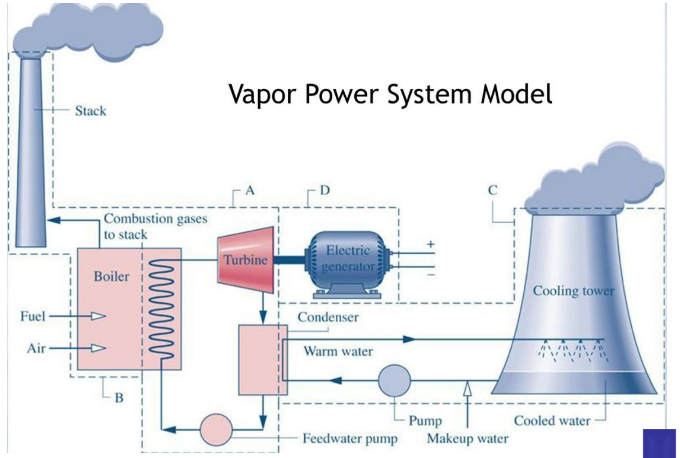


Refresh: Roadmap Engineering Thermodynamics 1

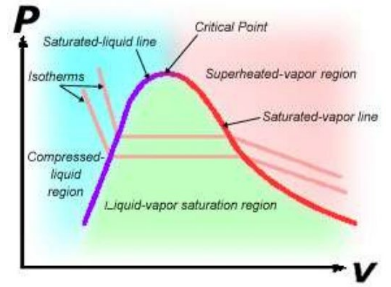
Thermodynamic cycles (Class 6)

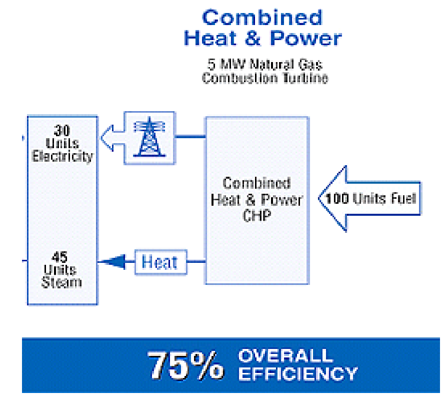


Vapor power cycles – Rankine cycle (Class 7, 8)

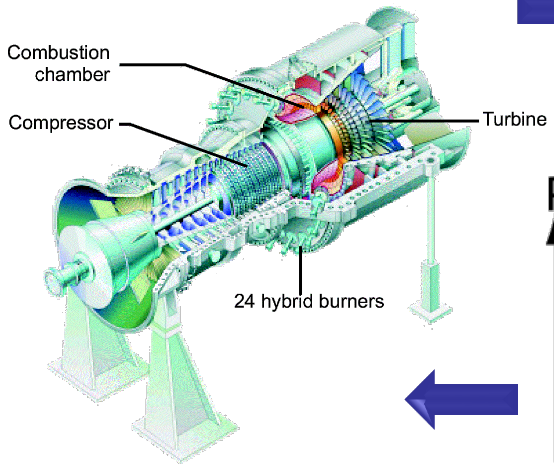


Properties of water (Class 3)

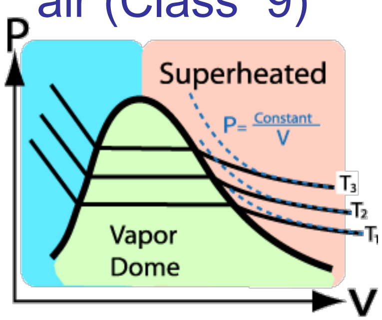




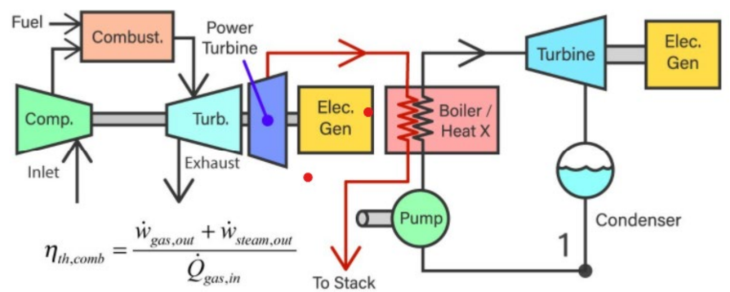
Gas power cycles – Brayton cycle (Class 10, 11)



Properties of air (Class 9)

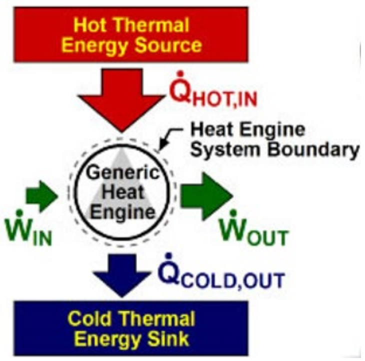


Combined cycles Combined heat & power (Class 8, 11)

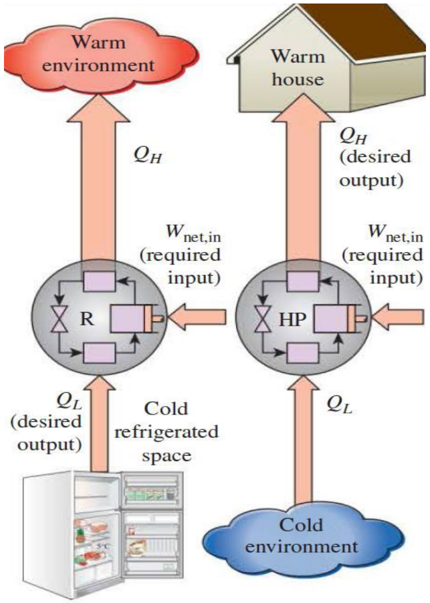


Roadmap Engineering Thermodynamics 2

Thermodynamic cycles (Class 6)

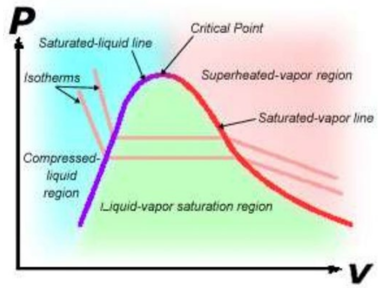


Vapor – compression cycles – refrigeration & heat pumps (Class 13)



(a) Refrigerator (b) Heat pump

Properties of R–134a (Class 3)



Math for Themo (Class 15, 16, 17)

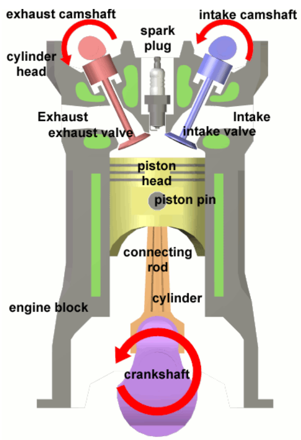
$$\left(\frac{\partial T}{\partial v}\right)_s = -\left(\frac{\partial P}{\partial s}\right)_v$$

$$\left(\frac{\partial T}{\partial P}\right)_s = \left(\frac{\partial v}{\partial s}\right)_P$$

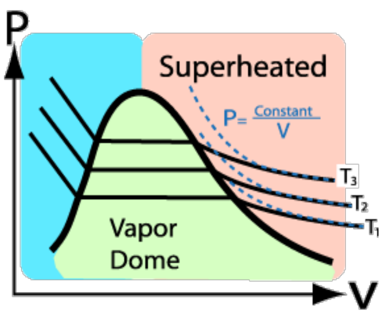
$$\left(\frac{\partial s}{\partial v}\right)_T = \left(\frac{\partial P}{\partial T}\right)_v$$

$$\left(\frac{\partial s}{\partial P}\right)_T = -\left(\frac{\partial v}{\partial T}\right)_P$$

Gas power cycles – Otto & Diesel cycle (Class 14)

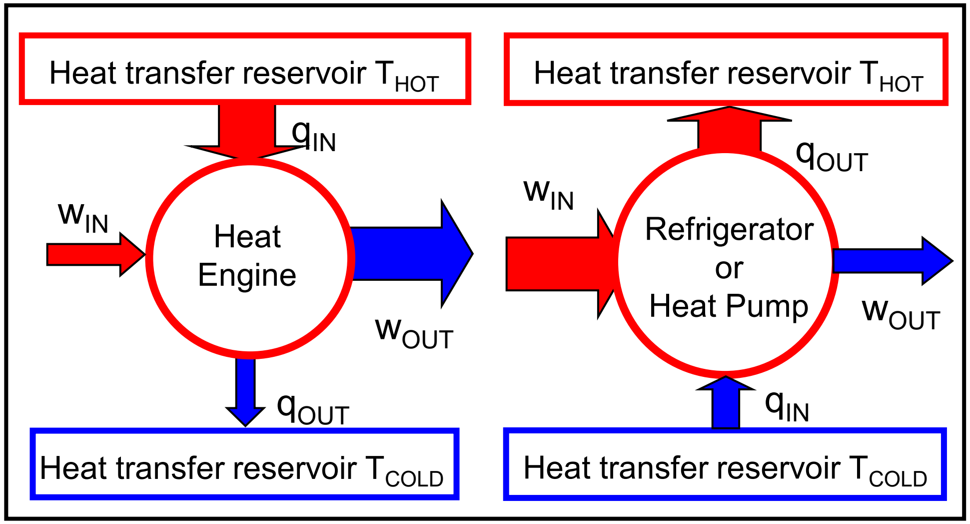


Properties of air (Class 9)



Recapitulate cooling class 6

- A **thermodynamic cycle** is composed of a series of processes which return to the initial state, it works between a hot and a cold thermal reservoir
  1. **Heat power cycles** produce power from heat
  2. **Refrigeration / heat pump cycles** transport heat using power
- First law for a cycle: $w_{net} = q_{net}$
- Second law for a cycle: $\sum_{i=1}^{n} \frac{q_{net,i}}{T_i} \leq 0$ or $\oint \frac{\delta q net, i}{T_i} \leq 0$
- Thermal efficiency for heat / power cycles: $\eta_{he} = \frac{w_{out} - w_{in}}{q_{in}} = 1 - \frac{q_{out}}{q_{in}}$
- COP for refrigeration and heat pump cycles
  - $COP_{ref} = \frac{q_{in,cold}}{w_{in}}$
  - $COP_{heat\ pump} = \frac{q_{out,hot}}{w_{in}}$
- Carnot (ideal) cycle has maximum COP

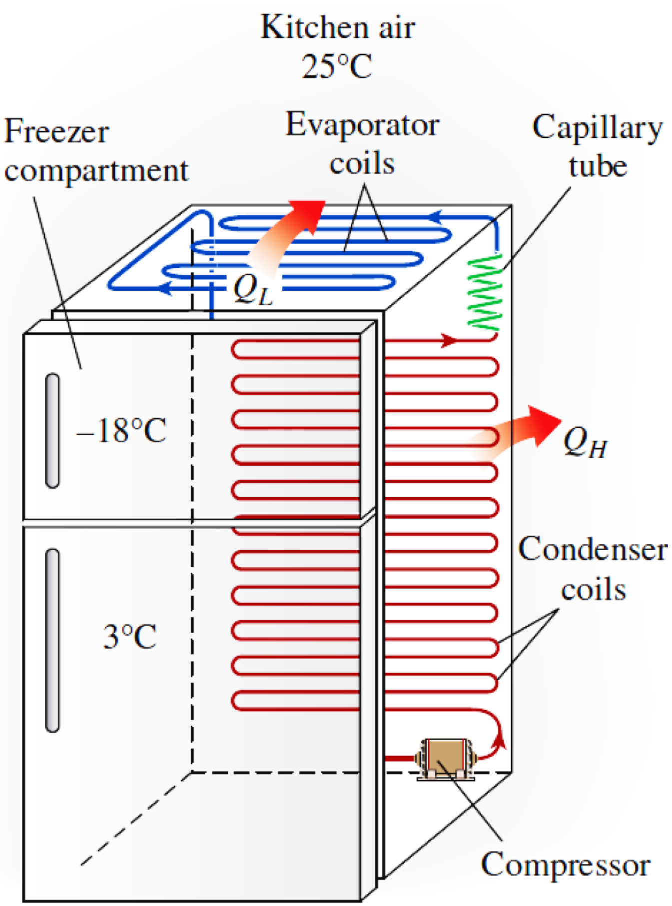


Energy flows in a heat engine (left) and in a refrigeration or heat pump cycle (right)

Content Class 13

- **Refrigeration & heat pump cycles – cycles transporting heat in the non-spontaneous direction using power**
  - Basics of cooling and heating / COP
  - Ideal and non-ideal vapor compression cycle
  - Comparison to Rankine cycle
  - Special cooling cycles
  - Heat pumps and air conditioners
  - Gas refrigeration cycle

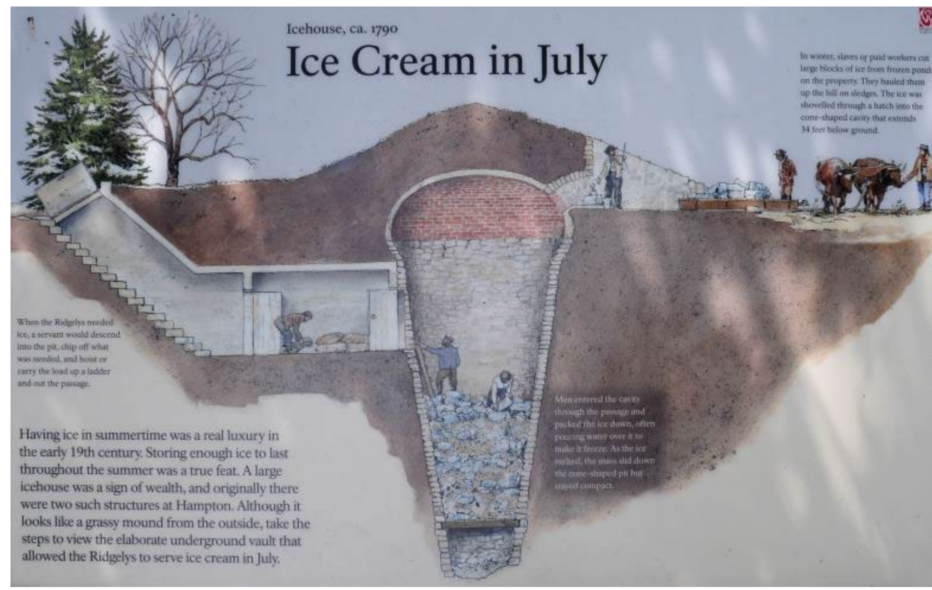
- **Learning goal:** recognize a thermodynamic system to produce cold/heat, explain the configuration, analyse the thermodynamic aspects from the view-point of the first law of thermodynamics, interpret and evaluate the results and suggest improvements



Household refrigerator

Early days: Icehouses for cooling

- Underground chambers, usually man made, but also buildings with various types of insulation, often straw or sawdust
- Store ice cut from lakes or rivers throughout the year (ice), prior to the invention of the refrigerator
- The ice remains frozen for many months, often until the following winter, and could be used as a source of ice during summer months.
- Main application was the storage of foods, but it could also be used simply to cool drinks or allow ice cream to be prepared



Left: On the estate of Twickel Castle in Delden is a double ice cellar, the only one in the Netherlands. The left-hand ice cellar was built in 1906, the right-hand is probably of an older date. http://www.cultuurwijzer.nl/oud/i000227.html

Nowadays: Refrigerators for cooling

- Nowadays ice cellars are no longer used
- The refrigerator is not that old yet!
- It was only after that it was well understood how thermodynamics worked that the technology for cooling could be further developed and the refrigerator was born
- First cooling systems were developed around 1900
- In the Netherlands in the first half of the 20th century
- Nowadays everyone has a refrigerator but at the time there was still a lot of advertising to convince people that it was a handy device
- See the American advertising video, Buy an electrical refrigerator, Electric League of Pittsburgh, 1926

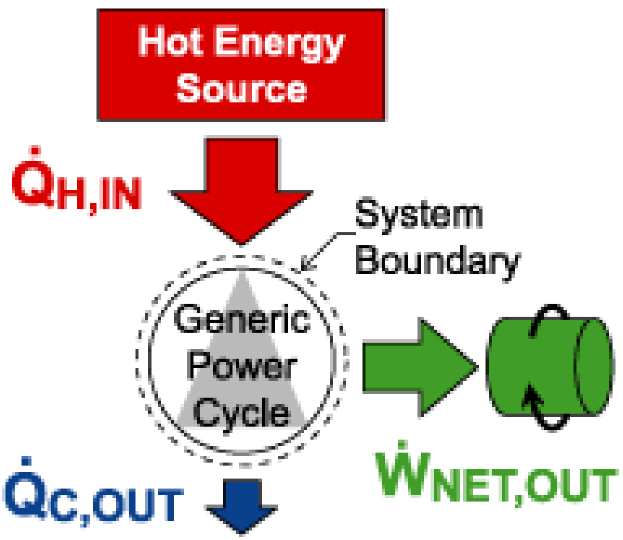
1926 silent film commercial for electric refrigerators
http://commons.wikimedia.org/wiki/File:Theater_commercial,_electric_refrigerator,_1926.ogg

Refrigeration Basics

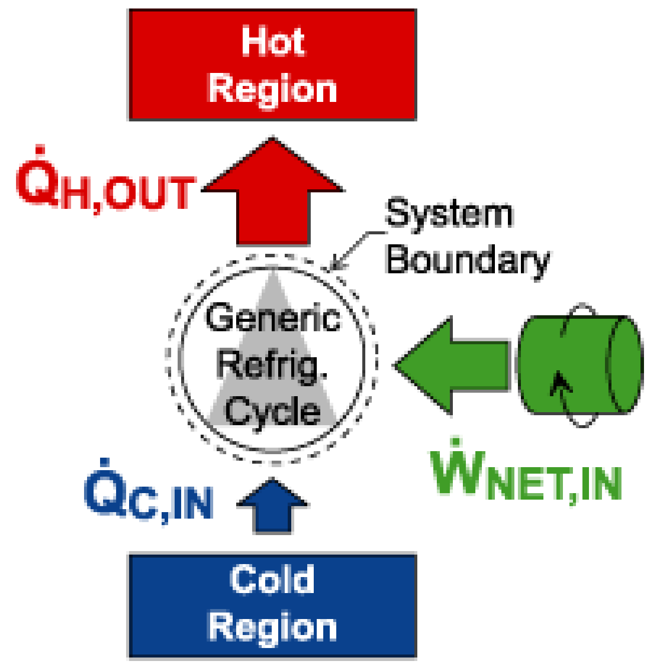
- For refrigeration or heat pump cycles the first law of thermodynamics, the basic energy balance is still full filled
- The first law for **all** cycles (power as well as refrigeration cycles) is

$$w_{IN} - w_{OUT} = q_{IN} - q_{OUT} \quad \rightarrow \quad w_{NET} = q_{NET}$$

- For refrigeration cycles, typically $w_{OUT} = 0$ $\quad \rightarrow \quad w_{IN} = q_{OUT} - q_{IN}$



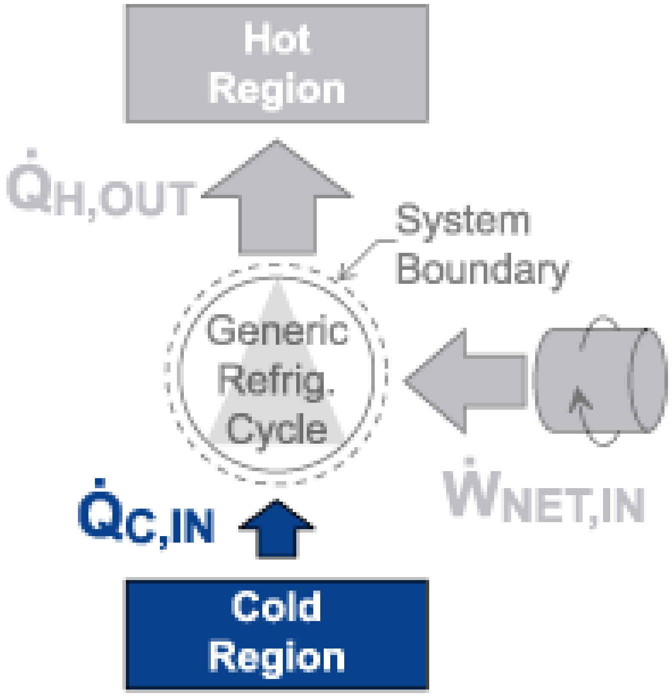
Generic Power Cycle



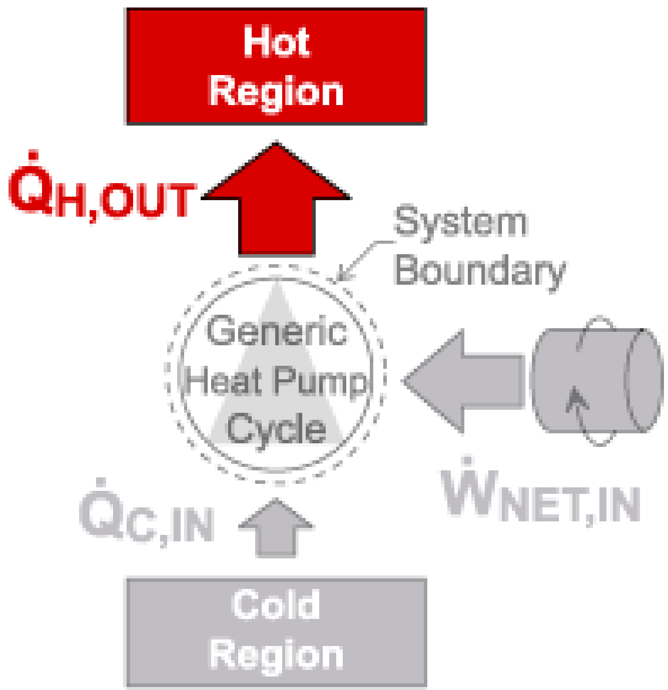
Generic Refrigeration Cycle

Refrigeration versus Heat Pump

- Refrigeration & heat pump cycles → It is the same cycle, but they have a different goal
  - Refrigeration, the goal is cooling → $q_{in,cold}$ (= $q_{evaporator}$)
  - Heat pump, the goal is heating → $q_{out,hot}$ (= $q_{condensor}$)



Generic Refrigeration Cycle



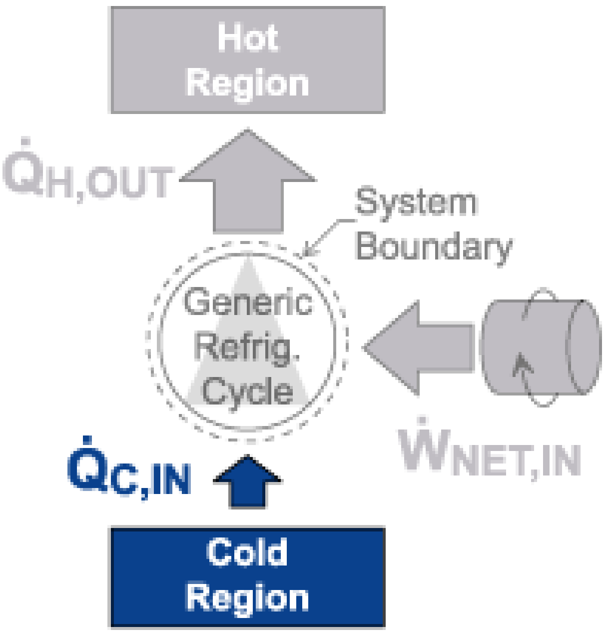
Generic Heat Pump Cycle

COP and desired output for Refrigeration

- For **refrigeration** cycles the goal is to cool a region and **the desired energy** is the energy subtracted from the cold region, $q_{in,cold}$ (= $q_{evapoator}$)
- The energy that is used to achieve his goal is the electricity needed to drive the compressor, the work input, w_{in}
- To quantify the performance of refrigeration the COP (Coefficient of Performance) is used and not an efficiency
- For **refrigeration** cycles mostly $w_{OUT} = 0$
- $$COP_{ref} = \frac{Energy\ desired}{Energy\ used} = \frac{q_{in,cold}}{w_{in}} = \frac{q_{evaporator}}{w_{in}}$$
- The maximum performance of a refrigerator is achieved for Carnot refrigeration

$$COP_{ref,Carnot} = \frac{1}{\frac{T_{hot}}{T_{cold}} - 1}$$

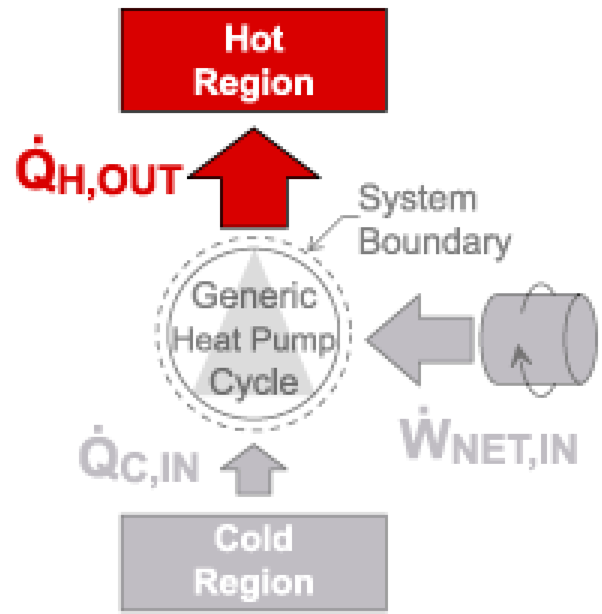
(see class 6)



Generic Refrigeration Cycle

COP and desired output for Heat Pumps

- For **heat pump** cycles the goal is to heat a region and **the desired energy** is the energy rejected to the hot region, $q_{out,hot}$ (= $q_{condensor}$)
- The energy that is used to achieve his goal is the electricity needed to drive the compressor, the work input, w_{in}
- To quantify the performance of a heat pump the COP (Coefficient of Performance) is used and not the efficiency
- For **heat pump** cycles mostly $w_{OUT} = 0$
- $COP_{heat\ pump} = \frac{Energy\ desired}{Energy\ used} = \frac{q_{out,hot}}{w_{in}} = \frac{q_{condenser}}{w_{in}}$



Generic Heat Pump Cycle

- The maximum performance of a heat pump is achieved for a Carnot heat pump

$$COP_{heat\ pump,Carnot} = \frac{1}{1 - \frac{T_{cold}}{T_{hot}}}$$

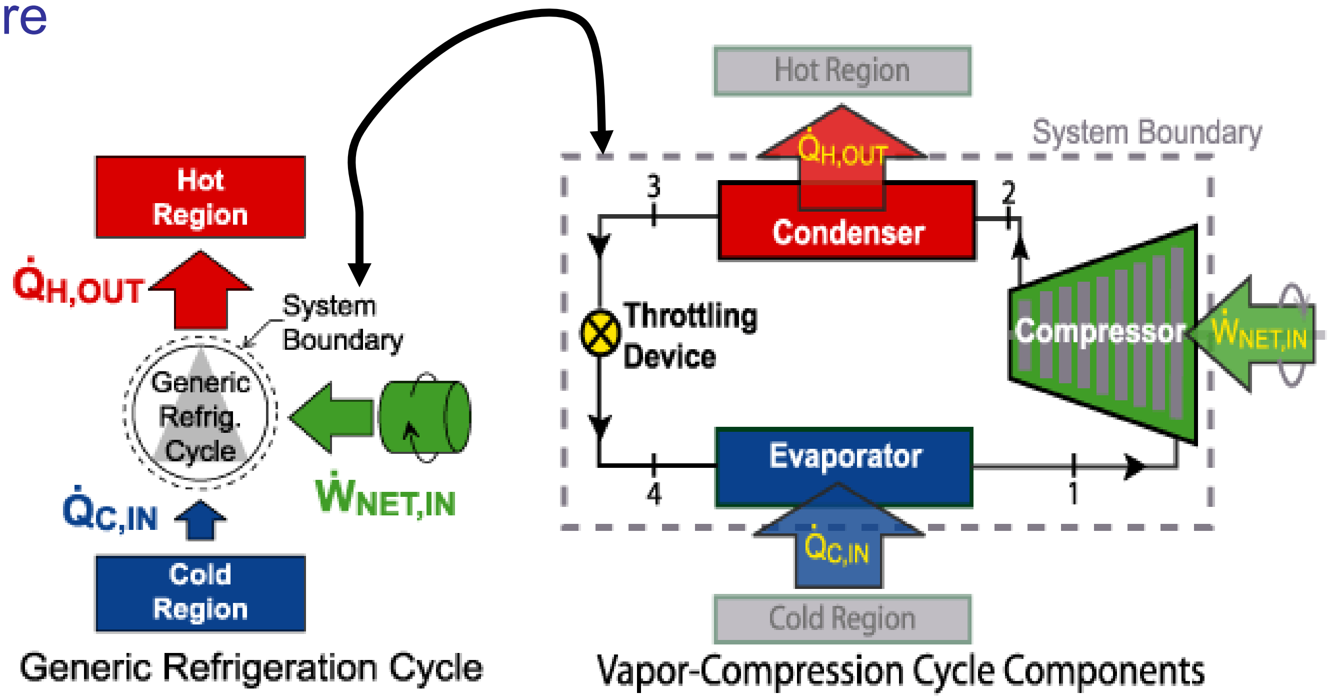
(see class 6)

- In general, $COP_{heat\ pump} - COP_{ref} = 1$

Components Basic Vapor-Compression Cycle

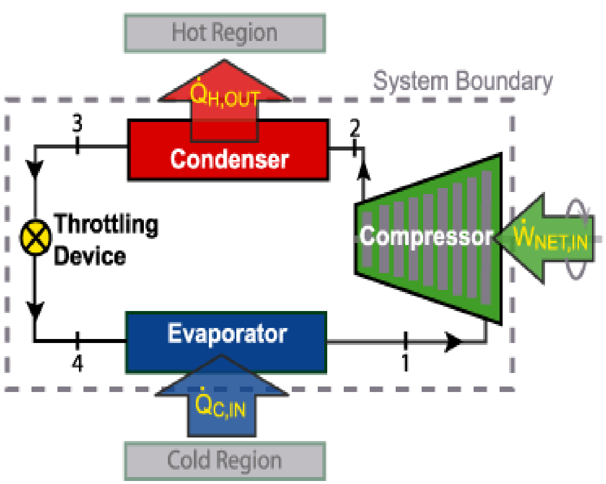
- The basic cooling cycle, called a vapor-compression, cycle consists of four components that are like the components of a Rankine cycle (vapor power)
- However, the fluid goes in **the reversed** direction and therefore, the cycle is also called a reversed Rankine cycle

- The components are
  - Throttle valve
  - Compressor
  - Condenser
  - Evaporator

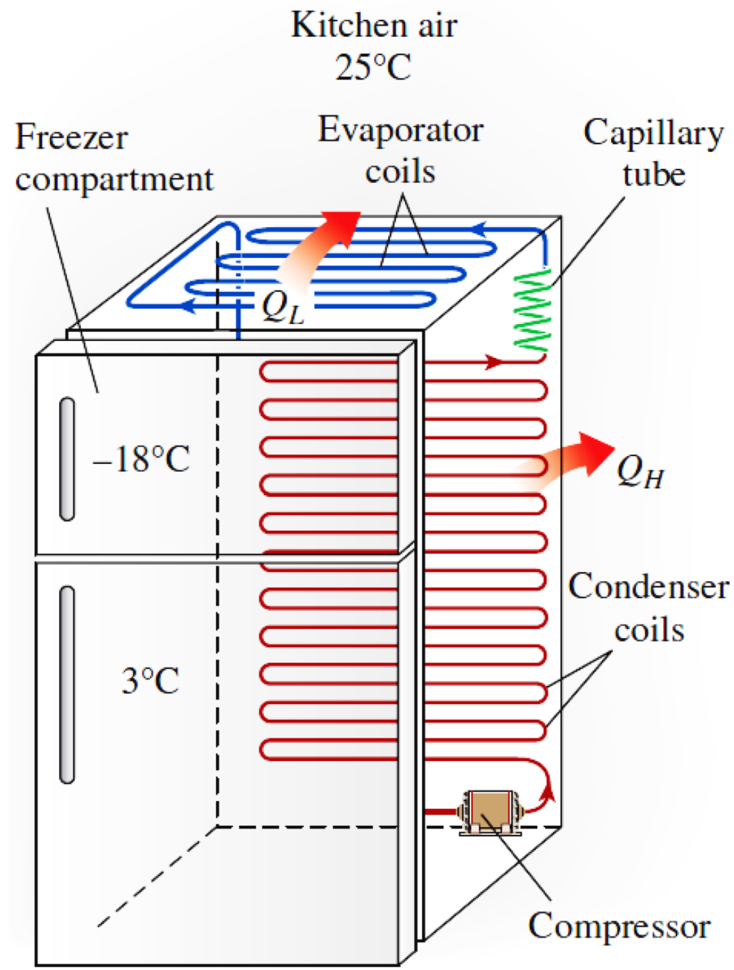


Components Basic Vapor Compression Cycle

- Compare the cooling cycle with an ordinary household refrigerator (with freezer compartment)
- Components:
  - Throttle valve (= capillary tube)
  - Compressor
  - Condenser (coils)
  - Evaporator (coils)



Vapor-Compression Cycle Components



Principle of Ideal Vapor Compression Cycle

- **1 → 2 Isentropic compression (w_{in})**

Saturated vapor at low pressure is compressed to high P and T (superheated vapor), the compressor is assumed to be adiabatic and ideal (reversible, isentropic)

- **2 → 3 Isobaric heat rejection ($q_{hot,out}$)**

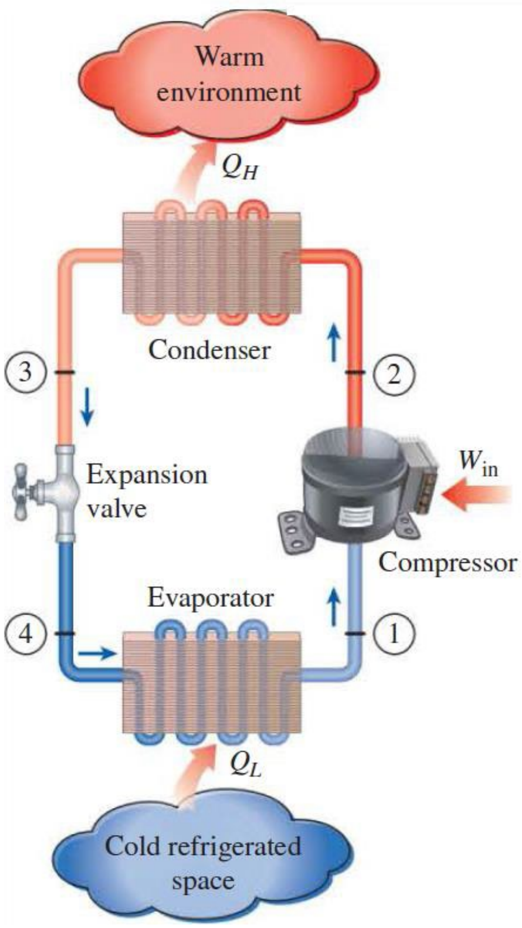
In the condenser, at high constant pressure heat rejection occurs from the high temperature working fluid to the high temperature reservoir, the superheated vapor changes phase to saturated liquid

- **3 → 4 Isenthalpic throttling (w_{out}=0, q=0)**

Reduction of the pressure by throttling, the saturated liquid is reduced in temperature and the outcome is a saturated mixture of low quality

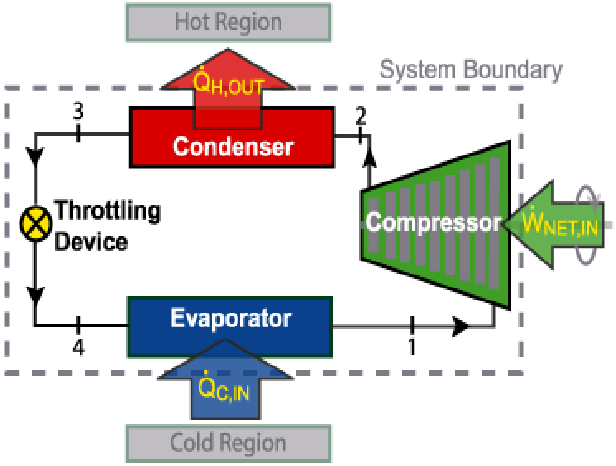
- **4 → 1 Isobaric heat addition ($q_{cold, in}$)**

In the evaporator heat is added at constant low pressure from the low temperature reservoir to the lower temperature working fluid, the liquid phase evaporates, and a saturated vapor remains



Vapor Compression Cycle Analysis

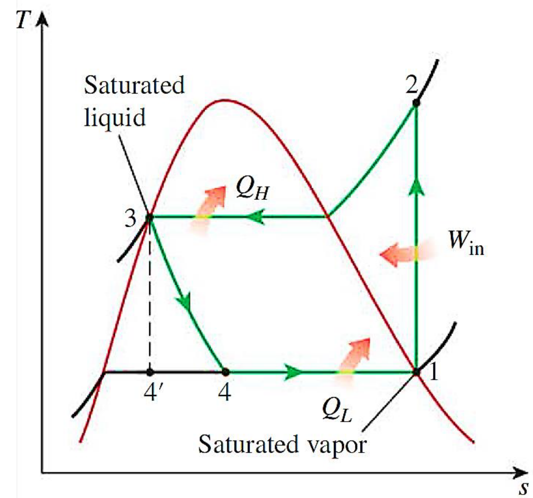
- Like the Rankine and Brayto cycle the vapor compression cycle consists of a series of processes occurring in open devices
- Analogue to the Rankine and Brayton cycle the devices should be analyzed separately



- Process 1 → 2, **isentropic pressure increase** by **ideal compressor:**

  $w_{compressor,in} = h_{out} - h_{in} = h_2 - h_1$

- Process 2 → 3, **isobaric heat rejection** in the **condenser:** $q_{hot,out} = h_2 - h_3$



- Process 3 → 4, **isenthalpic pressure reduction** by **throttling valve:** $h_3 = h_4$

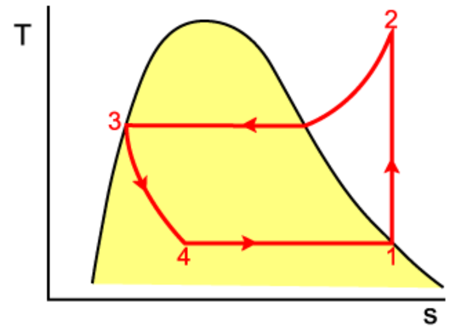
- Process 4 → 1, **isobaric heat addition** in the **evaporator:** $q_{cold,in} = h_1 - h_4$

Comparison Vapor Compr. to Rankine Cycle

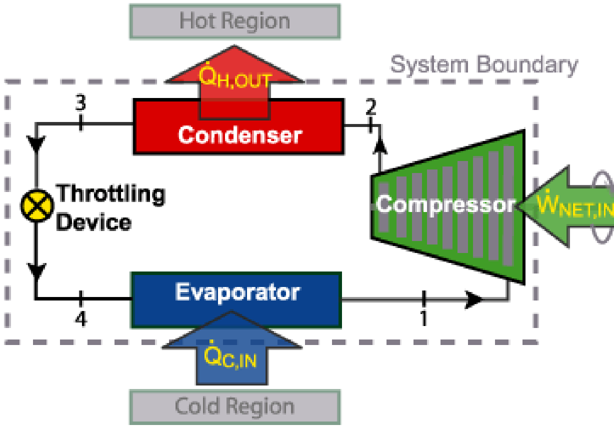
- A vapor-compression cycle acts like a reversed Rankine cycle, there are some differences:

- The pump is replaced by a compressor (why?)
- The turbine is replaced by a throttling valve
- Ideal Rankine 1→ 2: s = constant
- Ideal vapor compression 3 → 4: throttle valve h = constant BUT s increases
- Different working fluid
- **The working fluid goes in the reversed direction!**

Reversed Rankine cycle (vapor-compression cycle)

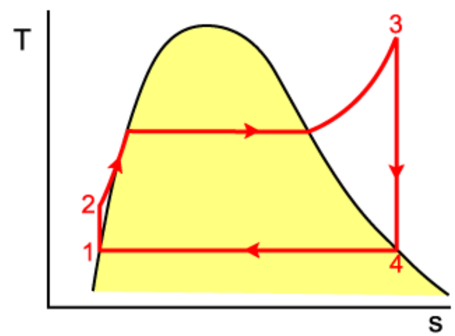


T-s Diagram for Ideal Vapor-Compression Cycle

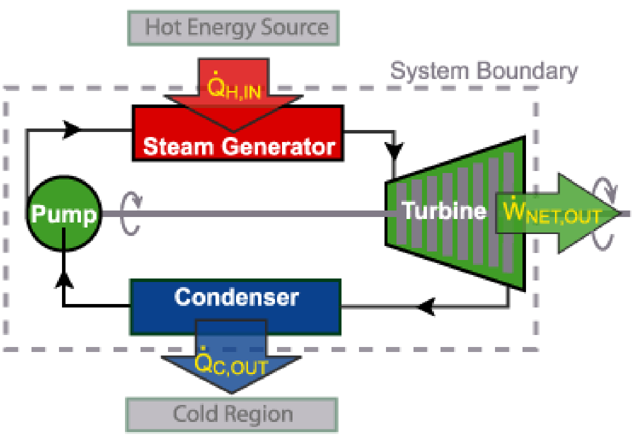


Vapor-Compression Cycle Components

Rankine cycle



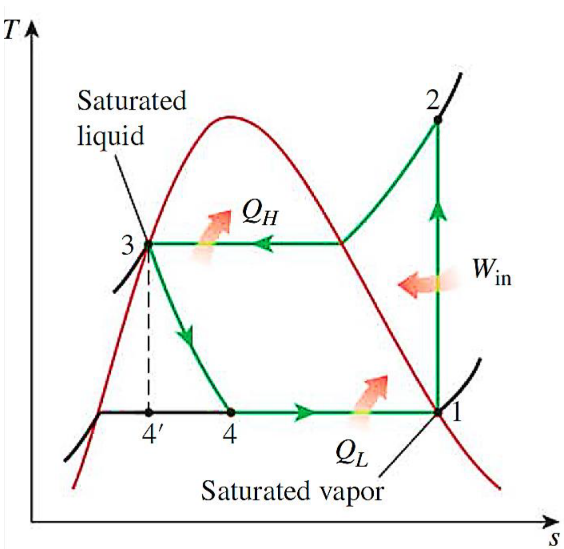
T-s Diagram for Ideal Rankine Cycle

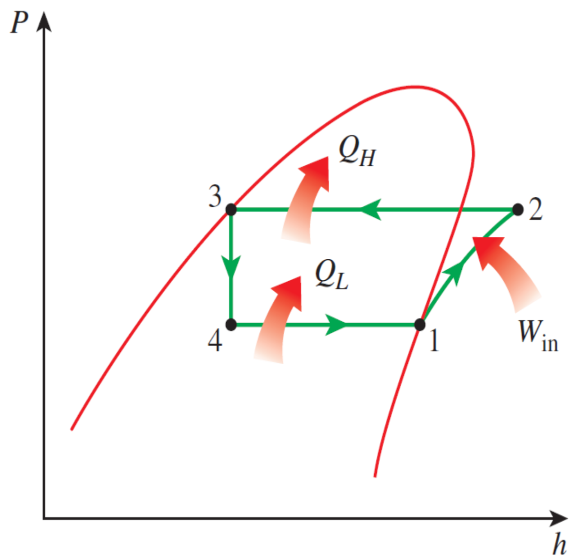


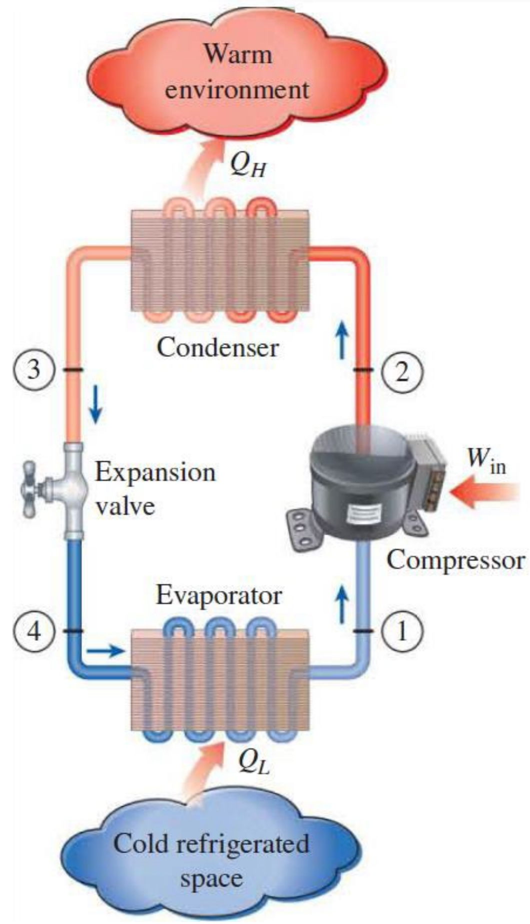
Rankine Cycle Components

Ideal Vapor Compression Cycle Diagrams

- There are different ways to represent the vapor-compression cycle in a diagram
- For refrigeration cycle cycles often a Ph-diagram is used to illustrate the process (this clearly shows the constant enthalpy process in the throttle valve / expansion valve)







Processes Ideal Vapor Compression Cycle

Process	Component	q	w	Constant Property
$1 \rightarrow 2$	Compressor	0	w_{IN}	Entropy, s
$2 \rightarrow 3$	Condenser	q_{OUT}	0	Pressure, P
$3 \rightarrow 4$	Throttling Device	0	0	Enthalpy, h
$4 \rightarrow 1$	Evaporator	q_{IN}	0	Pressure, P

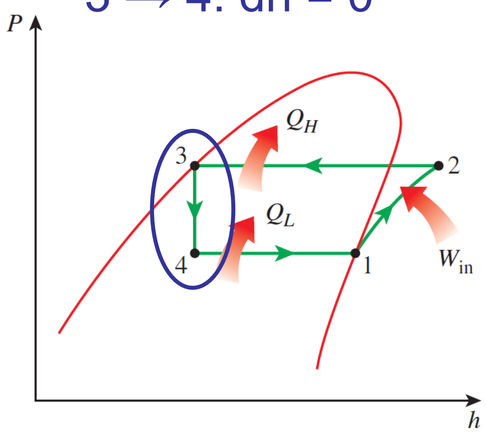
- Process $3 \rightarrow 4$, throttling:

  $dh = 0$ and $ds > 0$ because:

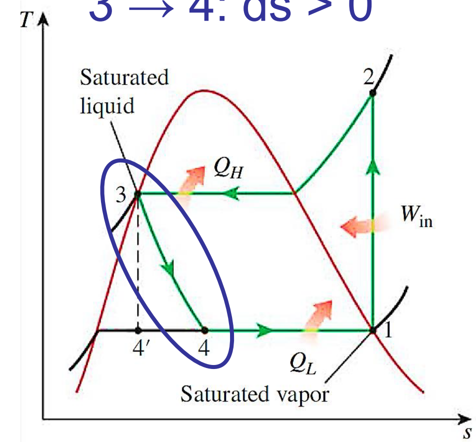
  $dh = Tds + vdP$

  $dP < 0 \rightarrow ds > 0$

$3 \rightarrow 4$: $dh = 0$



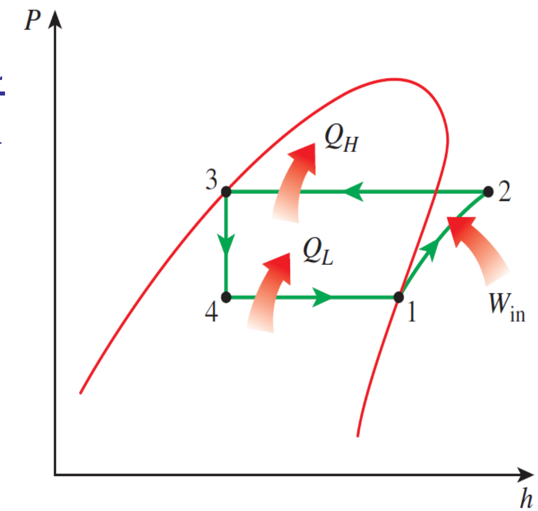
$3 \rightarrow 4$: $ds > 0$

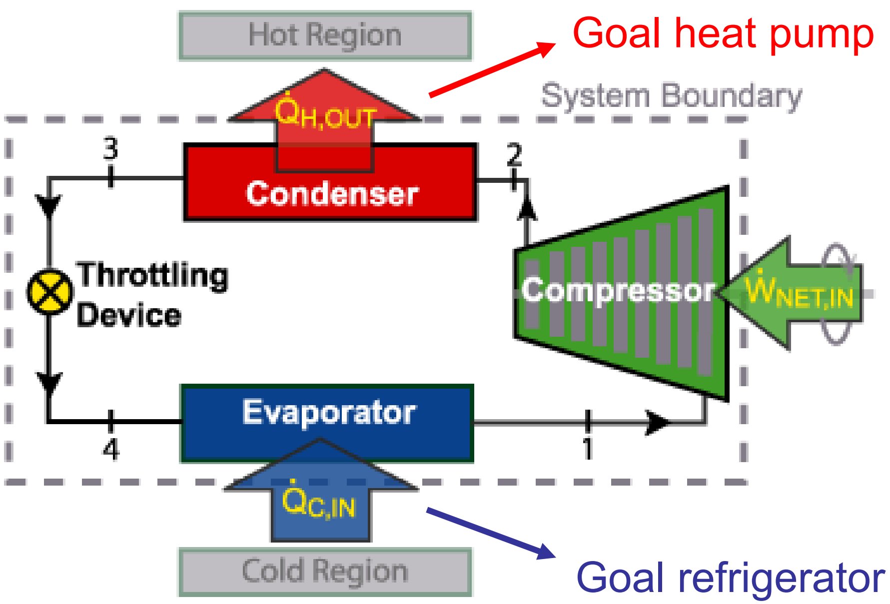


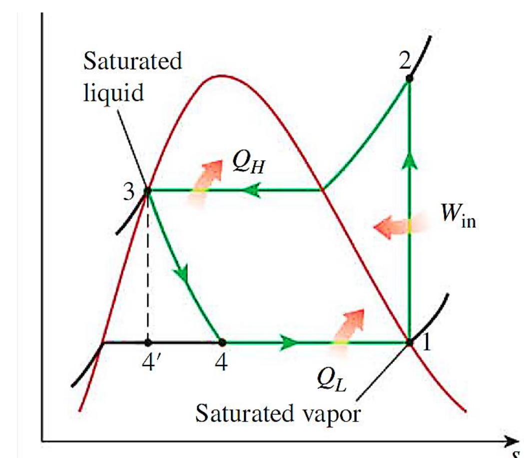
- Note: an ideal vapor compression cycle is not reversible, the process in the throttle valve cannot be reversed

COP Refrigerator or Heat Pump

- The Coefficient of Performance (COP) denotes how good the cycle is
- As the goal for refrigeration is different from the goal for a heat pump the COP is defined different
  - Refrigerator: $COP_{refrigerator} = \frac{q_{in,cold}}{w_{in}} = \frac{h_1 - h_4}{h_2 - h_1}$
  - Heat pump: $COP_{heat\ pump} = \frac{q_{out,hot}}{w_{in}} = \frac{h_2 - h_3}{h_2 - h_1}$







Refrigerator or Heat Pump Capacity

- The cooling or heating capacity, also called the load, denotes how much energy per second can be subtracted from the cold region to cool or can be rejected to the hot region to heat (like power in a heat engine)
  - Refrigeration/Air-Conditioning: $Load_{REF} = \dot{m}q_{in,evap} = \dot{Q}_{in,evap}$
  - Heat Pump: $Load_{HP} = \dot{m}q_{out,cond} = \dot{Q}_{out,cond}$

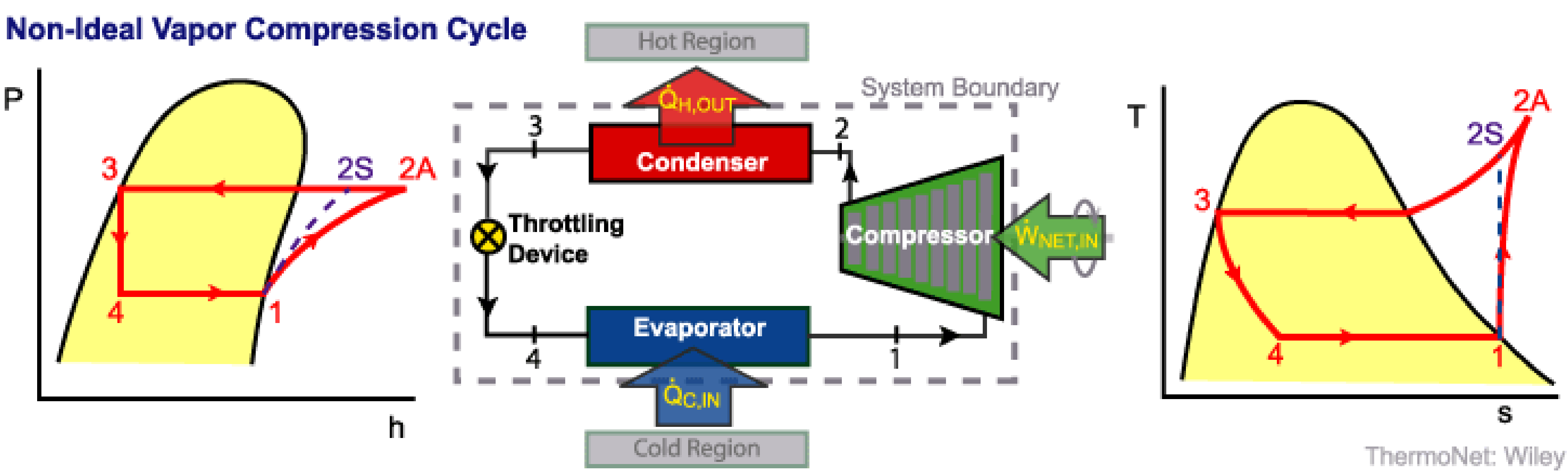
- The compressor power that is needed follows from required load:
  - Refrigeration/Air-Conditioning: $\dot{W}_{comp,in} = \frac{\dot{Q}_{in,evap}}{COP_{REF}}$
  - Heat Pump: $\dot{W}_{comp,in} = \frac{\dot{Q}_{out,cond}}{COP_{HP}}$

- By adjusting the mass flow of the refrigerant, the load of a system with certain parameters can be adjusted

Non-Ideal Vapor Compression Cycle

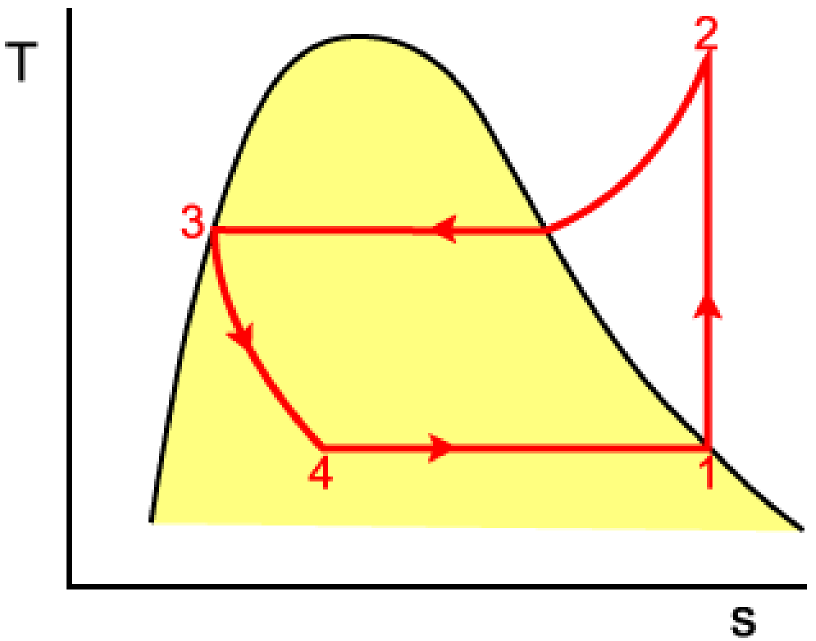
- Real vapor compression cycles have effects that deviate from the ideal cycle, the most important one of them is that the compressor between point 1 and 2 is not ideal, it is a non-isentropic compressor, and the isentropic efficiency of the compressor should be considered
- Calculate h_2 using the isentropic efficiency and $s_{2s} = s_1$

$$\eta_{COMP,S} = \frac{w_{IN,S}}{w_{IN,A}} = \frac{h_{2S} - h_1}{h_2 - h_1}$$



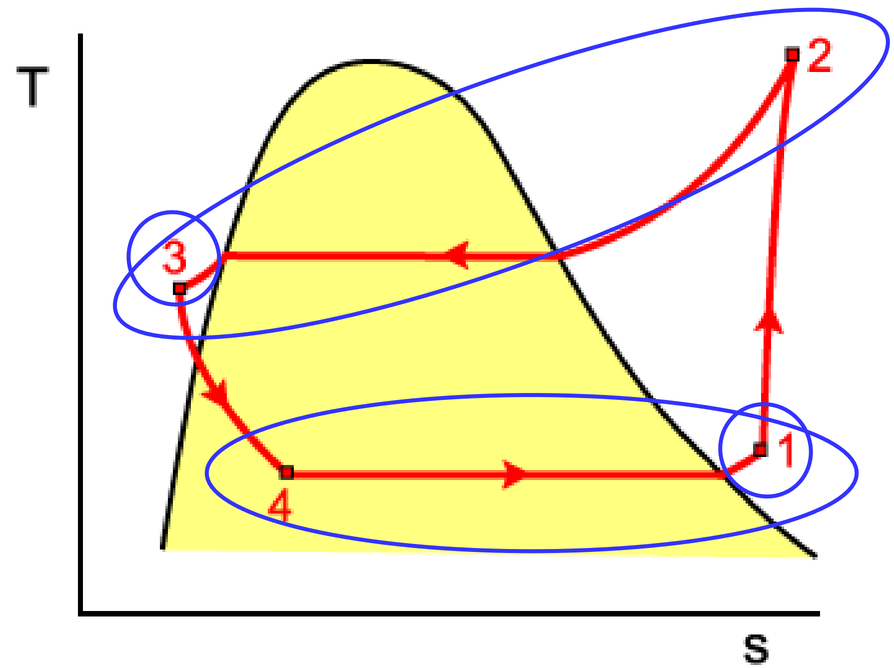
Non-Ideal Vapor Compression Cycle

- Other effects in real vapor compression cycles are
  - Sub - cooled liquid leaving condenser (at 3)
  - Superheated vapor leaving evaporator (at 1)
  - Pressure drops in condenser (2-3) and evaporator (4-1)



Ideal Vapor Compression Cycle

ThermoNet: Wiley

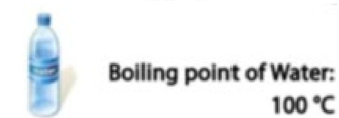


Non-Ideal Vapor Compression Cycle

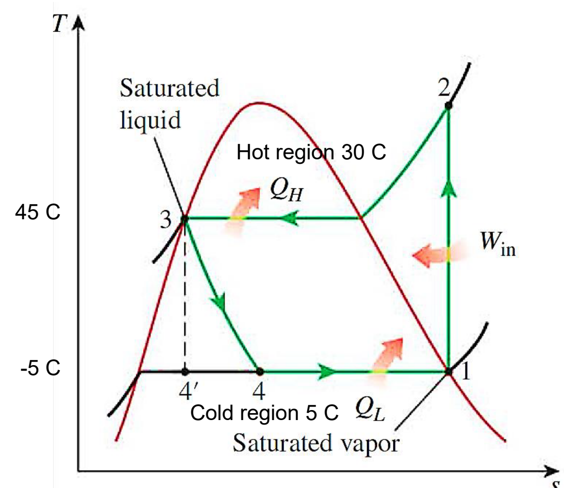
ThermoNet: Wiley

Working Fluid Vapor Compression Cycle

- For the cooling cycle a different working fluid, with a different boiling point is required → these are refrigerants with pressure dependent saturation temperatures in the desired working range (the fluid undergoes a phase change like water!)
  - Fluorocarbons (e.g., R-134a)
  - Hydrocarbons
  - Ammonia



- To select the right refrigerant, it is important to consider
  - The temperature of the cold region, inside the refrigerator
  - The temperature of the hot region, the environment



The boiling point at the high pressure should be above the T of the hot region, the environment, to be able to transfer the heat

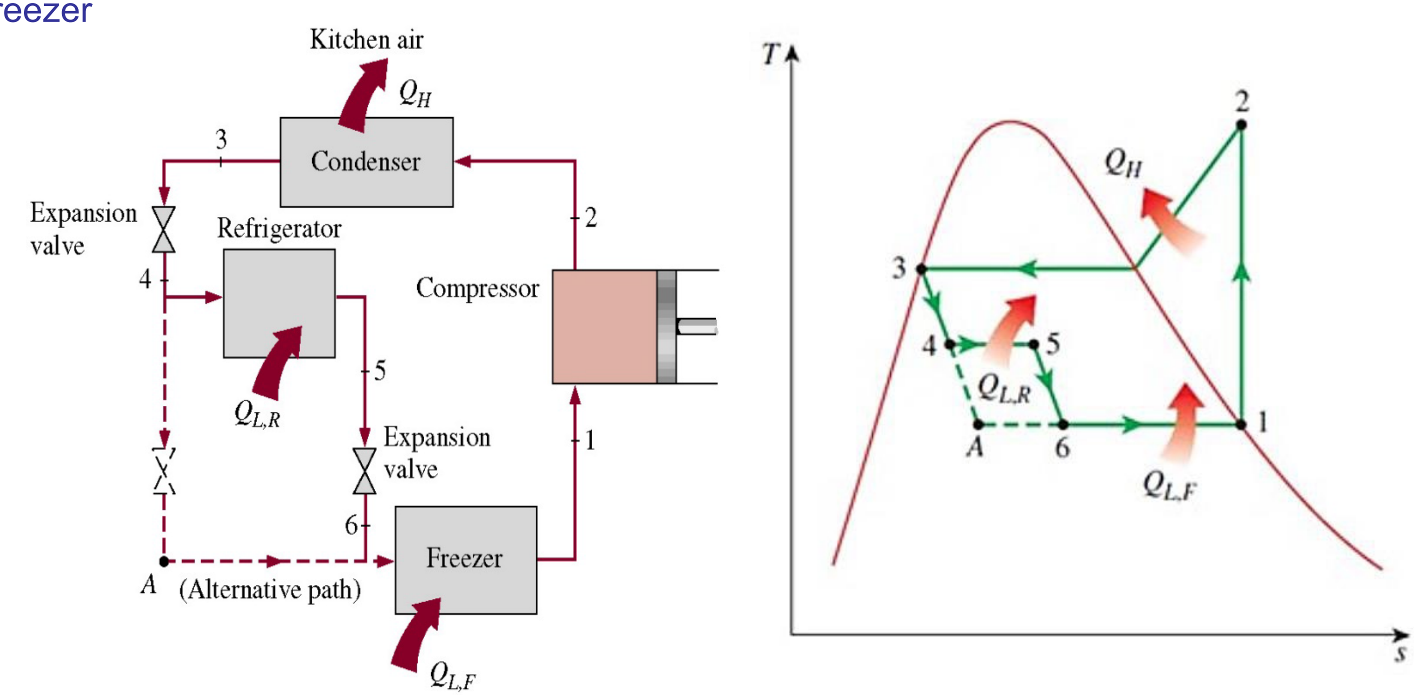
The boiling point at the low pressure should be a little below the desired T of the cold region to be able to transfer the heat

Working Fluid Vapor Compression Cycle

- Several refrigerants may be used in refrigeration systems such as chlorofluorocarbons (CFCs), ammonia, hydrocarbons (propane, ethane, ethylene, etc.), carbon dioxide, air (in the air-conditioning of aircraft), and even water (in applications above the freezing point).
- The industrial and heavy-commercial sectors use ammonia (it is toxic).
- R-11, R-12, R-22, R-134a, and R-502 account for over 90 percent of the market.
- R-11 is used in large-capacity water chillers serving A-C systems in buildings.
- R-134a (replaced R-12, which damages ozone layer) is used in domestic refrigerators and freezers, as well as automotive air conditioners.
- R-22 is used in window air conditioners, heat pumps, air conditioners of commercial buildings, and large industrial refrigeration systems, and offers strong competition to ammonia.
- R-502 (a blend of R-115 and R-22) is the dominant refrigerant used in commercial refrigeration systems such as those in supermarkets.
- CFCs allow more ultraviolet radiation into the earth's atmosphere by destroying the protective ozone layer and thus contributing to the greenhouse effect that causes global warming. Fully halogenated CFCs (such as R-11, R-12, and R-115) do the most damage to the ozone layer. Refrigerants that are friendly to the ozone layer have been developed.
- Two important parameters that need to be considered in the selection of a refrigerant are the temperatures of the two media (the refrigerated space and the environment) with which the refrigerant exchanges heat.

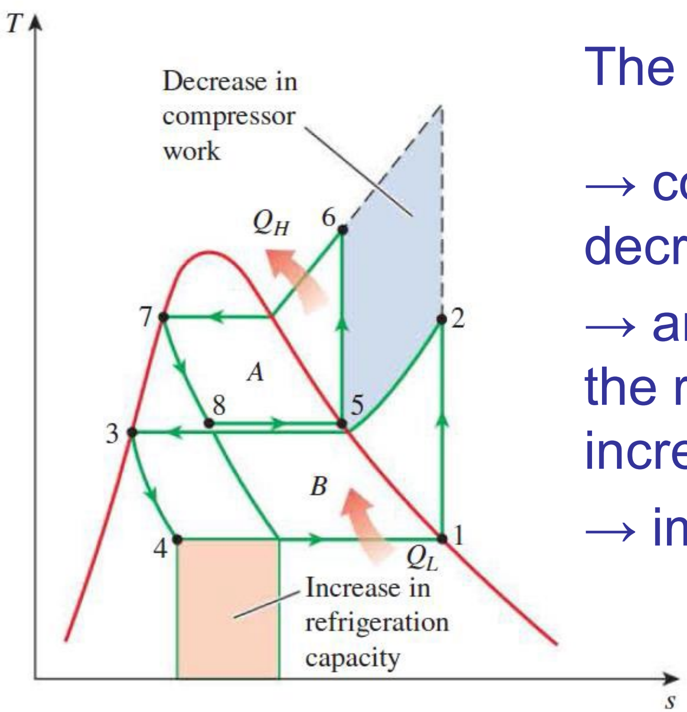
Freezer Compartment in Refrigeration Cycle

- In a refrigerator with a separate freezer compartment two regions with different temperatures are present
- This is achieved by adding an additional throttling valve to get three different pressure levels with he desired boiling temperatures
  1. Condenser T_{hot}
  2. Refrigerator $T_{refrigerator}$
  3. Freezer $T_{freezer}$



Cascade Refrigeration Systems

- Some industrial applications require moderately low temperatures, and the temperature range may be too large for a single refrigeration cycle
- A way to deal with this is to perform the refrigeration process in stages, two or more refrigerators operate in series at different pressures
- $\dot{Q}_{\text{L-upper}} = \dot{Q}_{\text{H-lower}}$

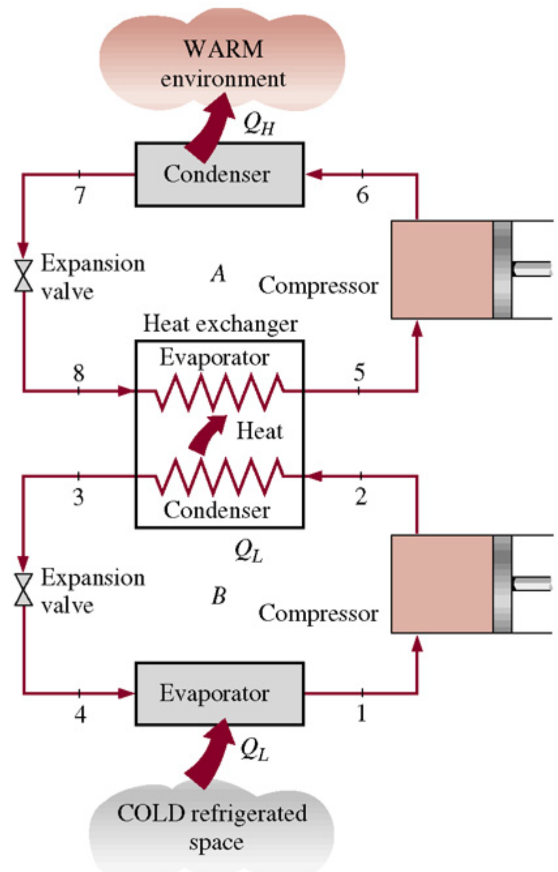


The Ts – diagram shows

→ compressor work decreases

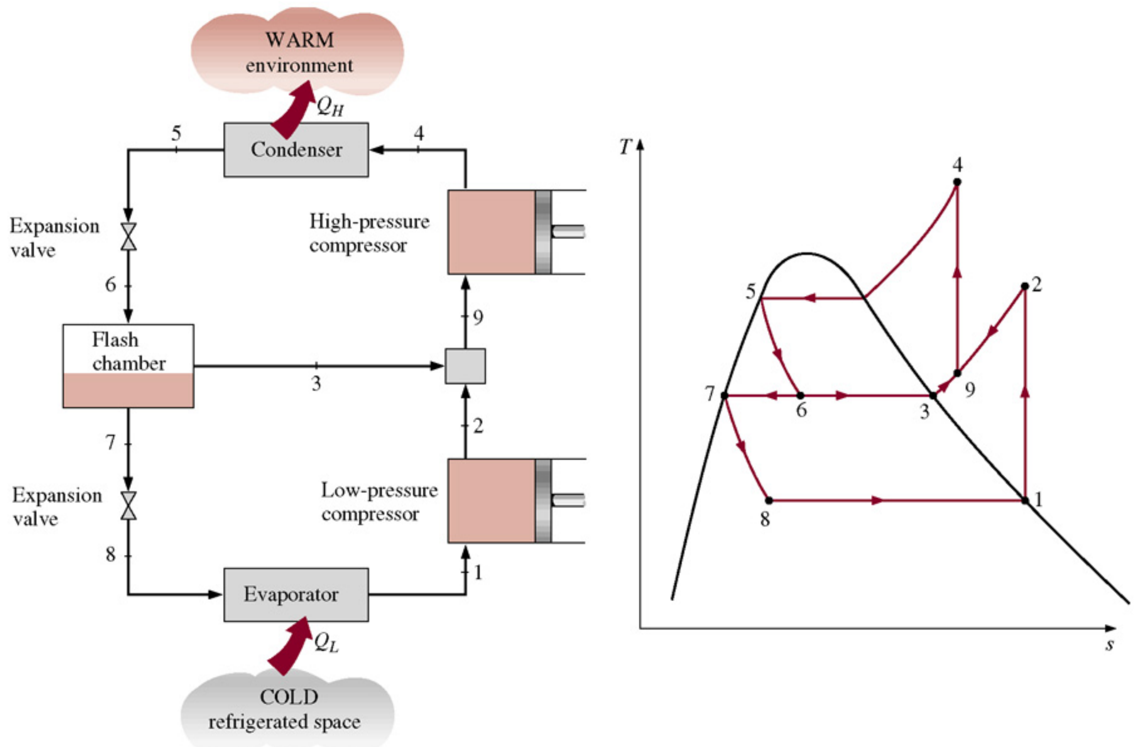
→ amount of heat from the refrigerated space increases

→ improves COP



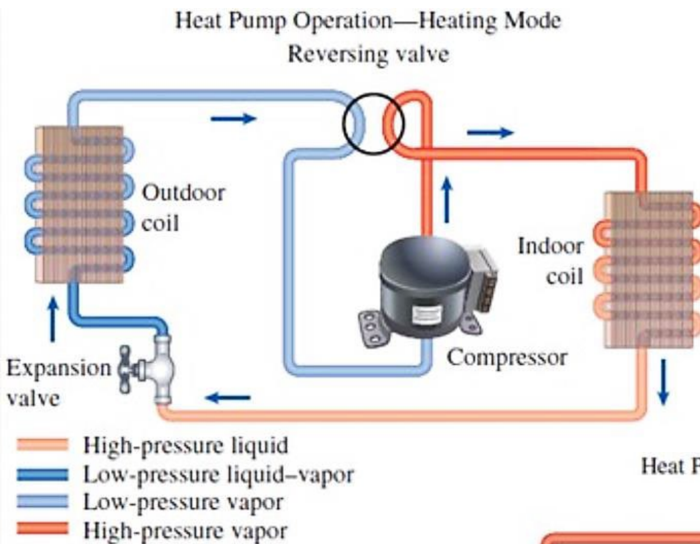
Multistage Compres. Refrigeration Systems

- When the fluid used throughout the refrigeration system is the same, the heat exchanger between the stages can be replaced by a mixing chamber since it has better heat transfer characteristics
- Liquid refrigerant condensed at high P expands in expansion valve (5 – 6)
- Part of the liquid vaporizes (saturated mixture in flash chamber)
- The saturated vapor (3) mixes with the superheated vapor (2) from comp.
- This is in essence a regeneration process
- This mixture enters the high P compressor (9)
- Sat. liquid (7) expands through a second valve into the evaporator and picks up heat from the refrigerated space
- Compressor work decreases

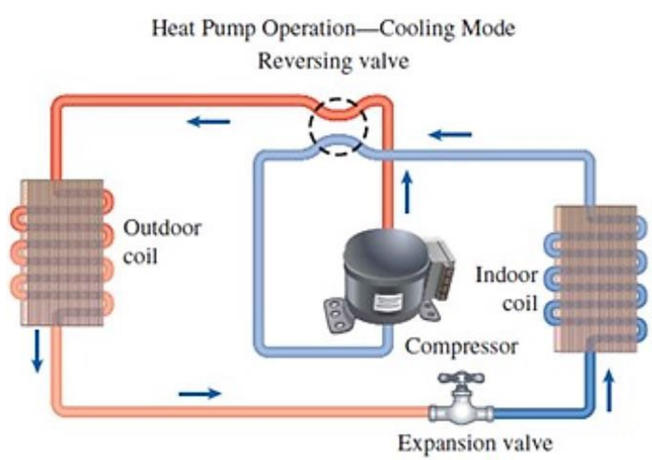


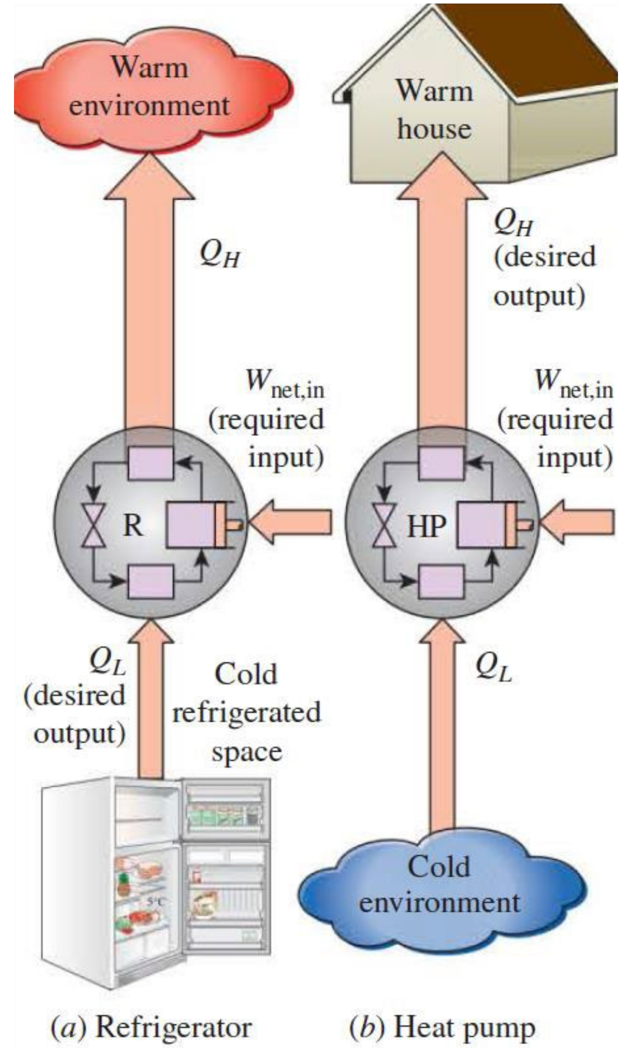
Air Conditioners and Heat Pumps

- The thermodynamic analysis of heat pumps and refrigeration systems is similar (except for the definition of the COP)
- Differences are in practical applications and different arrangement of the components



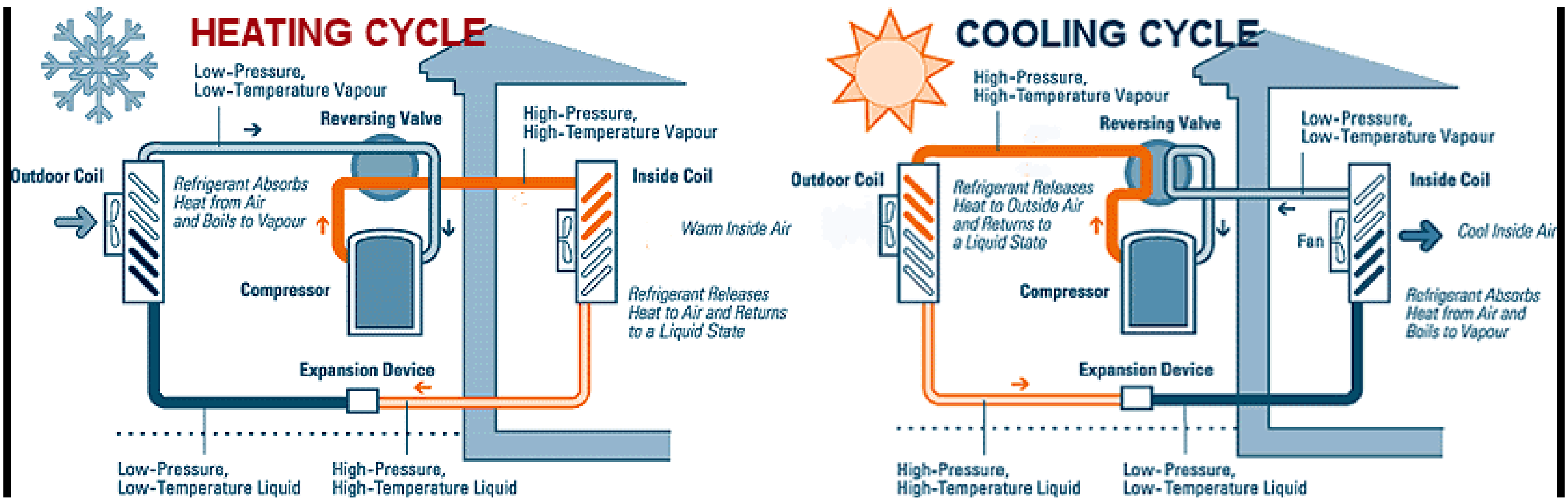
A heat pump can be used for heating in winter (top) and for cooling in summer (right)





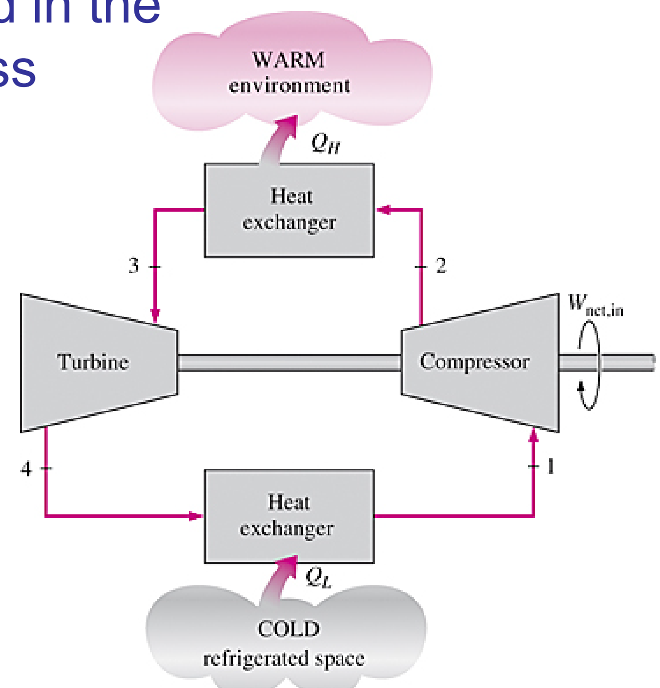
Air Conditioners and Heat Pumps

- Different arrangement of the components of the vapor – compression cycle for cooling and heating a house



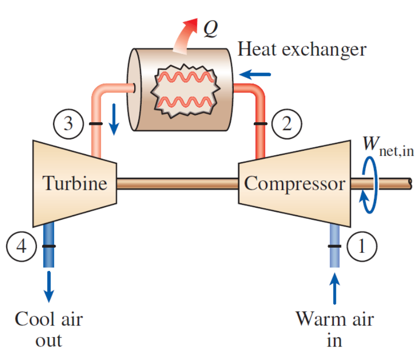
Gas Refrigeration Cycles

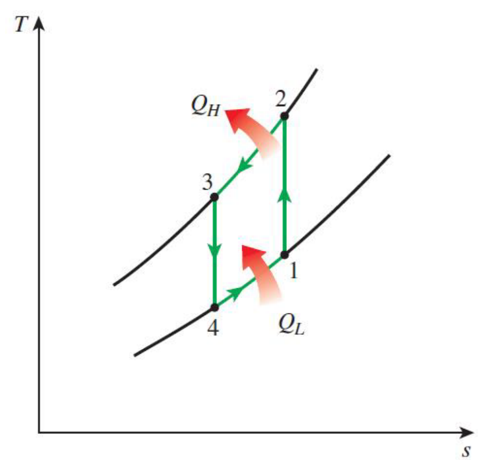
- **The vapor - compression cycle is the most widely used however some other cooling cycles are used for special applications**
- Reverse Brayton cycle, the throttle valve is replaced by a turbine
- In the ideal cycle it has isentropic expansion, ds = 0 instead of dh = 0
- The turbine converts some work during the pressure decrease
- Compressor requires more work than converted in the turbine → Still net work input is required, but less



- $$COP_{reverse\ Brayton} = \frac{q_{in,cold}}{w_{in,compressor} - w_{out,turbine}}$$

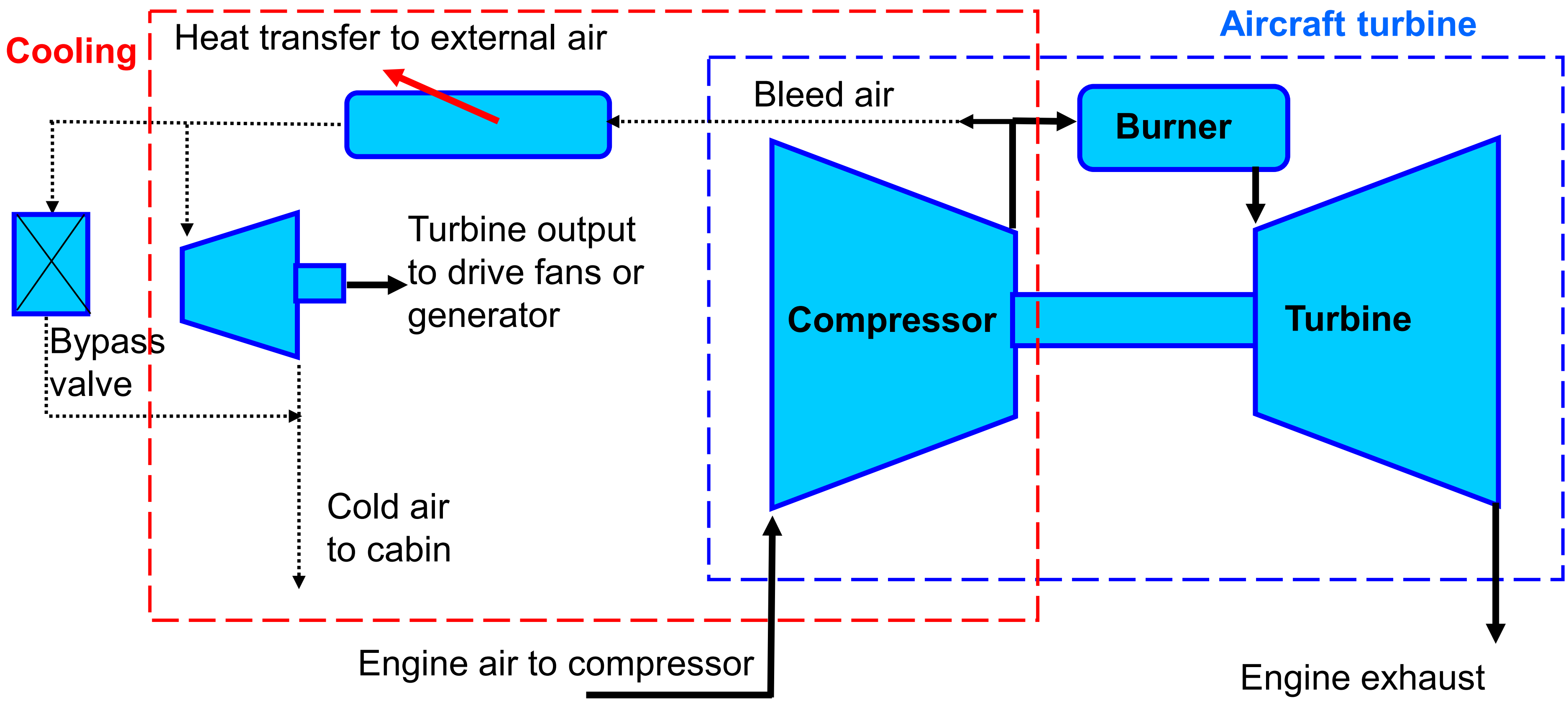
$$= \frac{h_1 - h_4}{(h_2 - h_1) - (h_3 - h_4)}$$





Reverse Brayton Cycle for Aircraft Cooling

- Reverse Brayton cycle → Aircraft air-conditioning systems to cool aircraft cabins

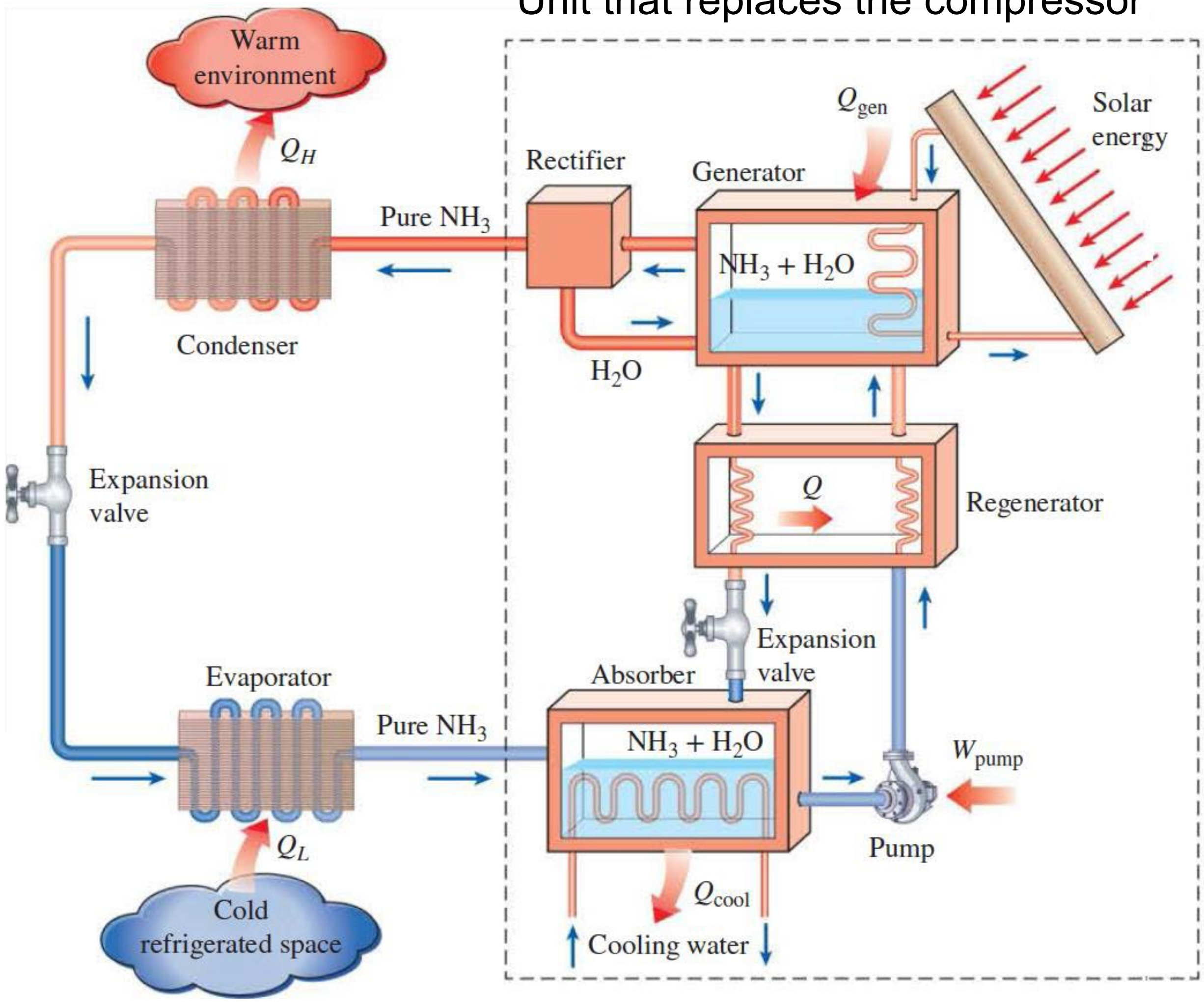


- Compressor of Brayton cycle for the engine & the reversed Brayton cycle for cooling is the same

Absorption Refrigeration Cycle

- Absorption refrigeration cycle uses (waste) heat for cooling
- Absorption refrigeration can be used when there is a source of inexpensive thermal energy at a temperature of 100 to 200°C.
- Some examples include geothermal energy, solar energy, waste heat from co-generation or process steam plants.
- The compressor is replaced by a unit that uses heat to compress the refrigerant

Unit that replaces the compressor



Not part of the exam

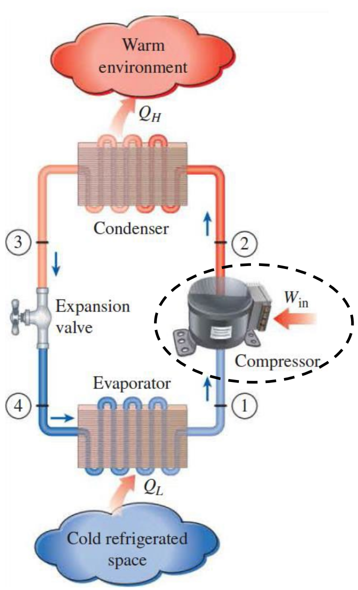
Absorption Refrigeration Cycle

- Absorption refrigeration systems (ARS) involve the absorption of a *refrigerant* by a *transport medium,* a two-component mixture.
- The most widely used system is the ammonia–water system, where ammonia (NH_3) serves as the refrigerant and water (H_2O) as the transport medium.
- Other systems include water–lithium bromide and water–lithium chloride systems, where water serves as the refrigerant. These systems are limited to applications such as A-C where the minimum temperature is above the freezing point of water.
- Compared with vapor-compression systems, ARS have one major advantage: A liquid is compressed instead of a vapor and as a result the work input is very small (on the order of one percent of the heat supplied to the generator) and often neglected in the cycle analysis.
- ARS are often classified as ***heat-driven systems***.
- ARS are much more expensive than the vapor-compression refrigeration systems. They are more complex and occupy more space, they are much less efficient thus requiring much larger cooling towers to reject the waste heat, and they are more difficult to service since they are less common.
- Therefore, ARS should be considered only when the unit cost of thermal energy is low and is projected to remain low relative to electricity.
- ARS are primarily used in large commercial and industrial installations.

Not part of the exam

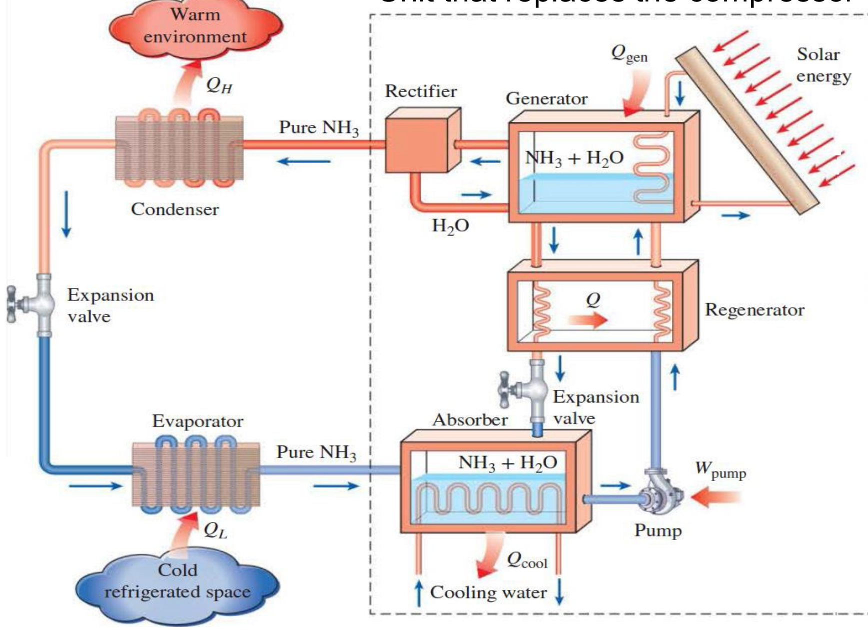
Absorption Refrigeration Cycle

- Waste heat $q_{in,gen}$ heats the high pressure two component mixture
- The low boiling point refrigerant is vaporized and goes to the condenser from where it runs through the cooling cycle
- The high boiling point absorbent goes back to the absorber by the throttle valve
- After the cooling process the low boiling point refrigerant vapor is absorbed into the high boiling point absorbent in the absorber and the two-component mixture
- The liquid is pressurized by the pump and uses less power as a $W_{comp} >> W_{pump}$
- COP defined as $COP_{absorption} = \frac{q_{in,evap}}{q_{in,gen}+w_{in,comp}}$
- $W_{in,pump}$ is small compared to $q_{in,gen}$



In an absorption cooling cycle the compressor of the vapor-compression cycle is replaced by a complicated unit using heat of low temperature to achieve the compression, this saves work input as a pump compresses a liquid, however the COP is lower, often $COP_{abs} < 1$ ((typically 0.7 – 0.8)

Unit that replaces the compressor

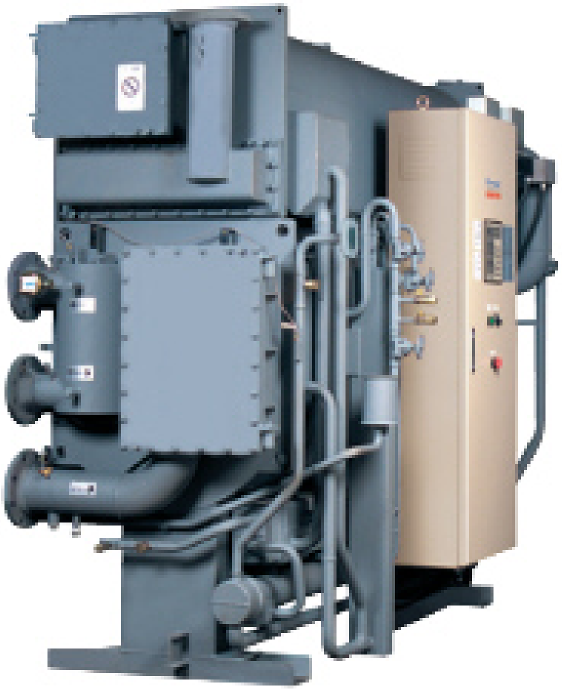


Not part of the exam

Application Absorption Refrigeration System

- **Absorption refrigeration systems** can be applied where (waste) heat of sufficient temperature is available, heat of about 80 degree is needed
  - Waste heat from heat engine
  - Geothermal energy, solar energy, thermal sources
  - City heating delivering heat in winter can in summer be used for cooling via absorption cooling
  - Waste heat from production process in factories

https://www.youtube.com/watch?v=nUW1OleNUrI



Not part of the exam

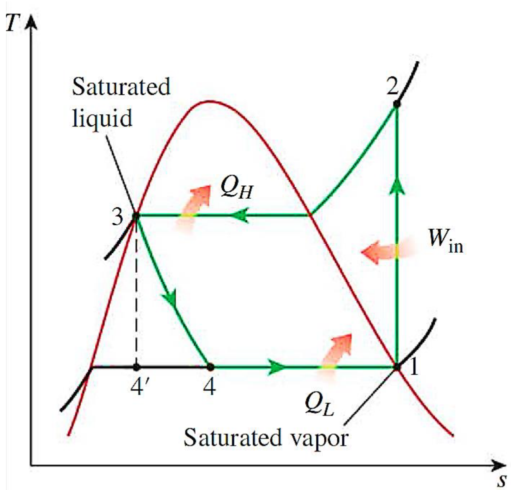
Bron: Carrier

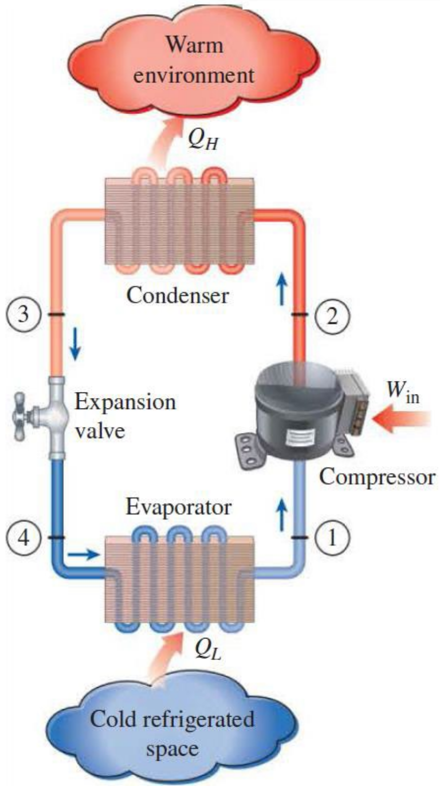
Recapitulate Class 13

- Vapor – compression cycle, cycle that transports heat in the non – spontaneous direction using work
- Thermodynamically the cycle for cooling (refrigeration) is like the cycle for heating (heat pump)
- **Coefficient of performance, COP**

$$COP_{ref} = \frac{q_{in,cold}}{w_{in}} \quad \text{and} \quad COP_{heat\ pump} = \frac{q_{out,hot}}{w_{in}}$$

- Ideal and non - ideal vapor - compression cycle for cooling / heating
  - Reversed Rankine cycle with throttling valve in stead of turbine (note: throttling $\mathbf{h_{in} = h_{uit}}$)
- Reverse Brayton cycle
- Special cooling cycles

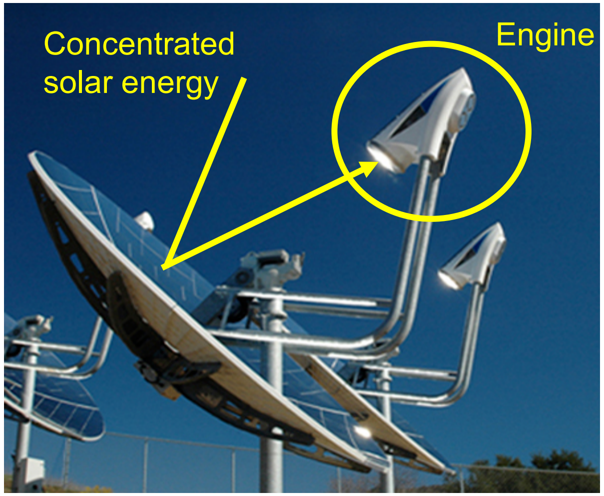




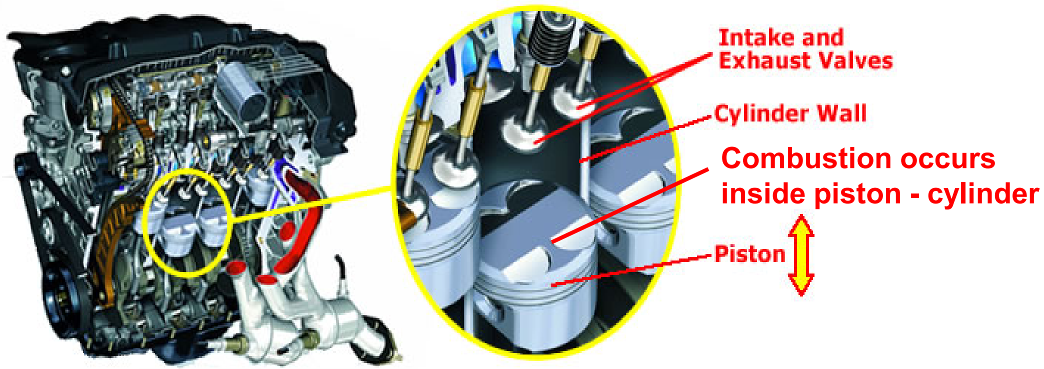
Vapor-compression cycle and Ts -diagram

Next Class 14: Stirling, Otto & Diesel Engine

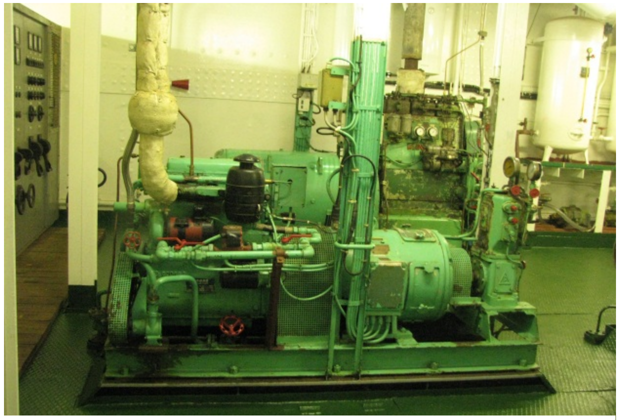
- The gas turbine cycle (Brayton cycle) uses gas as working fluid through the whole cycle (Class 10 & 11)
- Internal combustion engines, like Otto & Diesel engines also use gas as working fluid but these cycles are executed in a piston – cylinder device
- Stirling cycle
- Otto cycle
- Diesel cycle



Solar powered Stirling engine



Cutaway view of 4-Cylinder Gasoline Engine (Image Courtesy BMW) ThermoNet: Wiley



Diesel engine

Keep in mind: Important Formulas

- Specific volume v = V/m [m³/kg] and density ρ = 1/v = m/V [kg/m³]
- Volume work δw = Pdv
- Enthalpy h = u + Pv, (u internal energy, P pressure, v volume)
- Thermal efficiency $\eta_{thermal} = \frac{Net\ electrical\ power\ output}{Rate\ of\ fuel\ energy\ input} = \frac{\dot{W}_{net}}{\dot{Q}_{in}}$
- Mixture fraction $x = \frac{v - v_l}{v_v - v_l} \rightarrow v = v_l + x(v_v - v_l)$
- Ideal gas law $Pv = RT$, $c_p - c_V = R$
- For an ideal gas $du = c_V dT$ and $dh = c_p dT$
- Conservation of mass $m_{in} = m_{out}$, mass flow rate $\dot{m} = \rho vA$
- Conservation of energy, first law of thermodynamics
  - Closed system du= δw – δq → Δu = w - q
  - Open system $q_{in} + w_{in} + (h + ke + pe)_{in} = q_{out} + w_{out} + (h + ke + pe)_{out}$
- S increases, second law $ds_{total} = ds_{system} + ds_{surroundings} = \delta s_{gen} \geq 0$
- Inequality of Clausius $ds \geq \frac{\delta q_{net}}{T_{res}}$ (= for reversible process)
- Reversible heat transfer $\delta q_{net,rev} = Tds$, irreversible $\delta q_{net,irrev} < Tds$
- Gibbs equations Tds = du + Pdv and Tds = dh - vdP
- Isentropic efficiencies $\eta_{INPUT,S} = \frac{w_{IN,S}}{w_{IN,A}}$, $\eta_{OUTPUT,S} = \frac{w_{OUT,A}}{w_{OUT,S}}$
- Isentropic processes ideal gas Pv^k =constant, Tv^{k-1}=constant, $P^{(k-1)/k}/T$ = constant
- Thermal efficiency power cycles $\eta_{he} = \frac{w_{out} - w_{in}}{q_{in}} = 1 - \frac{q_{out}}{q_{in}}$ Carnot efficiency $\eta_{carnot} = 1 - \frac{T_{cold}}{T_{hot}}$

- Phase diagrams