Lecture 15

Topic 4
Power & Refrigeration Cycles

Topic

– 4.1 Refrigeration cycles

Reading:
Ch 9: 9.1 & 9.8-9.11 Borgnakke & Sonntag Ed. 8
Ch 11: 11-1 – 11-7 Cengel and Boles Ed. 7

4.0 Power and Refrigeration Cycles

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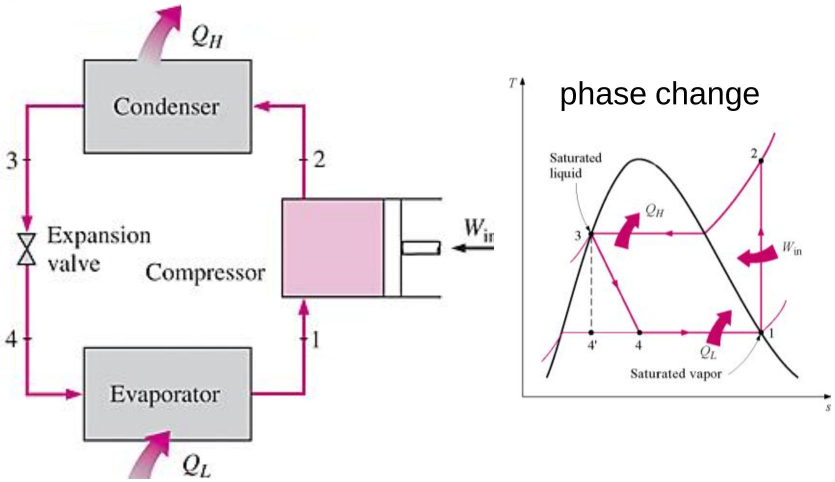
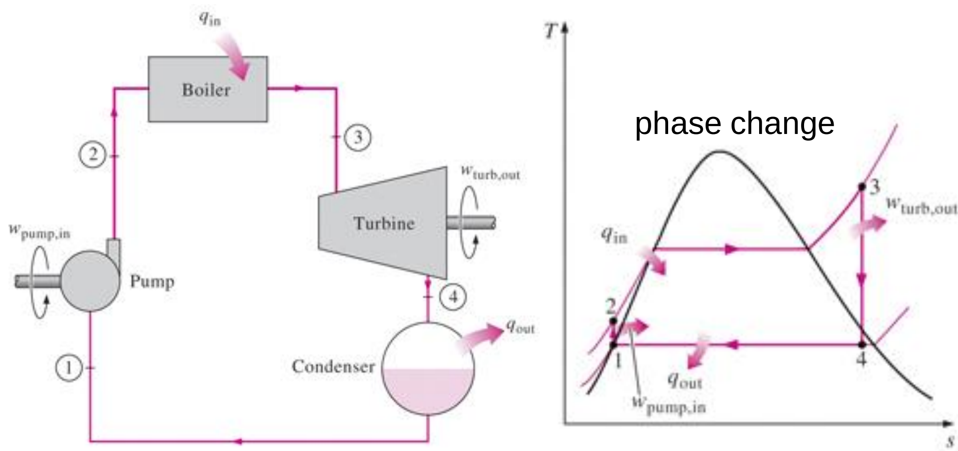
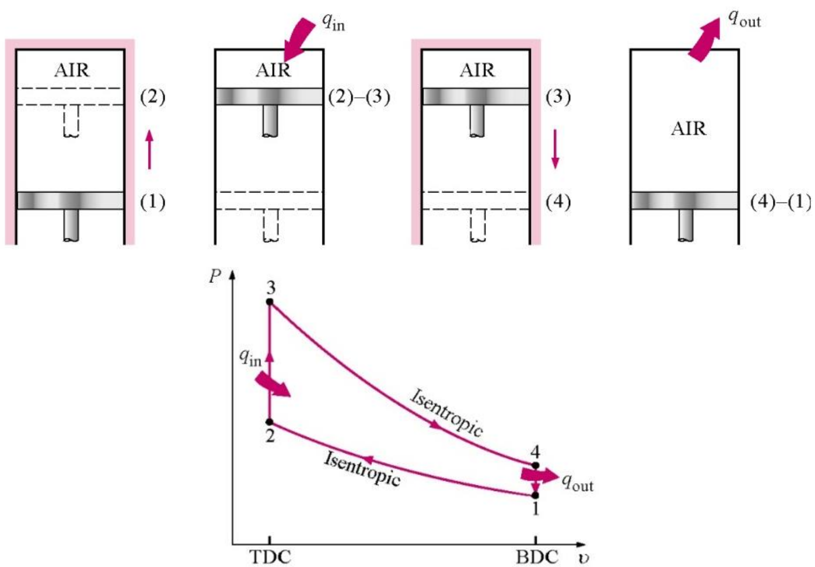
Refrigeration Cycle



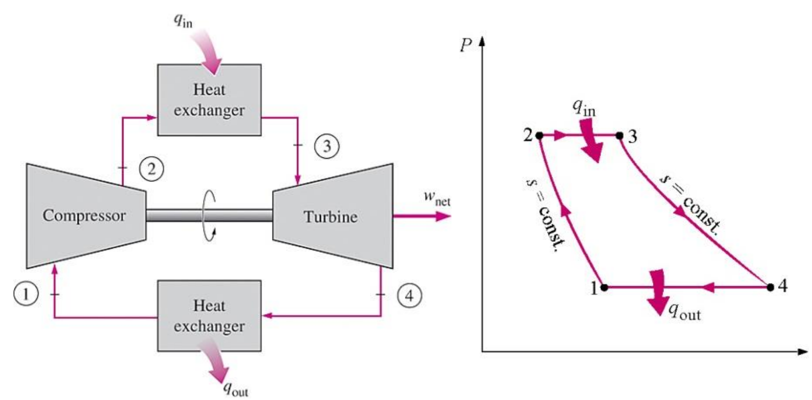
Rankine Cycle (power plant)



Otto/Diesel Cycle (IC engine)



Brayton Cycle (gas turbine)

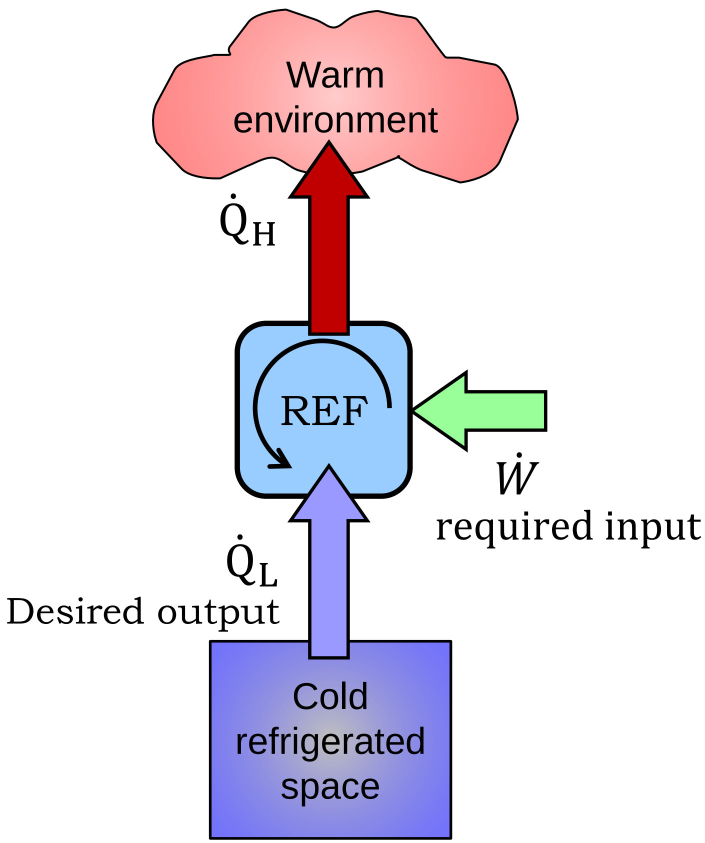


4.1 Refrigeration Cycle

Vapor compression refrigeration cycle – transfer heat from a low temperature to a high temperature reservoir

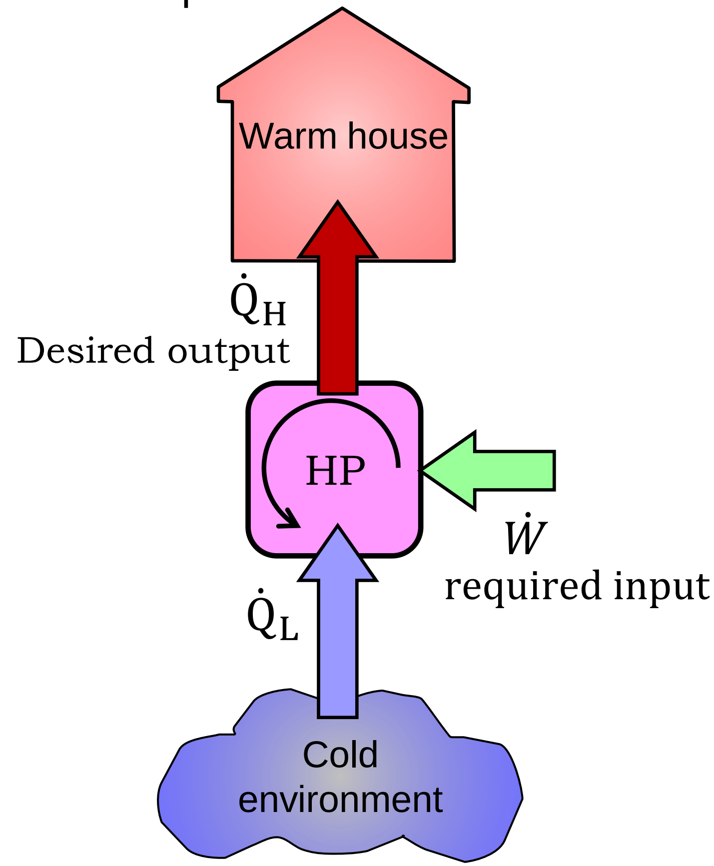
<u>Refrigerator</u>

Heat removal (cooling load) from a low-temperature medium.



<u>Heat pump (heating mode)</u>

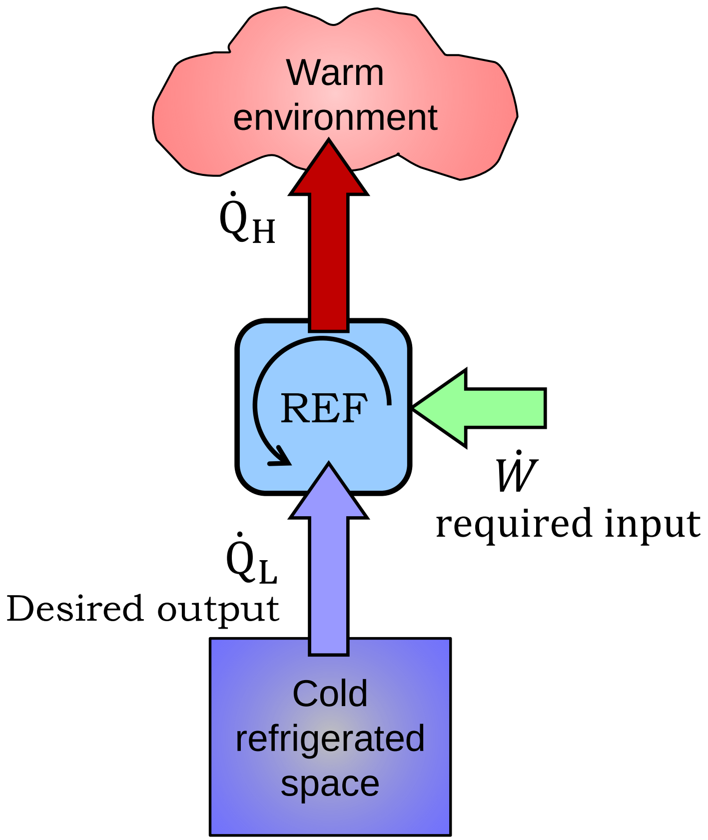
Heat addition (heating load) to a higher-temperature medium.



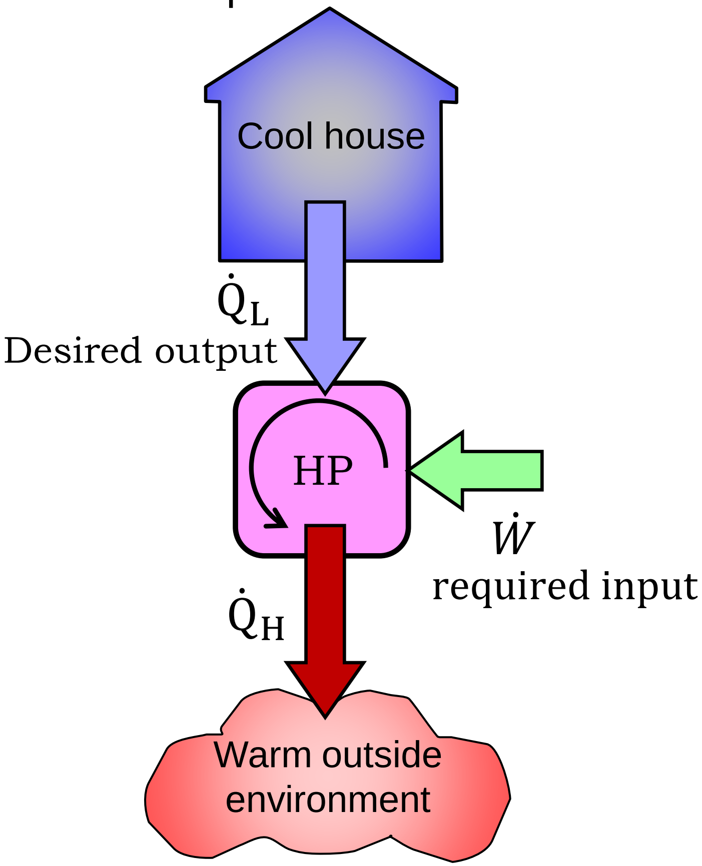
4.1 Refrigeration Cycle

Vapor compression refrigeration cycle – transfer heat from a low temperature to a high temperature reservoir

<u>Refrigerator</u>
Heat removal (cooling load) from a low-temperature medium.



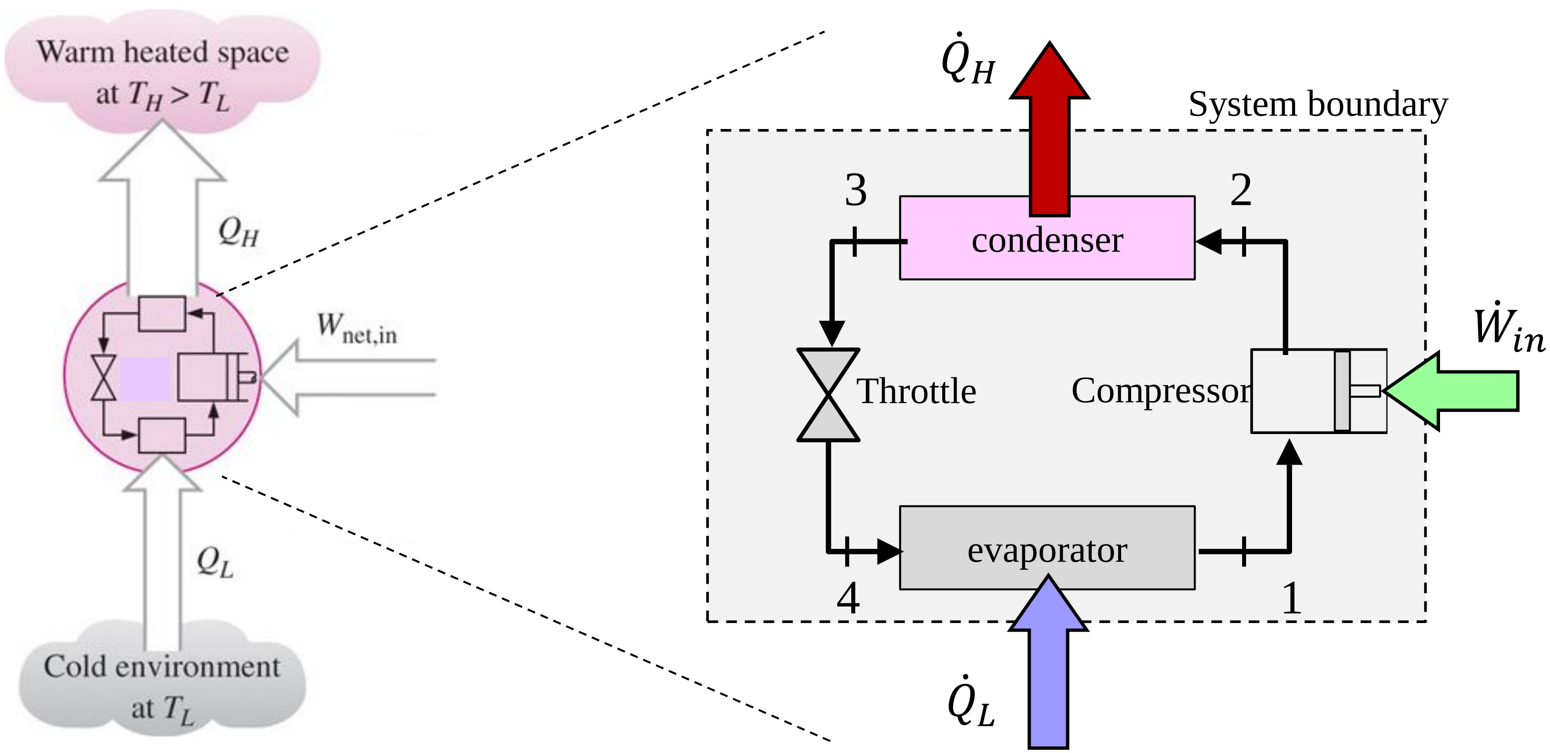
<u>Heat pump (cooling mode)</u>
Heat removal (cooling load) from a lower-temperature medium.



4.1 Refrigeration Cycle

Vapor compression refrigeration cycle – transfer heat from a low temperature to a high temperature reservoir

Vapor compression cycle

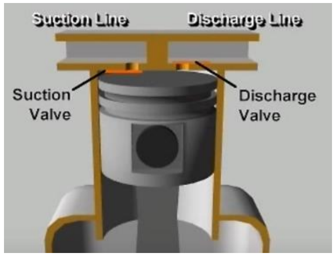


4.1 Refrigeration Cycle

Main Components of refrigeration cycle

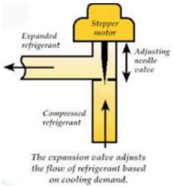
- Compressor
  - Compresses vapor to high temp./press.
  - Recirculates refrigerant through cycle

Piston/cyl compressor

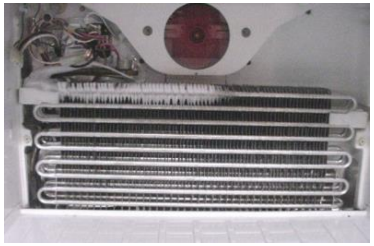


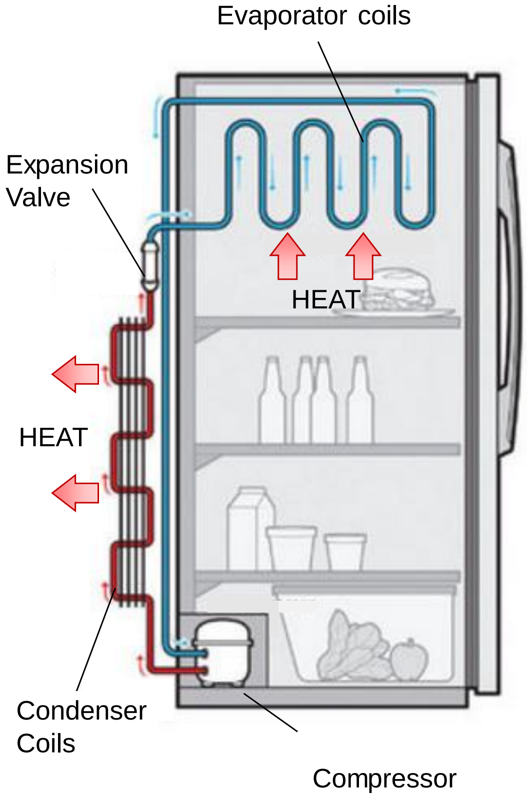
- Condenser
  - High temp. vapour looses heat and condenses to a liquid.
  - Heat rejected to the room.

- Throttle / expansion valve
  - Throttle to low P / T (very cold liquid-vapour mixture).



- Evaporator
  - Refrigerant absorbs heat from refrigerator.
  - Refrigerant evaporates to a vapour
  - Refrigerant re-enters compressor





4.1 Refrigeration Cycle

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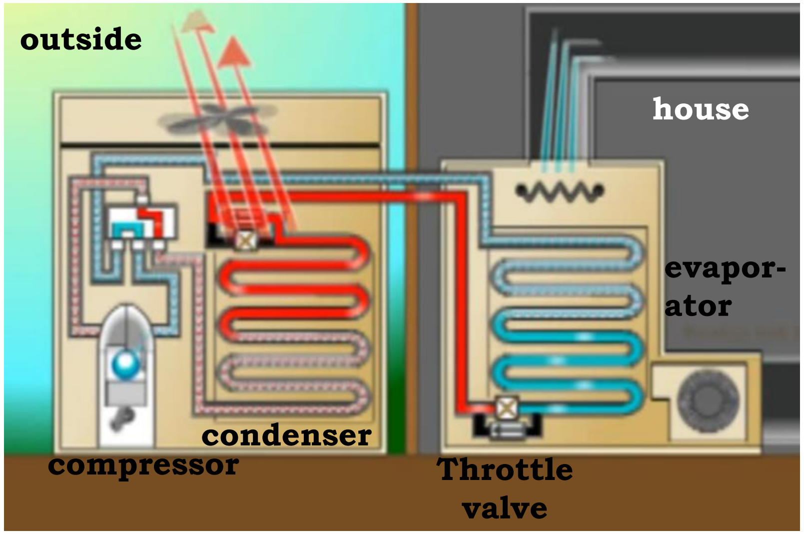
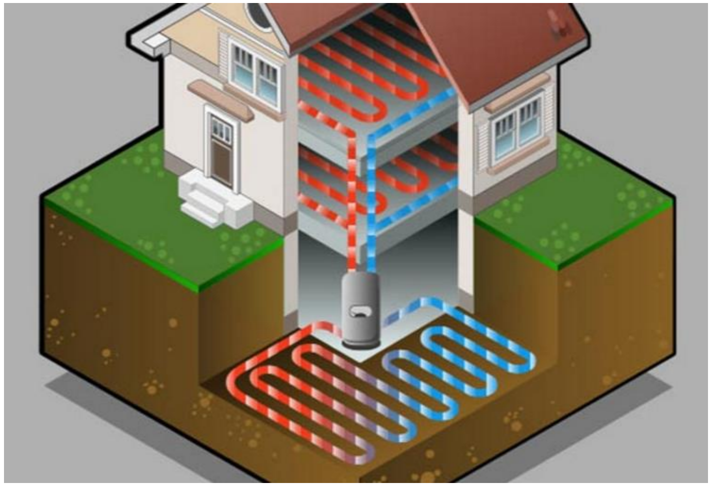




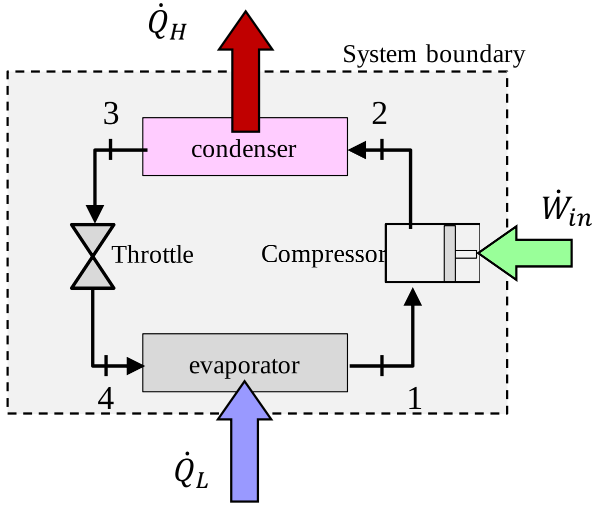
https://www.youtube.com/watch?v=14MmsNPtn6U

4.1 Ideal Vapour Compression Refrig. Cycle

Compressor

- Compresses refrigerant from low to high working pressure
- Steady State device

• Ideal: adiabatic, reversible, begins as saturated vapor



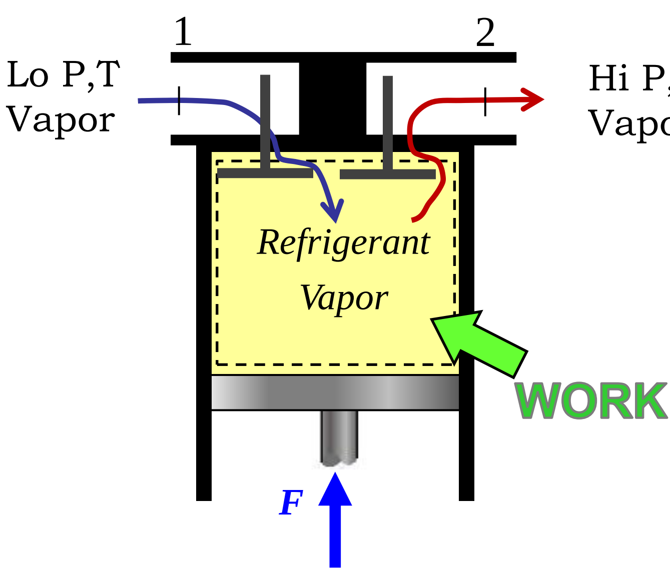
1st law: $\dot{W}_{21,IN} = \dot{m}(h_2 - h_1)$

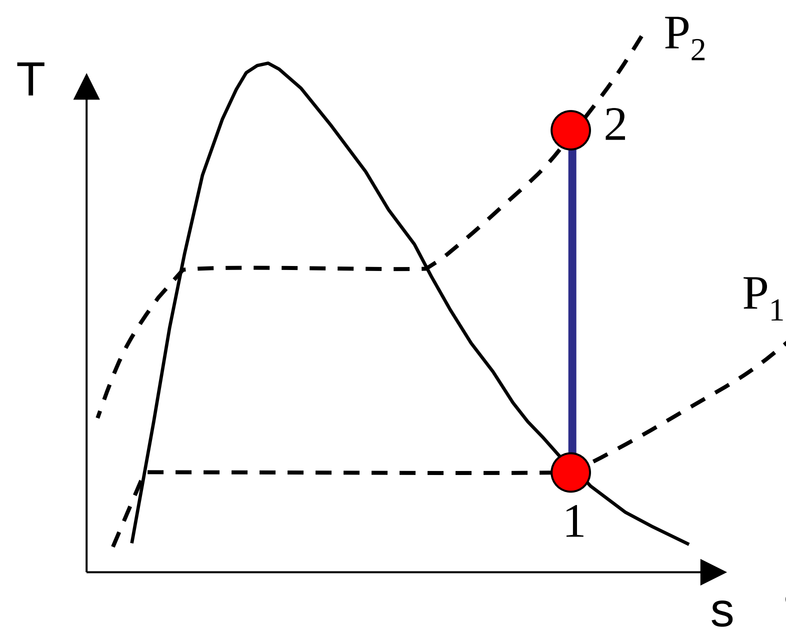
2nd law:

• Ideal: $s_2 - s_1 = 0$

• Reality: $s_2 - s_1 = \int \delta q/T + s_{gen}$

- not reversible & possible heat loss





4.1 Ideal Vapour Compression Refrig. Cycle

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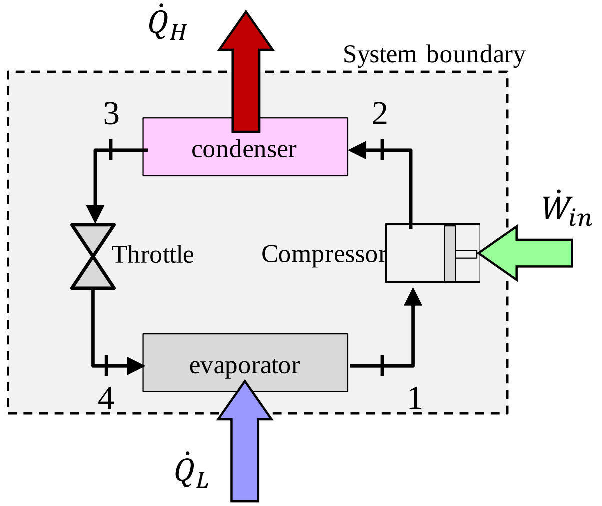
Condenser

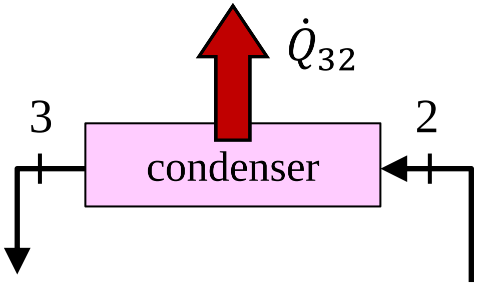
- Heat rejection
- Refrigerant condenses to liquid
- Steady state device

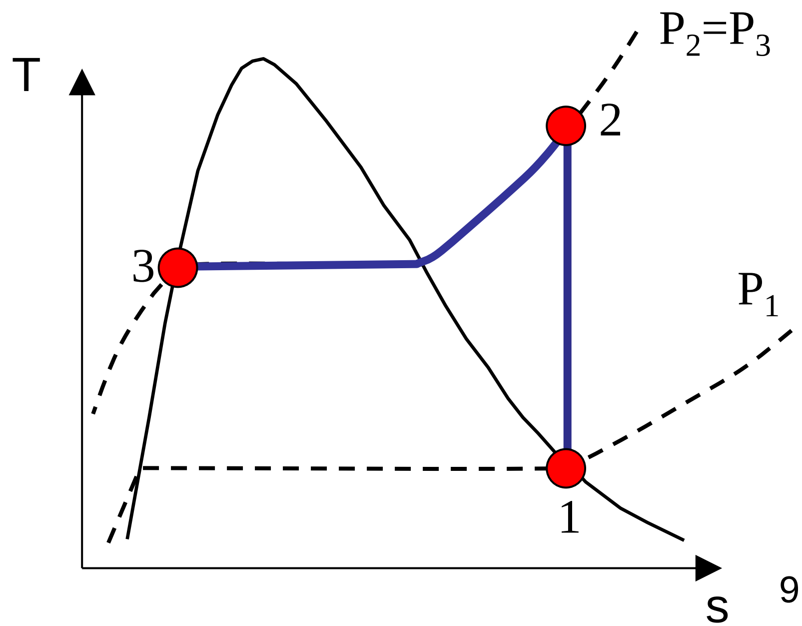
• Ideal: exits as saturated liquid, constant pressure



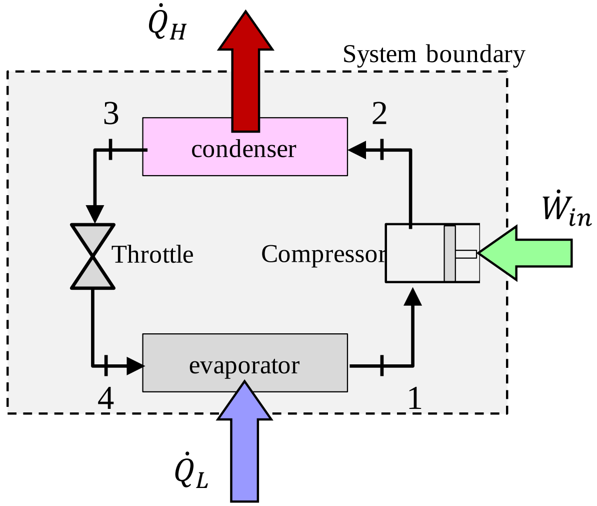
1st law: $\dot{Q}_{32,out} = \dot{m}(h_2 - h_3)$

2nd law: $s_3 - s_2 = -\int \delta q/T + s_{gen}$





4.1 Ideal Vapour Compression Refrig. Cycle



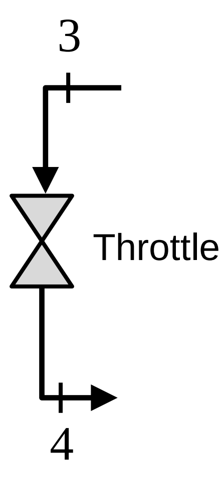
Throttle

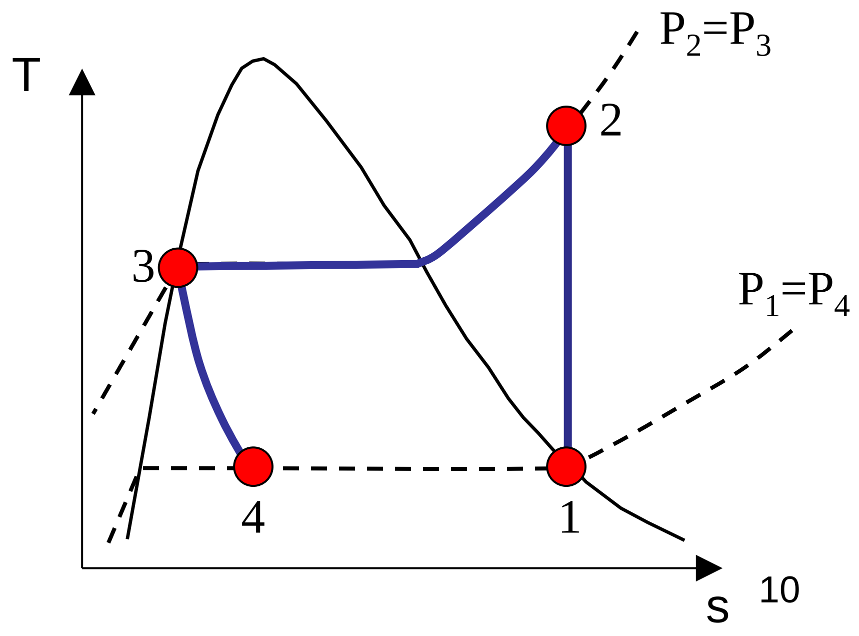
- Throttled to low pressure, low temperature vapour-liquid mixture
- Throttle to lower working pressure
- Steady state device

• Ideal: adiabatic, begins as saturated liquid

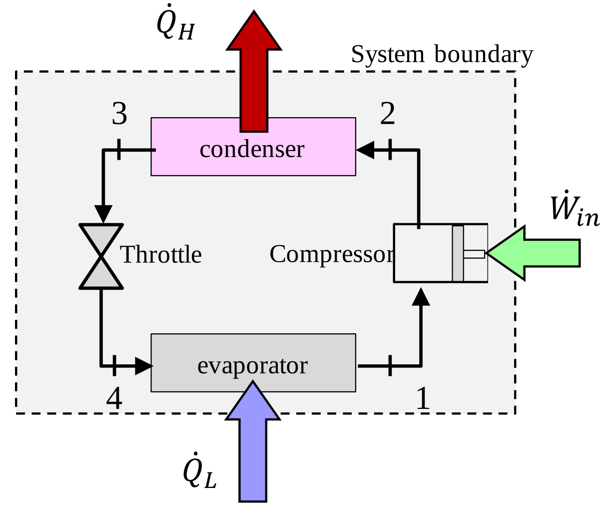
1st law: $h_3 = h_4$

2nd law: $s_4 - s_3 = s_{gen}$





4.1 Ideal Vapour Compression Refrig. Cycle



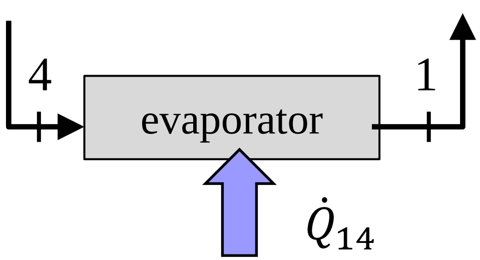
Evaporator

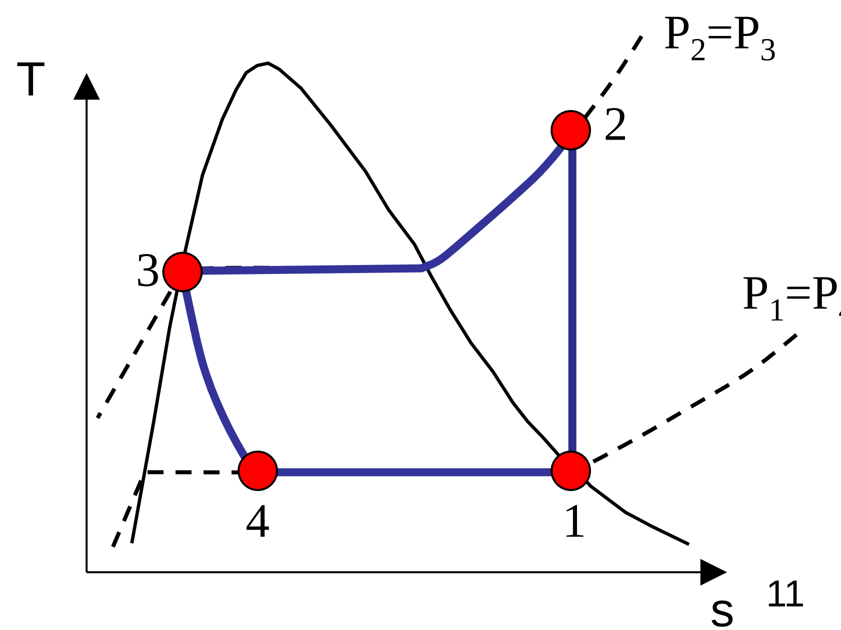
- Heat addition
- Refrigerant evaporates to saturated vapour
- Steady state device

- Ideal: constant pressure, exits as a saturated vapor

1st law: $\dot{Q}_{14,IN} = \dot{m}(h_1 - h_4)$

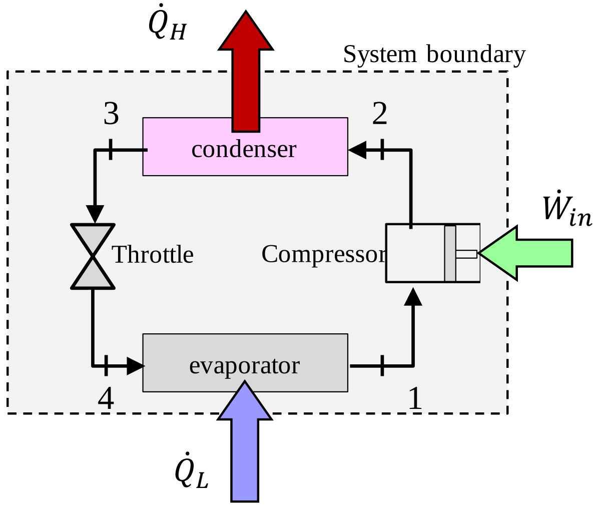
2nd law: $s_1 - s_4 = \int \delta q/T + s_{gen}$





4.1 Ideal Vapour Compression Refrig. Cycle

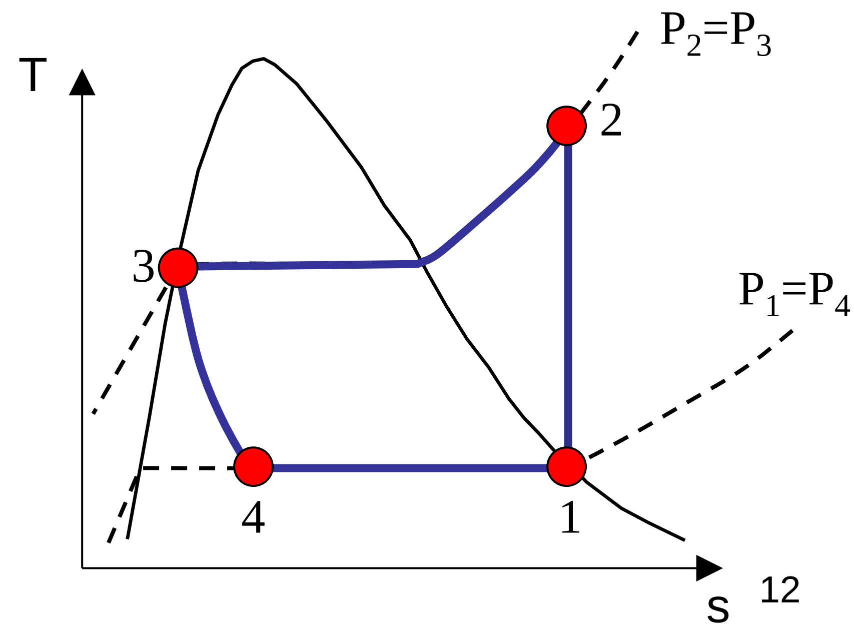
- Process 1-2: Adiabatic, reversible compression
- Process 2-3: Constant pressure heat rejection
- Process 3-4: Adiabatic throttling
- Process 4-1: Constant pressure heat addition



- Operating pressures
  - $P_2 = P_3 > P_1 = P_4$

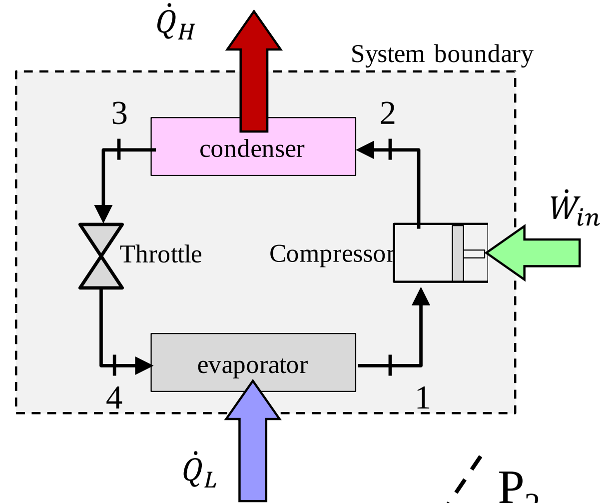
$$COP_{R,HP\ cool} = \frac{\dot{Q}_L}{\dot{W}_{net,in}} = \frac{h_1 - h_4}{h_2 - h_1}$$

$$COP_{HP\ heat} = \frac{\dot{Q}_H}{\dot{W}_{net,in}} = \frac{h_2 - h_3}{h_2 - h_1}$$

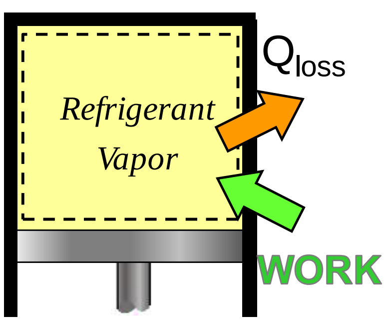


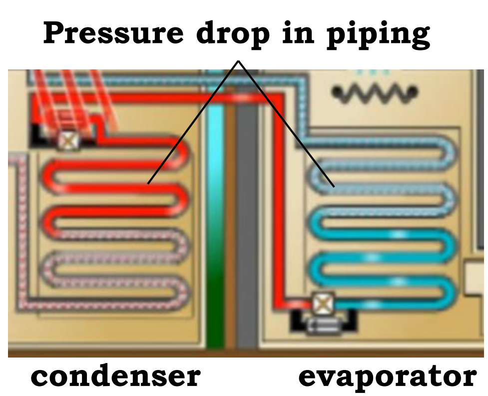
4.1 Refrigeration Cycle

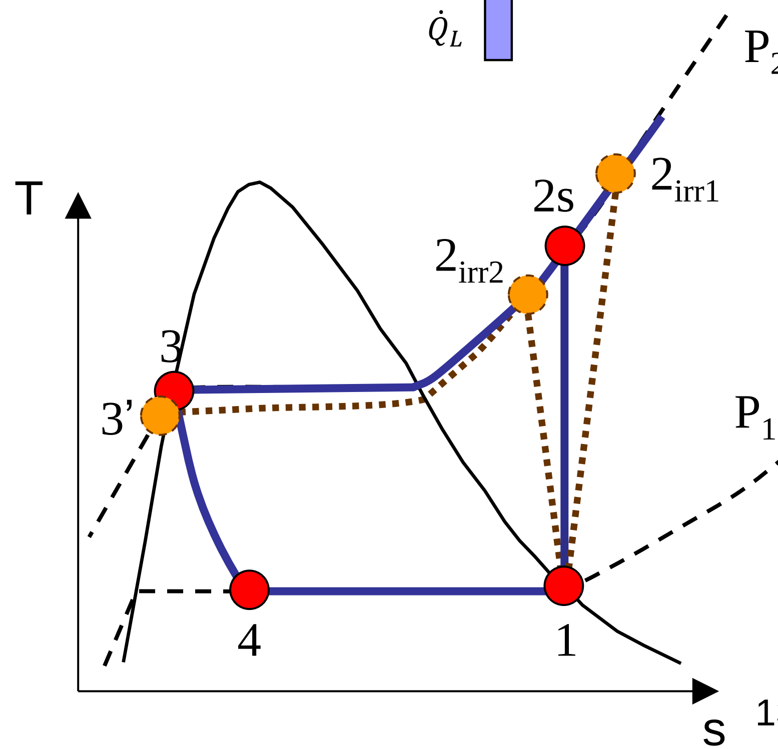
Deviations from the ideal Vapour Compression Refrigerant Cycle



- Process 1-2: non-adiabatic, irreversible compression
  - $s_2 = s_1 + \int_1^2 \delta q_{in}/T + s_{gen}$
    - Irreversibilities will increase s_2
    - Heat loss will decrease s_2
- Process 2-3: Condensation
  - $P_3 < P_2$; pressure loss in pipes (T reduces)





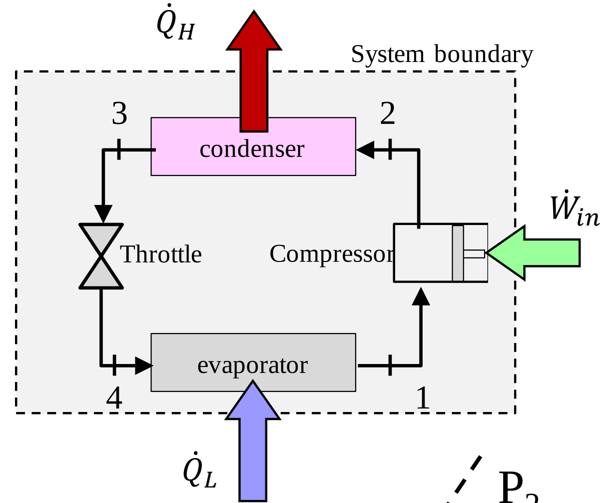


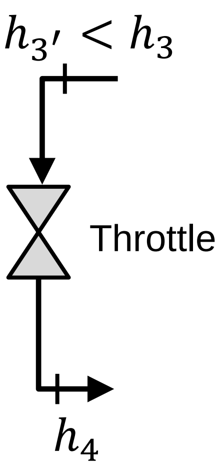
4.1 Refrigeration Cycle

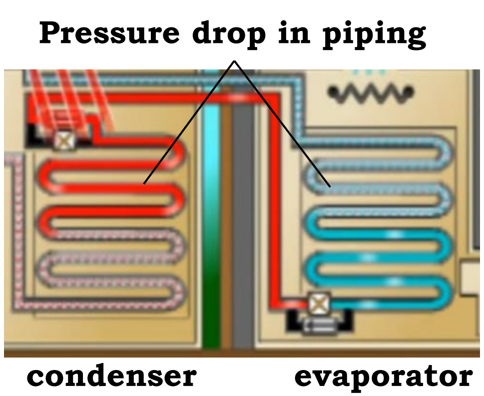
Deviations from the ideal Vapor Compression Refrigerant Cycle

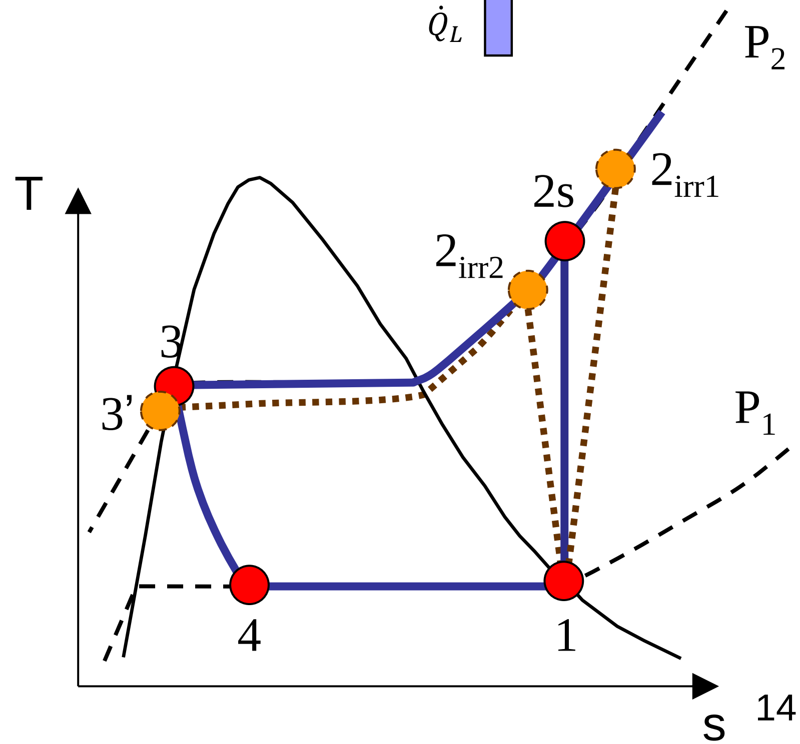
- Process 3-4: Throttling
  - Device that behaves most like the ideal device

Process 4-1: Evaporation
  - $P_1 < P_{4'}$; pressure loss in pipes (T reduces)









4.1.1 Example

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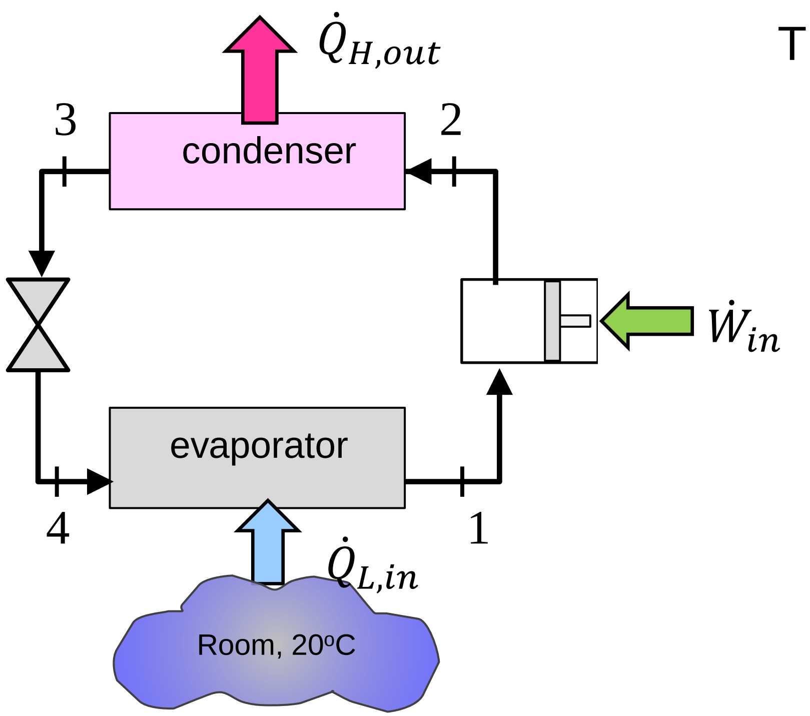
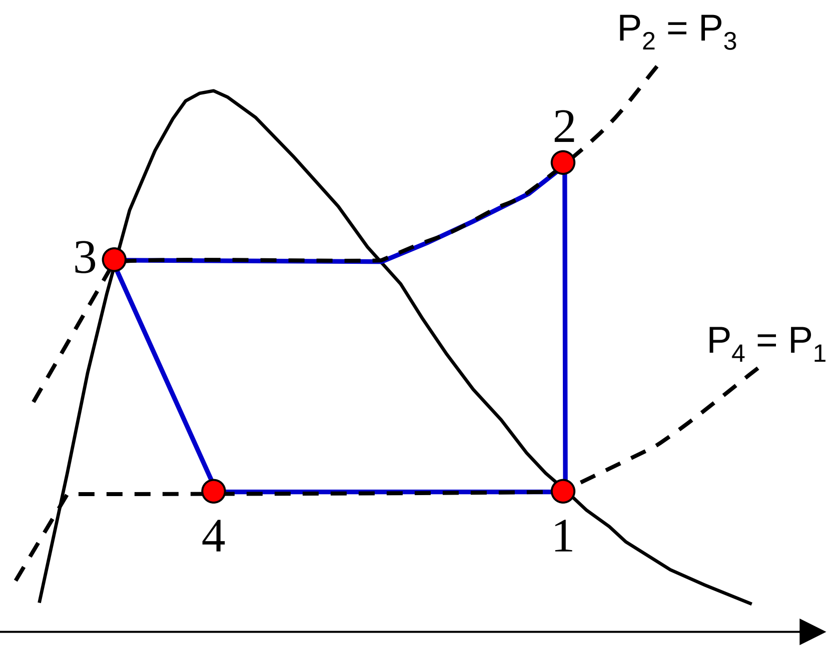
Example 4-1: A refrigerator operating with 0.2 kg/s R-134a removes heat from a 20ºC room. Consider an <u>ideal</u> refrigeration cycle, where saturated vapour at -20ºC enters the compressor. The R-134a exits the condenser as a saturated liquid at 1000 kPa.

a) Determine the maximum working temperature in the cycle.

b) Determine the required power input into the compressor

c) Determine the refrigerator COP





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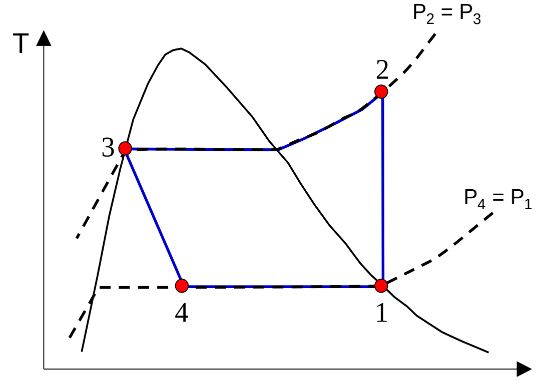
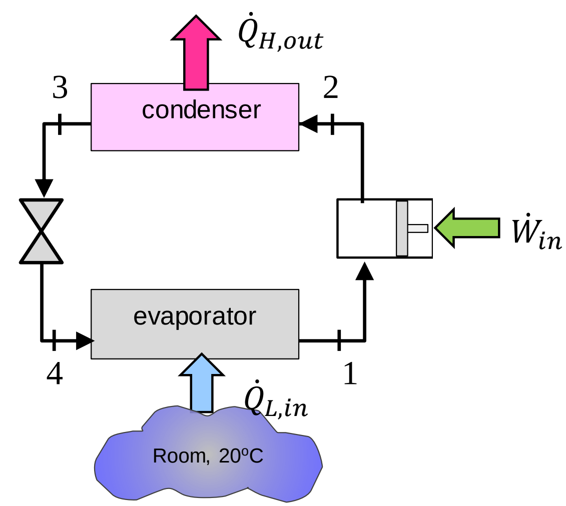


TABLE B.5.1 *(continued)*
Saturated R-134a

Temp. (°C)	Press. (kPa)	Enthalpy, kJ/kg Sat. Liquid h_f	Evap. h_{fg}	Sat. Vapor h_g	Entropy, kJ/k-K Sat. Liquid s_f	Evap. s_{fg}	Sat. Vapor s_g
–25	107.2	167.38	215.57	382.95	0.8754	0.8687	1.7441
–20	133.7	173.74	212.34	386.08	0.9007	0.8388	1.7395
35	887.6	249.10	168.42	417.52	1.1673	0.5465	1.7139
40	1017.0	256.54	163.28	419.82	1.1909	0.5214	1.7123



Superheated R-134a

Temp. (°C)	v (m^3/kg)	u (kJ/kg)	h (kJ/kg)	s (kJ/kg-K)
	1000 kPa (39.37°C)			
Sat.	0.02038	399.16	419.54	1.7125
40	0.02047	399.78	420.25	1.7148
50	0.02185	409.39	431.24	1.7494

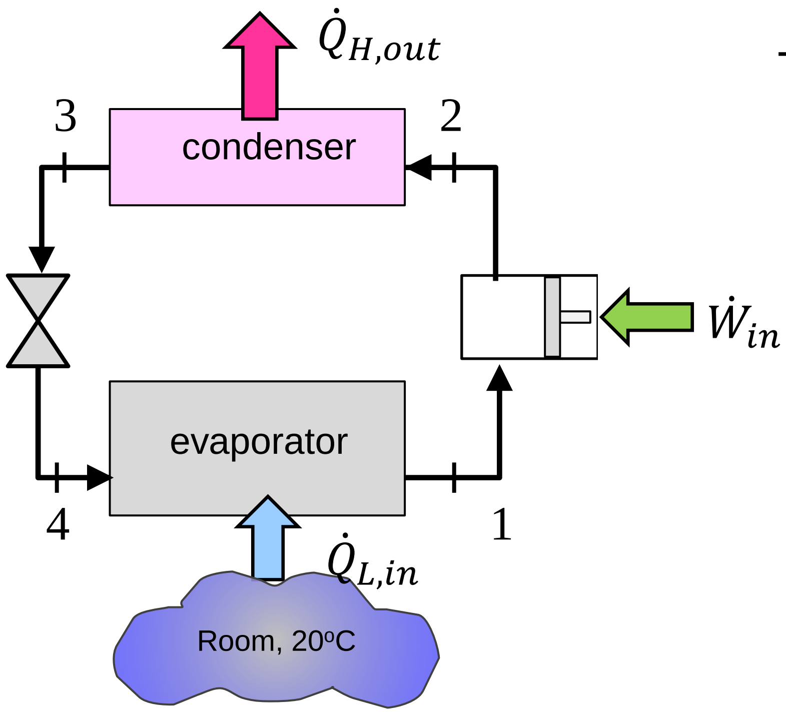
4.1.1 Example

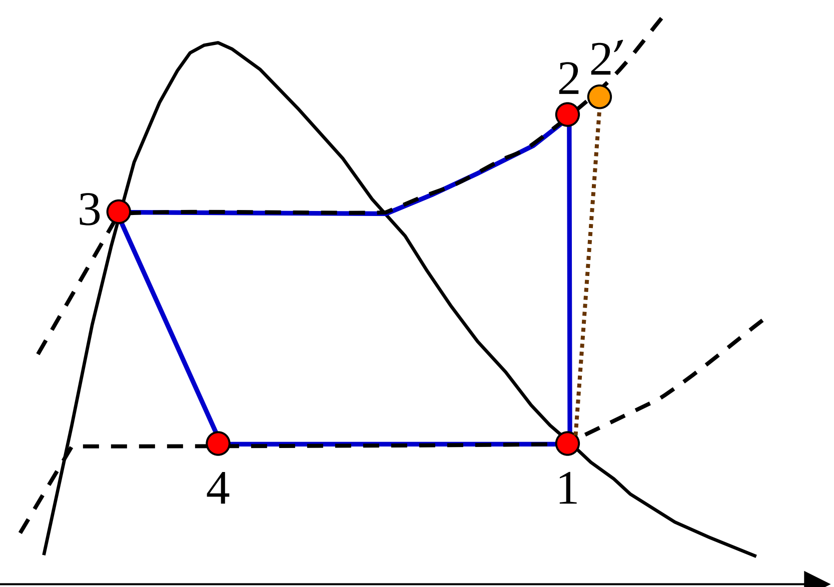
Example 4-2: Take Example 4-1. Now the compressor adiabatic, but not reversible. The compressor operates with an isentropic efficiency of 80%.

a) Determine the required input power to overcome the irreversibilities.

b) Determine the entropy generation (in kW/K) during the compressor process.

c) Determine the refrigerator COP_{actual}





4.1.1 Example

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−25	107.2	167.38	215.57	382.95	0.8754	0.8687	1.7441
−20	133.7	173.74	212.34	386.08	0.9007	0.8388	1.7395
35	887.6	249.10	168.42	417.52	1.1673	0.5465	1.7139
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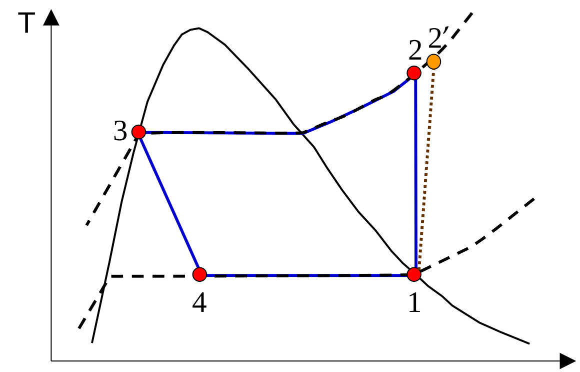

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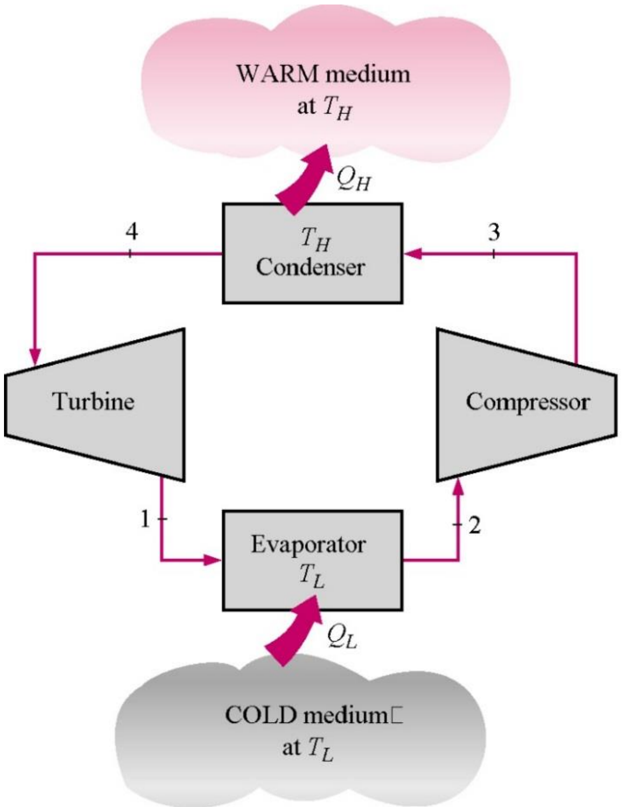
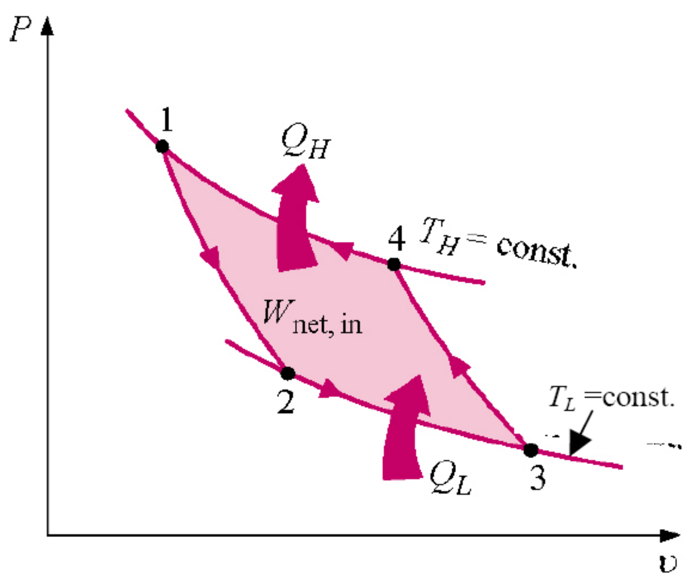
Temp. (°C)	v (m³/kg)	u (kJ/kg)	h (kJ/kg)	s (kJ/kg-K)
	1000 kPa (39.37°C)			
Sat.	0.02038	399.16	419.54	1.7125
40	0.02047	399.78	420.25	1.7148
50	0.02185	409.39	431.24	1.7494
60	0.02311	418.78	441.89	1.7818

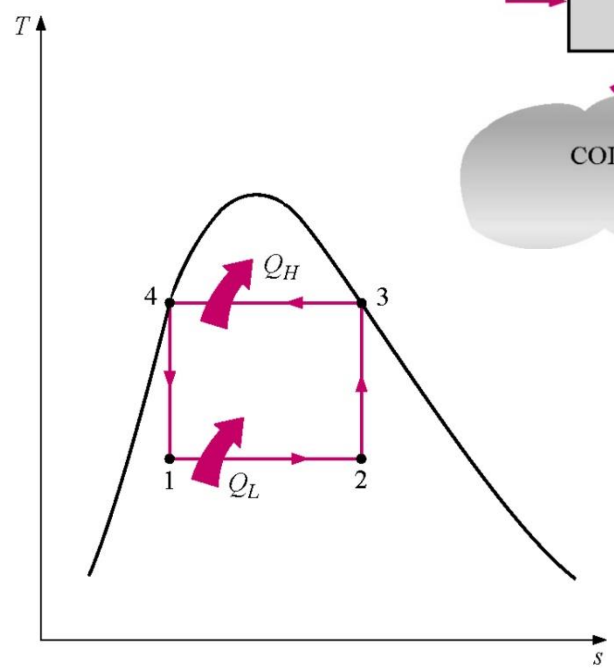
4.1 Refrigeration Cycle - Extra

REMINDER – The Reversible Carnot Cycle

Recall that the Carnot cycle is a totally reversible cycle that consists of two reversible isothermal and two isentropic processes. It has maximum efficiency for given temperature limits and it serves as a standard against which actual power cycles can be compared. Since it is a reversible cycle, all four processes that comprise the Carnot cycle can be reversed. Reversing the cycle also reverses the directions of any heat and work interactions.







4.1 Refrigeration Cycle - Extra

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REMINDER – Coefficient of performance

The performance of refrigerators and heat pumps is expressed in terms of coefficient of performance (COP), defined as

$$COP_R = \frac{\text{Desired output}}{\text{Required input}} = \frac{\text{Cooling effect}}{\text{Work input}} = \frac{Q_L}{W_{net,in}}$$

$$COP_{HP} = \frac{\text{Desired output}}{\text{Required input}} = \frac{\text{Heating effect}}{\text{Work input}} = \frac{Q_H}{W_{net,in}}$$

Both COP_R and COP_{HP} can be larger than 1. Under the same operating conditions, the COPs are related by

$$COP_{HP} = COP_R + 1$$

Refrigerators, air conditioners, and heat pumps are rated with an SEER number or seasonal adjusted energy efficiency ratio. The SEER is defined as the Btu/hr of heat transferred per watt of work energy input. The Btu is the British thermal unit and is equivalent to 778 ft-lbf of work (1 W = 3.4122 Btu/hr).

Refrigeration systems are also rated in terms of tons of refrigeration. The capacity of a refrigeration system that can freeze 1 ton of liquid water at 0ºC into ice at 0ºC in 24 hours is said to be 1 ton.

4.1 Refrigeration Cycle - Extra

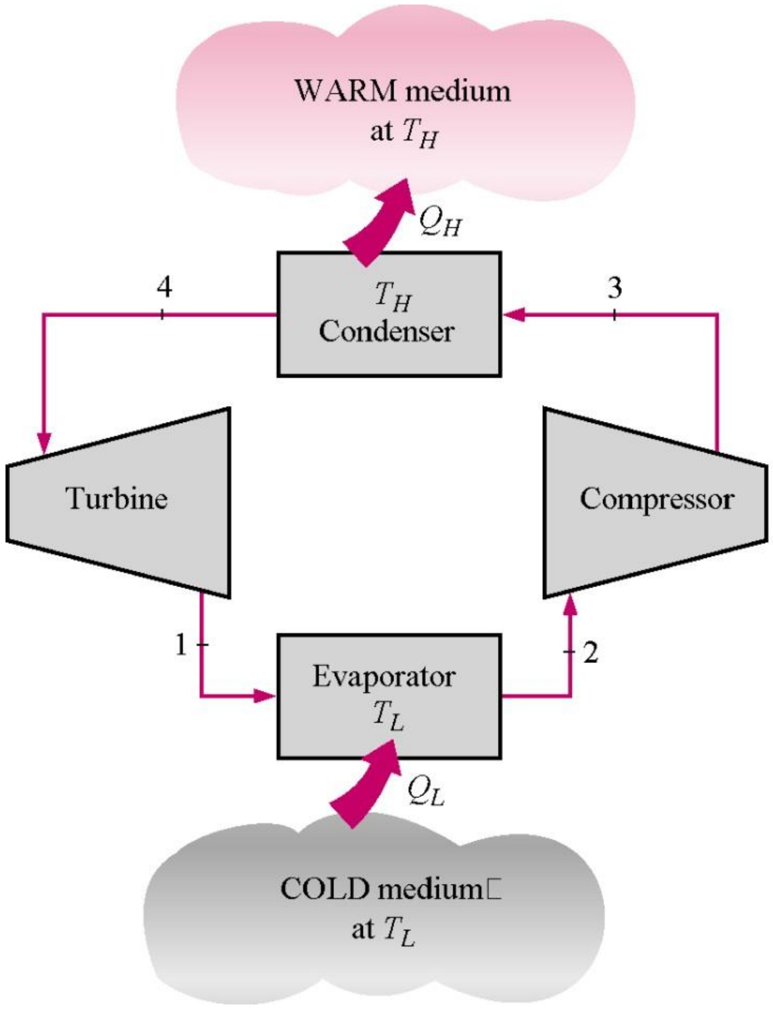
A refrigerator or a heat pump that operates on the reversed Carnot cycle is called a Carnot refrigerator or a Carnot heat pump, and their Coefficients of Performance are shown below

$$COP_{R,Carnot} = \frac{1}{T_H / T_L - 1} = \frac{T_L}{T_H - T_L}$$

$$COP_{HP,Carnot} = \frac{1}{1 - T_L / T_H} = \frac{T_H}{T_H - T_L}$$

Note: both *COP*s increase as the difference between the two temperatures decreases, that is as T_L rises or T_H falls.

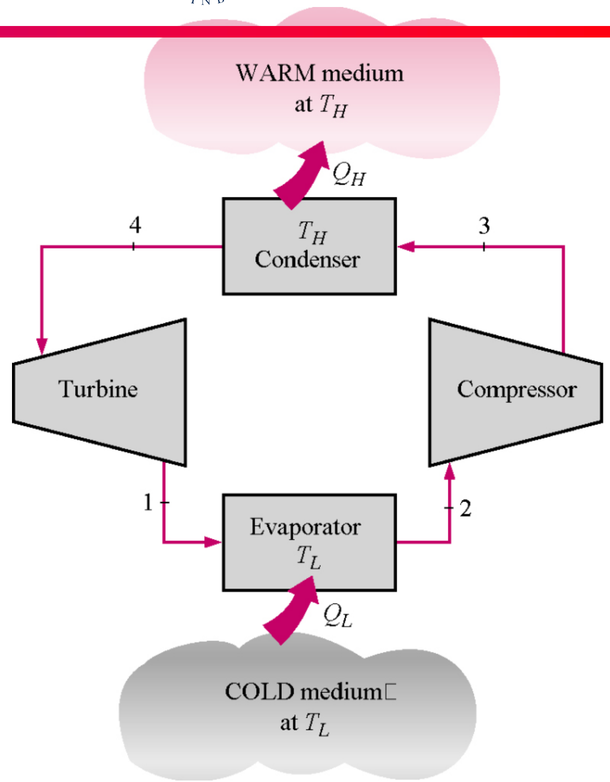
Also since a turbine is used for the expansion process between the high and low-temperatures, some of the work produced by the turbine can be used to supply work to the compressor.

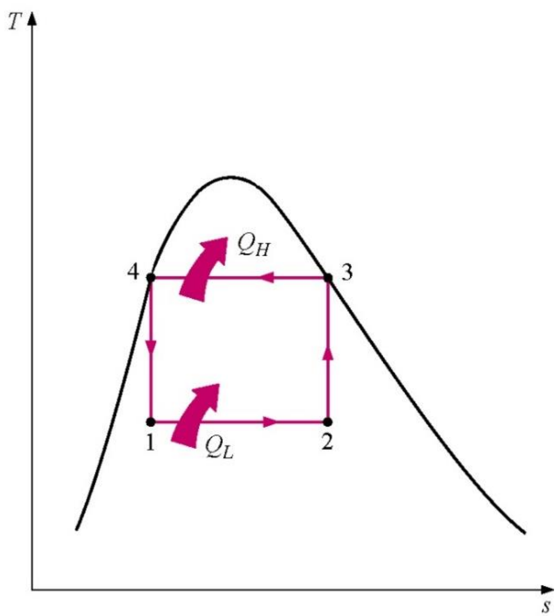


4.1 Refrigeration Cycle - Extra

Challenges for using a reversed Carnot cycle in reality

- Processes 1-2 and 3-4 can be approached closely in evaporators and condensers.
- Processes 2-3 and 4-1 cannot, however, be approximated closely in practice. Process 2-3 involves the compression of a liquid-vapour mixture which would require compression of two phases. Process 4-1 would involve the expansion of high-moisture refrigerant in a turbine. It is also cheaper to have irreversible expansion through an expansion valve rather than in a turbine





- The reversed Carnot cycle can be executed outside the saturated region to avoid these problems. But this would then make it difficult to maintain isothermal conditions during the heat-rejection (and possibly also heat-absorption) processes.
- Therefore we conclude that the reversed Carnot cycle cannot be approximated in real devices and is not a realistic model for refrigeration cycles. We can, however, compare real refrigeration cycles to it.