THERMODYNAMICS (MECHANICAL) 4

REVISION of Thermodynamics 2

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Content

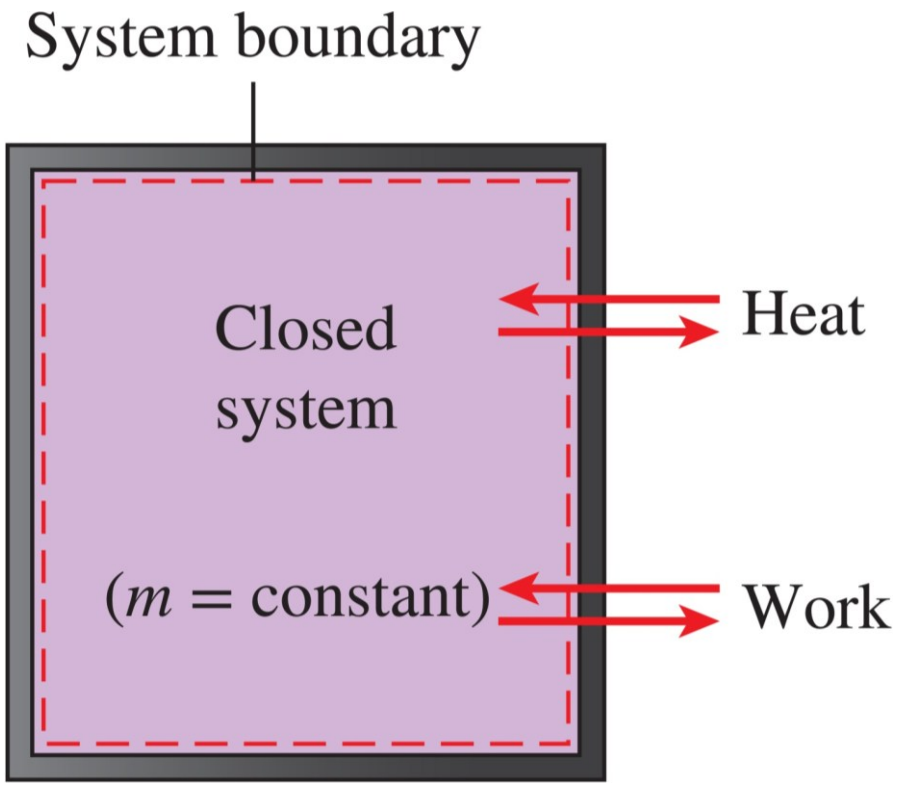
- Revision of key concepts from Thermodynamics 2*
- Initial examples illustrating some of these concepts

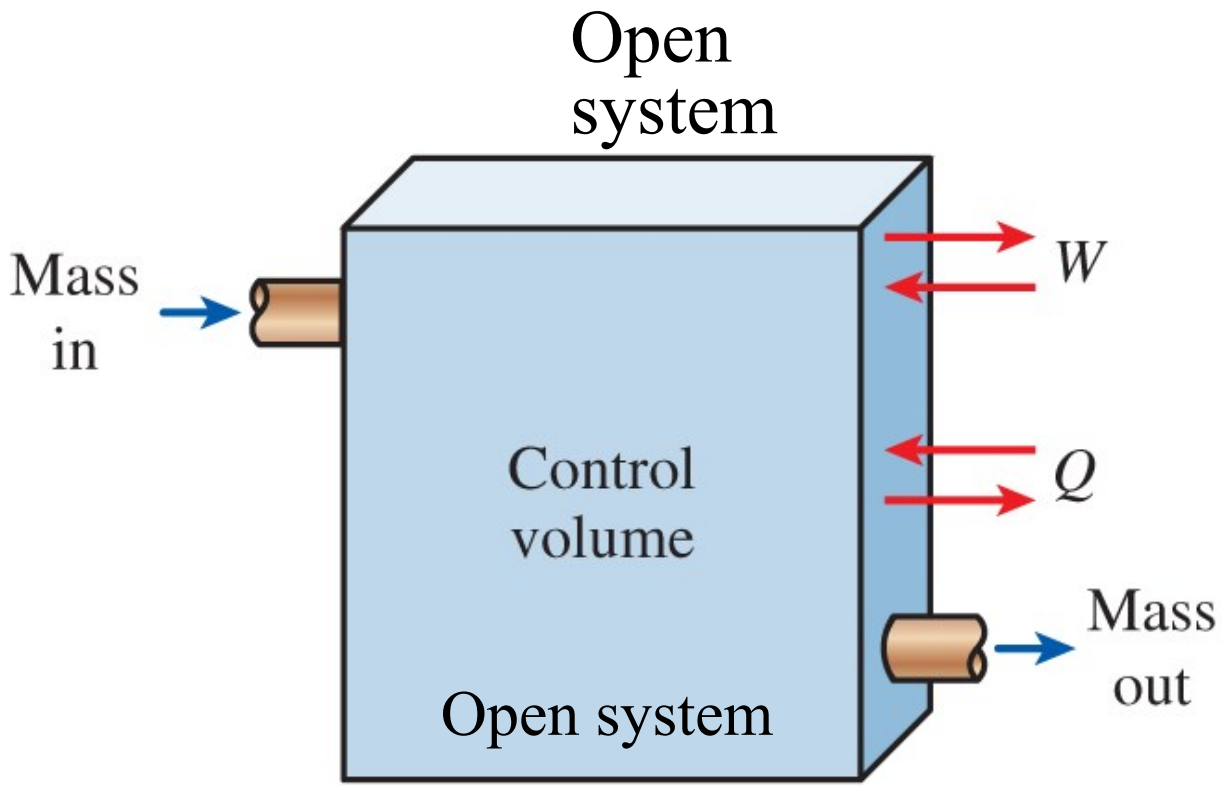
AIM

- Review/provide overview of material that is assumed background knowledge for this course

*The full Thermodynamics 2 lecture series is available on Learn

Systems Overview





- Conservation of mass
- Conservation of energy

$$\sum_{\text{in}} \dot{m} = \sum_{\text{out}} \dot{m}$$

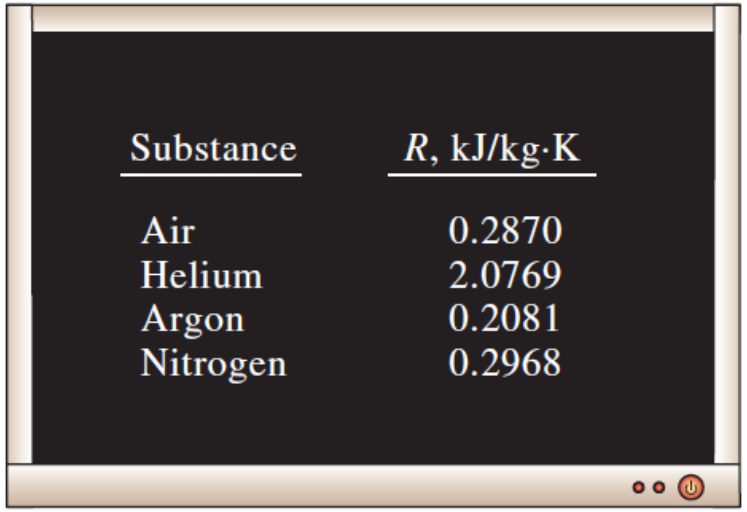
Ideal Gas - Equation of State

- Equation of State gives relationship between the state variables, temperature, pressure, and specific volume
- Know when ideal gas equation of state is appropriate

$$P = R\left(\frac{T}{v}\right) \qquad Pv = RT \qquad P = \rho RT$$

$$PV = mRT \qquad R = \frac{R_u}{M} \quad \text{(kJ/kg·K)}$$

- Be careful to use correct units



Substance	R, kJ/kg·K
Air	0.2870
Helium	2.0769
Argon	0.2081
Nitrogen	0.2968

Different substances have different gas constants

where R_u is the universal gas constant and M is the molar mass (molecular weight) of the gas. The constant R_u is the same for all substances, and its value is **8.31447 kJ/kmol·K**.

Dimension and Unit

International System of Units (SI): The Seven Base Quantities

Quantity	Dimension	Unit
Length	[L]	m
Mass (*m*)	[M]	kg
Time	[t]	s
Electrical Current Magnitude	[A]	A
Temperature (*T*)	[T]	K
Luminous intensity	[J]	cd
Amount of substance	[mol]	mol

Dimension and Unit

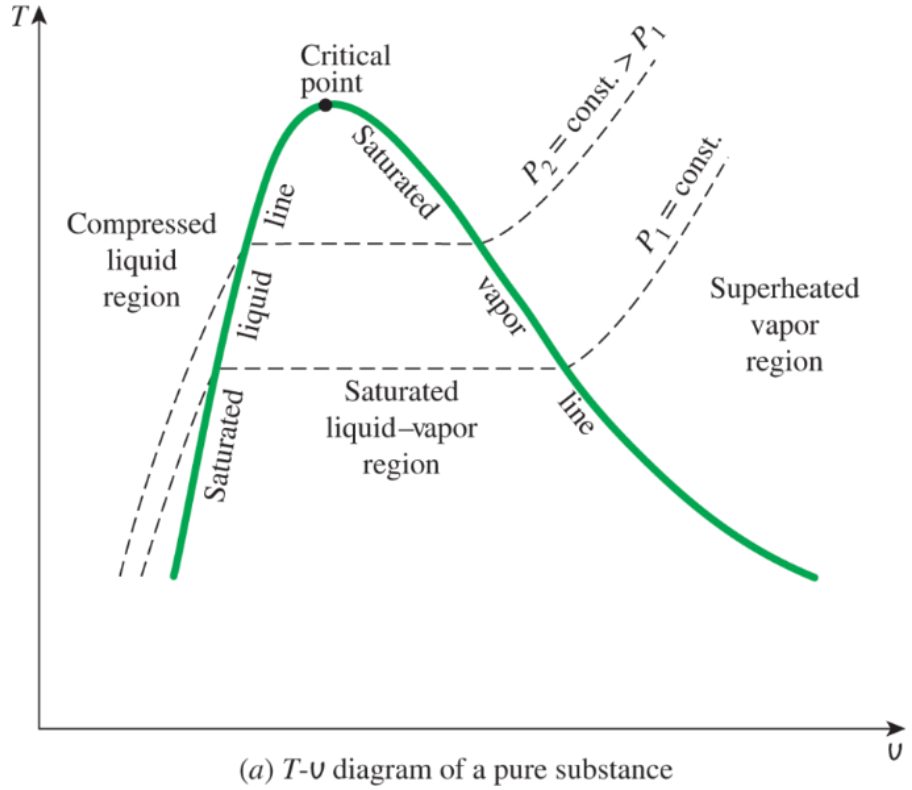
Important quantities derived from the 7 base quantities

Quantity	Dimension	Unit
Area (A)	$[L]^2$	m^2
Volume (V)	$[L]^3$	m^3
Specific Volume (v)	$[L]^3\,[mol]^{-1}$	$m^3\,mol^{-1}$
Molar density/Molar Volume	$[mol]\,[L]^{-3}$	$mol\,m^{-3}$
Mass Density (ρ)		$kg\,m^{-3}$
Concentration (c)	$[mol]\,[L]^{-3}$	$mol\,m^{-3}$
Velocity	$[L]\,[t]^{-1}$	$m\,s^{-1}$
Acceleration	$[L]\,[t]^{-2}$	$m\,s^{-2}$
Force (F)	$[M]\,[L]\,[t]^{-2}$	$N = kg\,m\,s^{-2}$
Pressure (P)	$[F]\,[L]^{-2}$	$Pa = N\,m^{-2} = kg\,m^{-1}\,s^{-2}$
Energy (W or Q)	$[F]\,[L]$	$J = N\,m = kg\,m^2\,s^{-2}$
Power ($\dot{W}$ or $\dot{Q}$)	$[F]\,[L]\,[t]$	$W = J\,s^{-1} = kg\,m^2\,s^{-3}$

'Fundamental' dimensions have a single symbol eg. [L], while derived dimensions are expressed as a combination of fundamental dimensions eg. [L/T], [L^2].

Phases and Property Tables

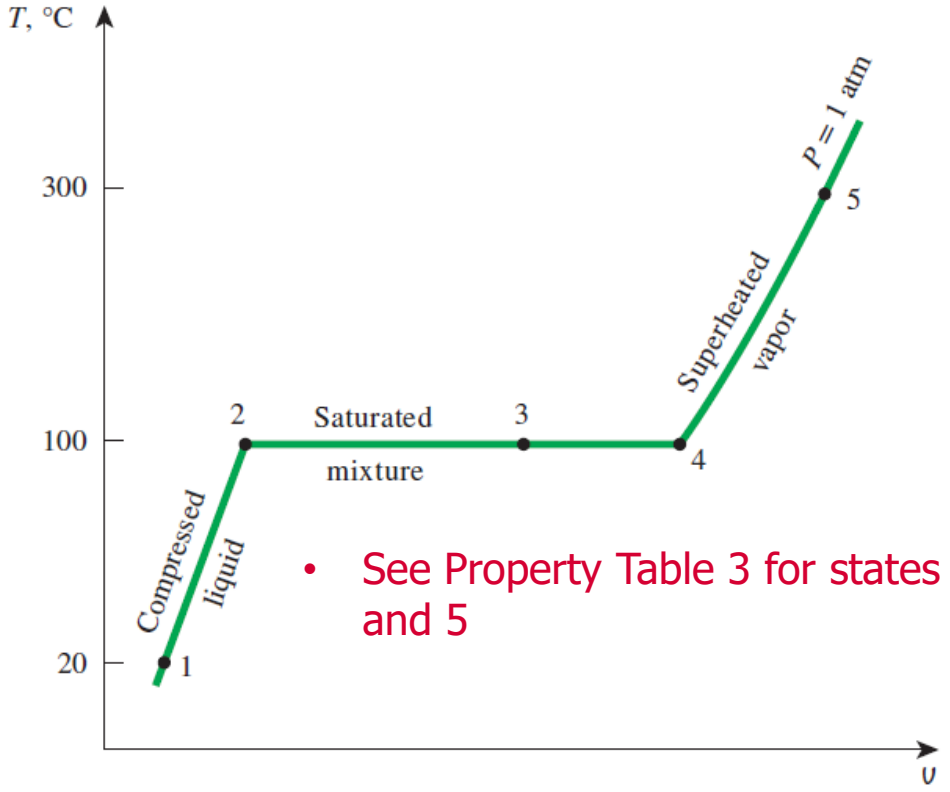
The correct table to use to find the thermodynamic properties of a real substance can be determined by comparing the known state properties to the properties in the saturation region once two independent properties are known.



(a) T-υ diagram of a pure substance

T-v diagram for the heating process of water at constant pressure

If the entire process between state 1 and 5 is reversed by cooling the water while maintaining the pressure at the same value, the water will go back to state 1, retracing the same path, and in so doing, the amount of heat released will exactly match the amount of heat added during the heating process.



- See Property Table 3 for states 1 and 5

Phases and Property Tables

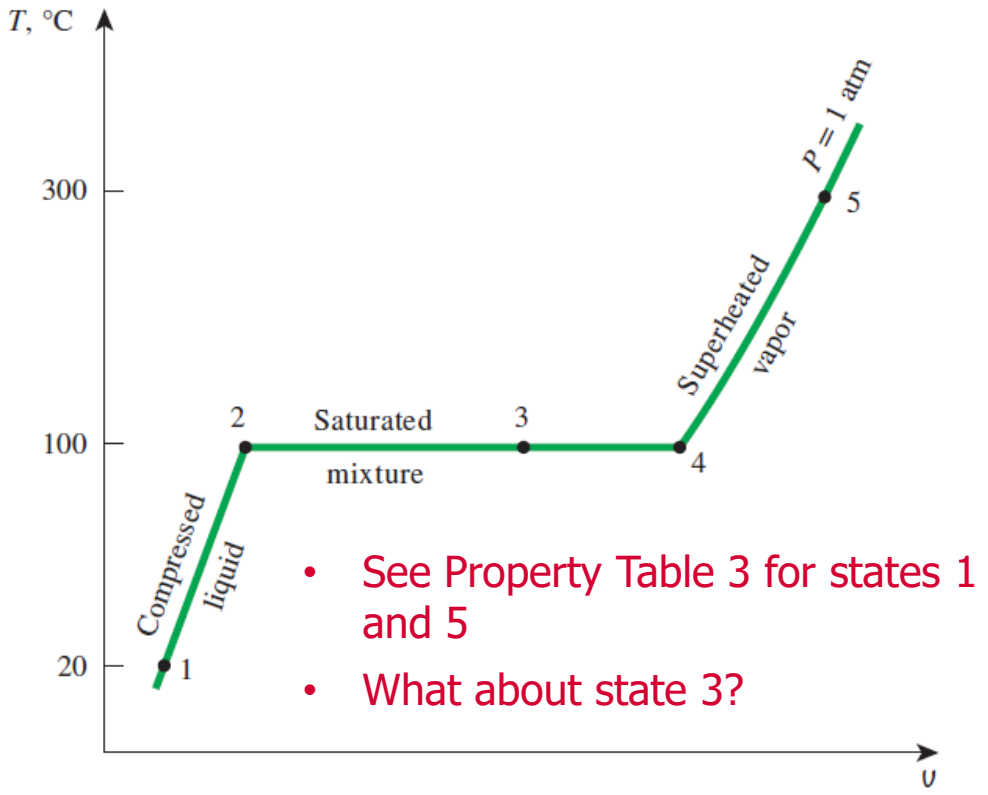
The correct table to use to find the thermodynamic properties of a real substance can be determined by comparing the known state properties to the properties in the saturation region once two independent properties are known.

Table 1: Saturated Water and Steam - Temperature (triple point to 100°C)

T	P	v_f	v_g	u_f	u_g	h_f	h_{fg}	h_g	s_f	s_g
°C	bar (abs)	m^3/kg	m^3/kg	kJ/kg	kJ/kg	kJ/kg	kJ/kg	kJ/kg	kJ/kgK	kJ/kgK
0.01	0.006117	0.001000	206.0	**0**	2374.9	0.0006118	2500.9	2500.9	**0**	9.155
1	0.006571	0.001000	192.4	4.18	2376.3	4.177	2498.6	2502.7	0.0153	9.129
2	0.007060	0.001000	179.8	8.39	2377.7	8.392	2496.2	2504.6	0.0306	9.103
3	0.007581	0.001000	168.0	12.60	2379.0	12.60	2493.8	2506.4	0.0459	9.076
4	0.008135	0.001000	157.1	16.81	2380.4	16.81	2491.4	2508.2	0.0611	9.051
5	0.008726	0.001000	147.0	21.02	2381.8	21.02	2489.1	2510.1	0.0763	9.025
6	0.009354	0.001000	137.6	25.22	2383.2	25.22	2486.7	2511.9	0.0913	8.999
7	0.01002	0.001000	128.9	29.42	2384.5	29.43	2484.3	2513.7	0.1064	8.974
8	0.01073	0.001000	120.8	33.62	2385.9	33.63	2481.9	2515.6	0.1213	8.949
9	0.01148	0.001000	113.3	37.82	2387.3	37.82	2479.6	2517.4	0.1362	8.924
10	0.01228	0.001000	106.3	42.02	2388.7	42.02	2477.2	2519.2	0.1511	8.900
11	0.01313	0.001000	99.79	46.21	2390.0	46.22	2474.8	2521.1	0.1659	8.876
12	0.01403	0.001001	93.72	50.41	2391.4	50.41	2472.5	2522.9	0.1806	8.851
13	0.01498	0.001001	88.07	54.60	2392.8	54.60	2470.1	2524.7	0.1953	8.828
92	0.7568	0.001037	2.198	385.3	2496.4	385.4	2277.4	2662.8	1.216	7.453
94	0.8154	0.001039	2.050	393.7	2498.8	393.8	2272.2	2666.0	1.239	7.427
96	0.8777	0.001040	1.914	402.1	2501.2	402.2	2267.0	2669.2	1.262	7.403
98	0.9439	0.001042	1.788	410.6	2503.6	410.7	2261.7	2672.4	1.284	7.378
100	1.0142	0.001043	1.672	419.0	2506.0	419.1	2256.5	2675.6	1.307	7.354

T-v diagram for the heating process of water at constant pressure

If the entire process between state 1 and 5 is reversed by cooling the water while maintaining the pressure at the same value, the water will go back to state 1, retracing the same path, and in so doing, the amount of heat released will exactly match the amount of heat added during the heating process.



- See Property Table 3 for states 1 and 5
- What about state 3?

Saturated Liquid-Vapour Mixture

Quality, x : The ratio of the mass of vapour to the total mass of the mixture. Quality is between 0 and 1 **(0: sat. liquid, 1: sat. vapour).**

The properties of the saturated liquid are the same whether it exists alone or in a mixture with saturated vapour.

$$x = \frac{m_{\text{vapour}}}{m_{\text{total}}} \qquad m_{\text{total}} = m_{\text{liquid}} + m_{\text{vapour}} = m_f + m_g$$

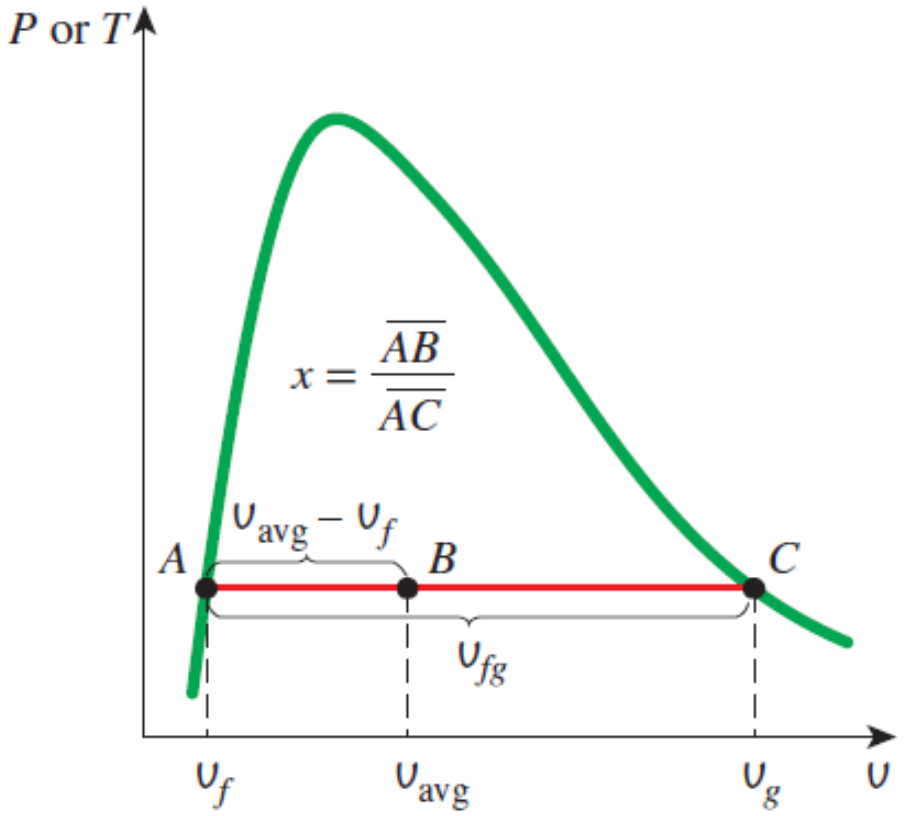
$$v_{avg} = (1-x)v_f + xv_g = v_f + xv_{fg} \qquad v_{fg} = v_g - v_f$$

Similarly,

$$u_{\text{avg}} = u_f + xu_{fg}$$

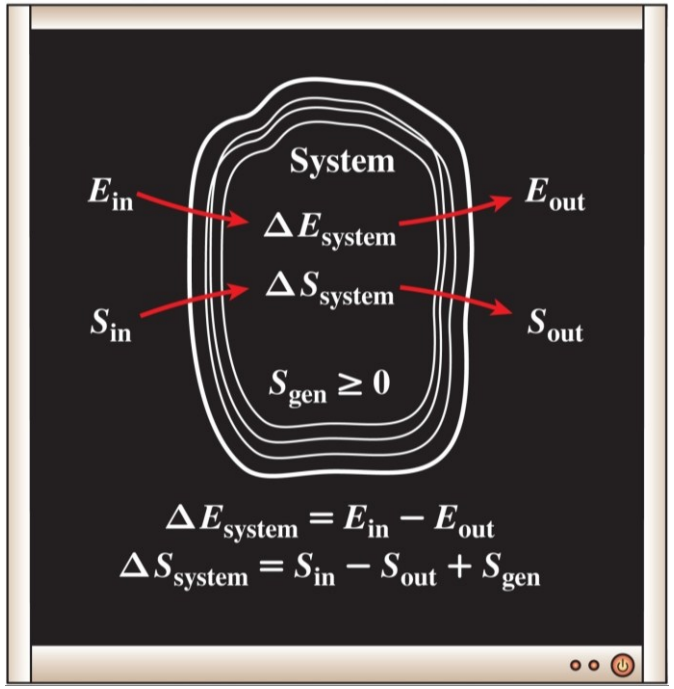
$$h_{\text{avg}} = h_f + xh_{fg}$$

The subscript “avg” (for “average”) is usually dropped for simplicity.



2nd Law of Thermodynamics and Entropy

- $\Delta S_{system} = \oint \frac{dQ}{T} + S_{gen}\,;\; S_{gen} = \Delta S_{total} = \Delta S_{sys} + \Delta S_{surr} \geq 0$
- Understand difference between the system and the surroundings
  - Does heat transfer cross the system boundary to the surroundings?
- Know when you can neglect a given term
  - Reversible, Adiabatic, Isentropic
- Use isentropic relations (ideal gas or pure substance)
- Identify irreversible processes. Why are they irreversible?
- What is the difference between internally reversible vs. externally reversible?



Entropy balance: *The entropy change of a system during a process is equal to the net entropy transfer through the system boundary and the entropy generated within the system.*

2nd Law of Thermodynamics and Entropy

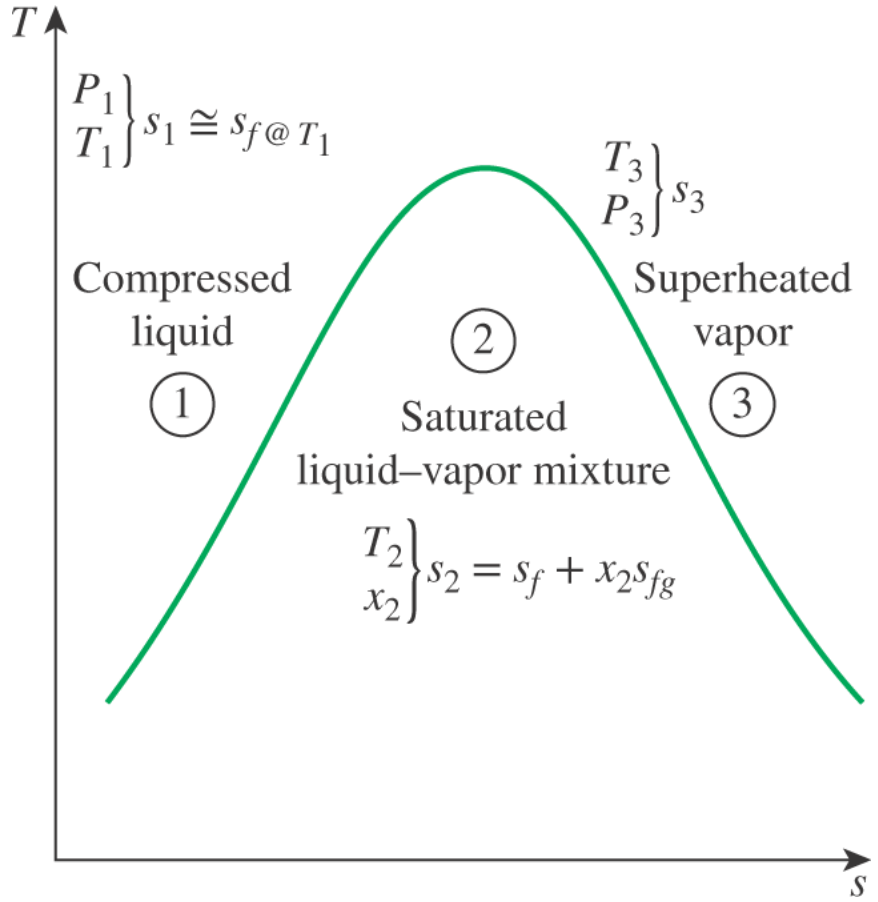
- Entropy is a property, and thus the value of entropy of a system is fixed once the state of the system is fixed.

$$s = s_f + xs_{fg} \quad \text{(kJ/kg·K)}$$

$$s_{@\,T,P} \cong s_{f\,@\,T} \quad \text{(kJ/kg·K)}$$

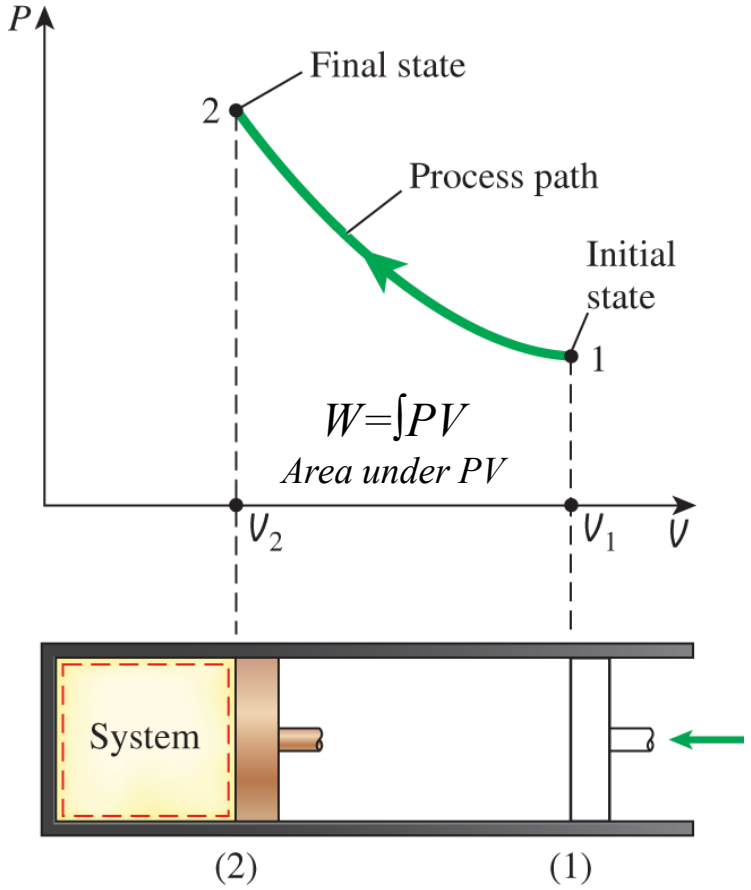
Entropy change

$$\Delta S = m\Delta s = m(s_2 - s_1) \quad \text{(kJ/K)}$$

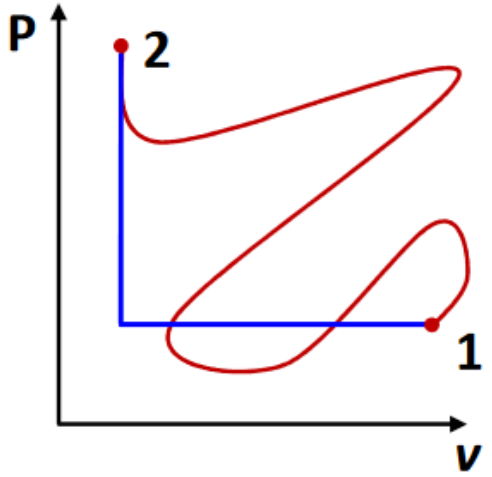


Entropy change of pure substances - determined from the tables (like other properties).

Processes



SCEE08006:
Engineering Thermodynamics 2

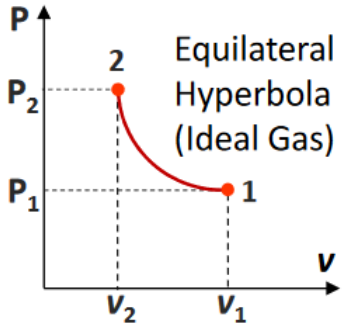


- State is independent of the process path
- Process path often defines the energy involved in the process

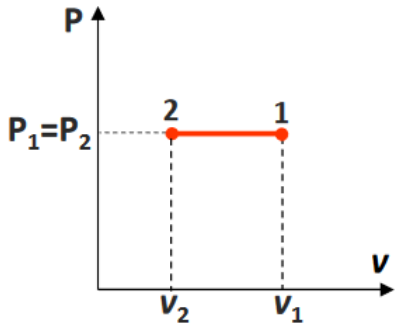
Processes

- Isobaric, isothermal, isochoric, and isentropic process
  - The prefix ***iso***- is often used to designate a process for which a particular property remains constant. An **isothermal process**, for example, is a process during which the temperature *T* remains constant; an **isobaric process** is a process during which the pressure *P* remains constant; and an **isochoric** (or **isometric**) **process** is a process during which the specific volume *v* remains constant.

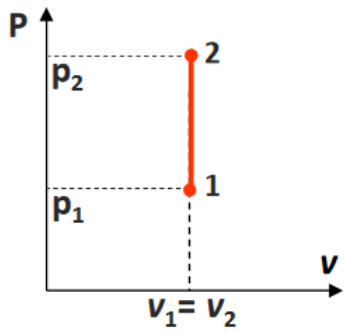
ISOTHERM



ISOBAR



ISOCHOR



Isentropic = adiabatic + reversible

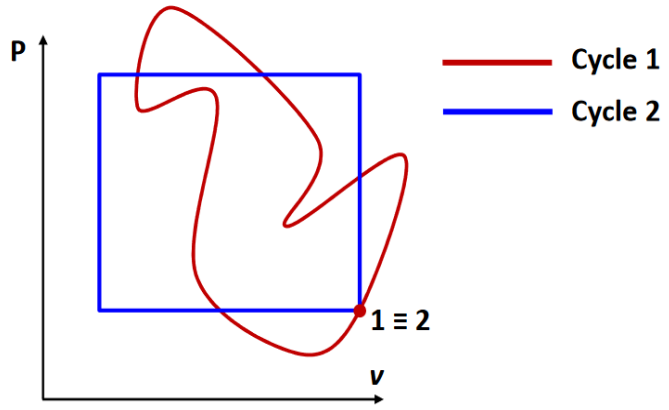
Cycles

- A system is said to have undergone a **cycle** if it returns to its initial state at the end of the process. That is, for a cycle the initial and final states are identical.
- We will assume you are already familiar with and can analyse (see tutorial examples)
  - Carnot cycle
  - Ideal Brayton cycle (also Otto and Diesel)
  - Ideal Rankine cycle
  - Ideal vapour compression refrigeration cycle
- Identify each process
  - When is worked performed?
  - When is heat added / rejected?
  - Where is entropy generated?

THERMODYNAMIC CYCLES

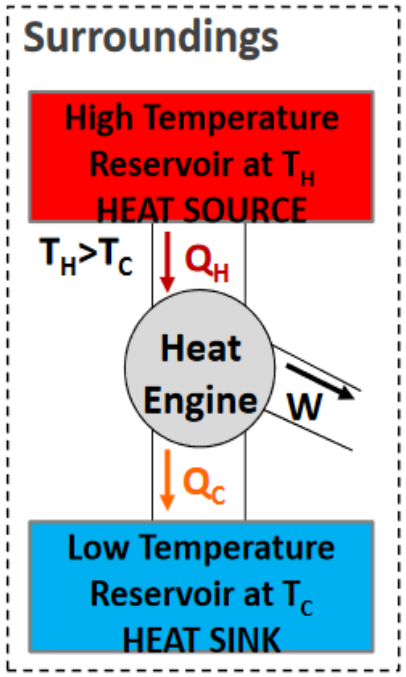
A Thermodynamic Cycle is composed by a sequence of interlinked thermodynamic transformations that start from an initial thermodynamic state (1) and end in a final thermodynamic state (2) where (1) ≡ (2).

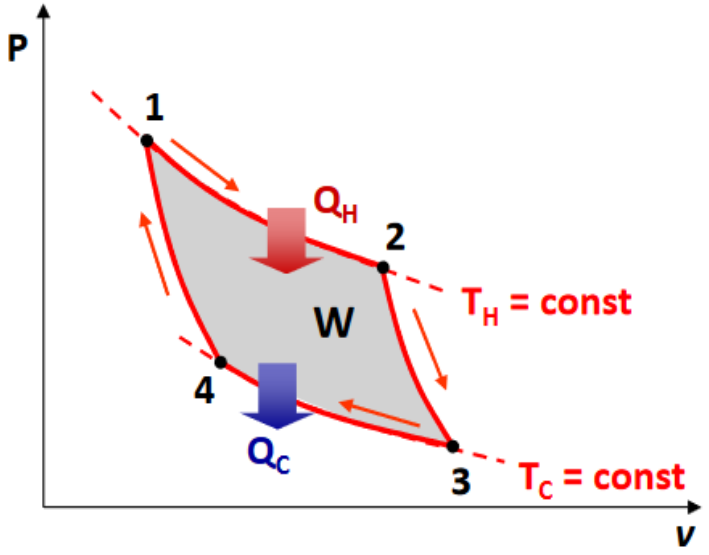
Example:



Carnot Cycle

CARNOT CYCLE (direct)





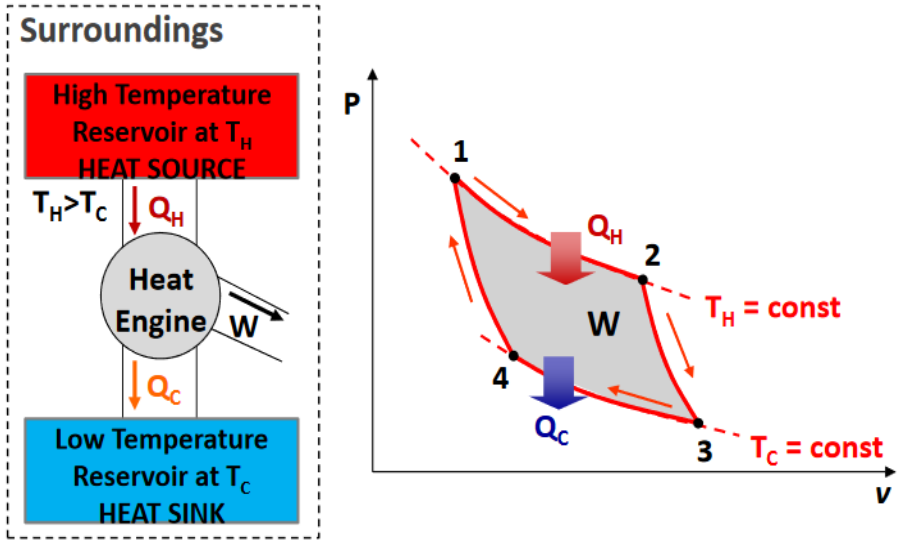
The cycle absorbs heat Q_H at temperature T_H (isotherm) and releases heat Q_2 at temperature T_C (isotherm). In the 2nd law statement heat is not transferred to any reservoir at intermediate temperature, therefore the remaining two transformations have to be adiabatic.

At constant W, the ratio $|Q_C|/|Q_H|$ is independent of the particular working fluid, P and *v*. The ratio $|Q_C|/|Q_H|$ only depends on the temperatures of the two isotherms.

$$\frac{|Q_C|}{|Q_H|} = f(T_C, T_H)$$

Carnot Cycle

- The Carnot cycle is a cycle in which each of its processes is reversible.
- A Carnot heat engine is the theoretical heat engine that operates on a Carnot cycle.
- Processes of a Carnot cycle:
  - *Process 1-2, Reversible Isothermal Expansion, Q_H added at T_H*
  - *Process 2-3, Reversible Adiabatic Expansion*
  - *Process 3-4, Reversible Isothermal Compression, Q_L removed at T_L*
  - *Process 4-1, Reversible Adiabatic Compression*
- The Carnot cycle is the most efficient cycle operating between specified temperature limits.



The thermal efficiency of any reversible heat engine is called the Carnot efficiency and is given by

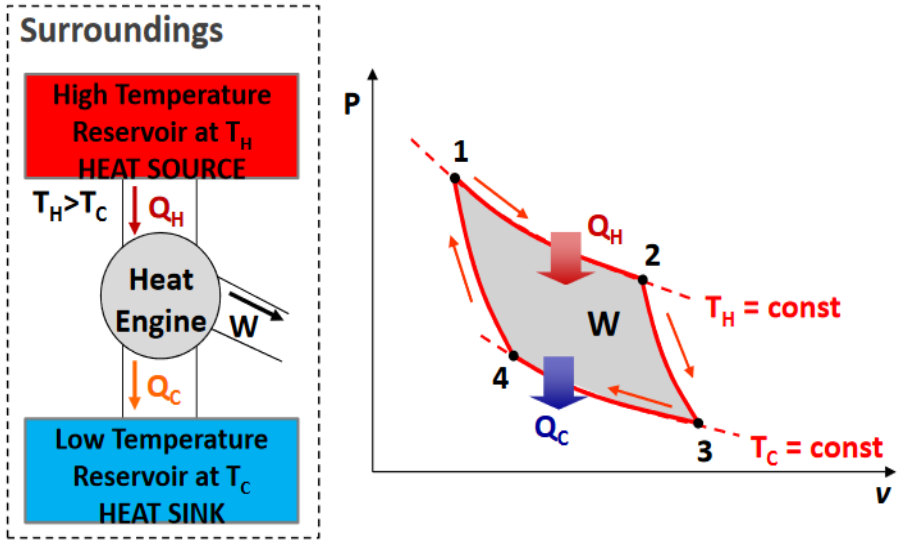
$$\eta_{th,rev} = 1 - T_C/T_H$$

where T_C and T_H are absolute temperatures.

Carnot Cycle

The Carnot Principles are:

1. The efficiency of an irreversible heat engine is always less than the efficiency of a reversible one operating between the same two temperature reservoirs.
2. The efficiencies of all reversible heat engines operating between the same two temperature reservoirs are the same.



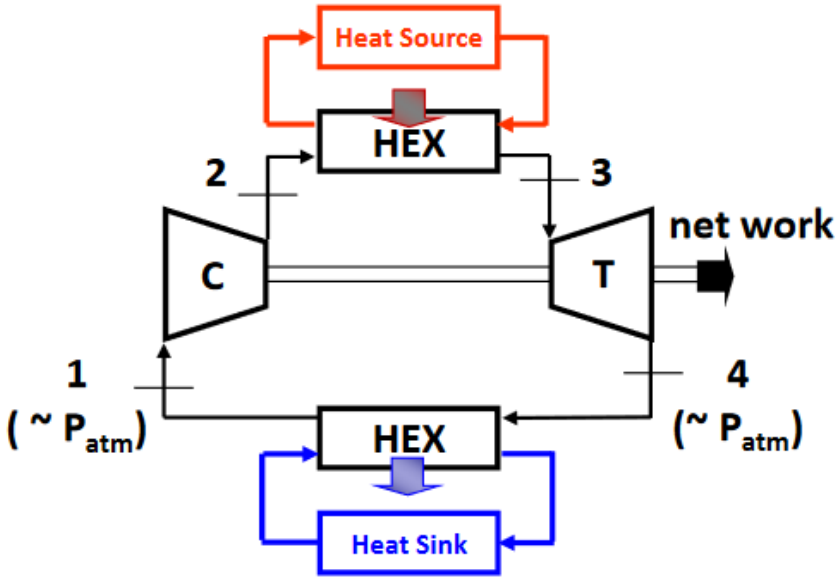
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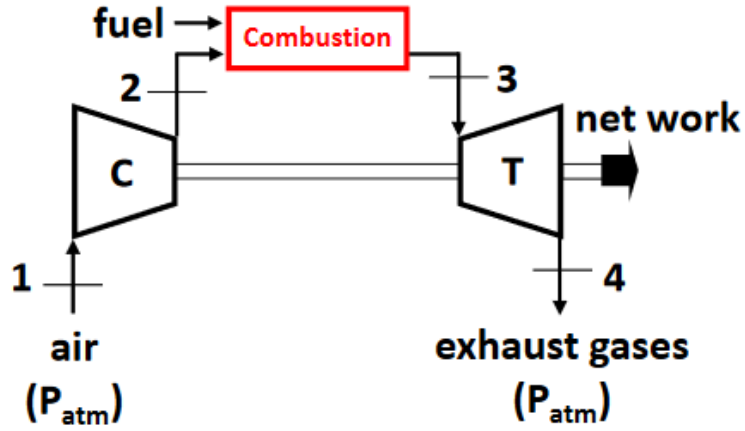
BRAYTON CYCLE

CLOSED CYCLE
(external combustion)



Low volumetric power density [MW_{el} m^{-3}] but being closed, a number of different working fluids can be used.

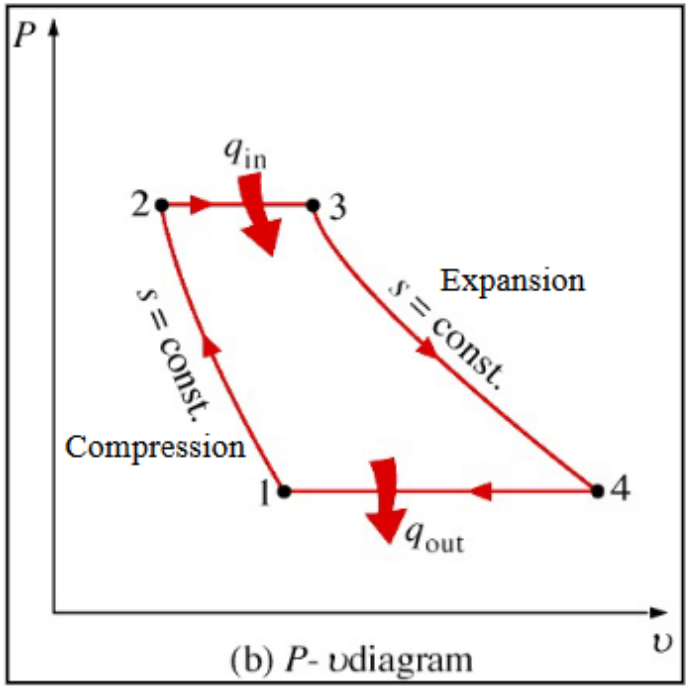
OPEN CYCLE
(internal combustion)



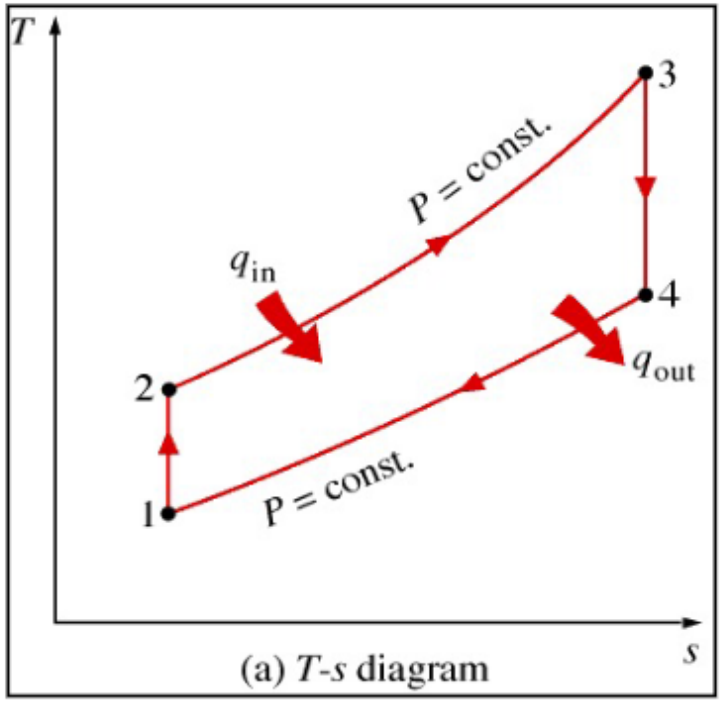
Less components → High Integration
→ High power density
Used mostly for aircraft propulsion.

Brayton Cycle - Processes.

- Brayton cycle is used as the standard with which to compare actual gas turbine engines.



(b) *P*- υdiagram

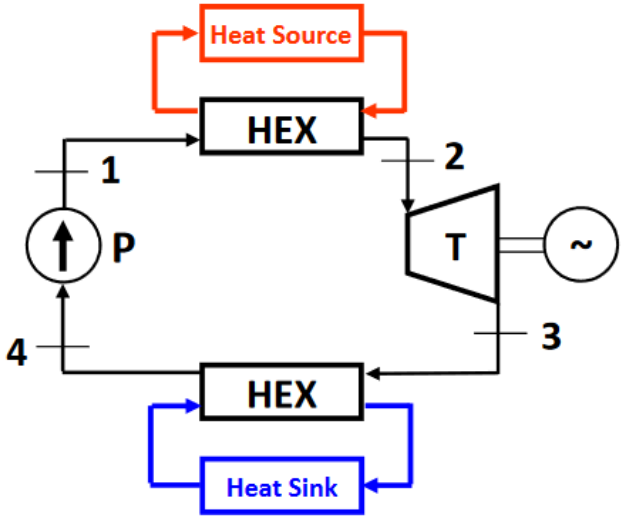


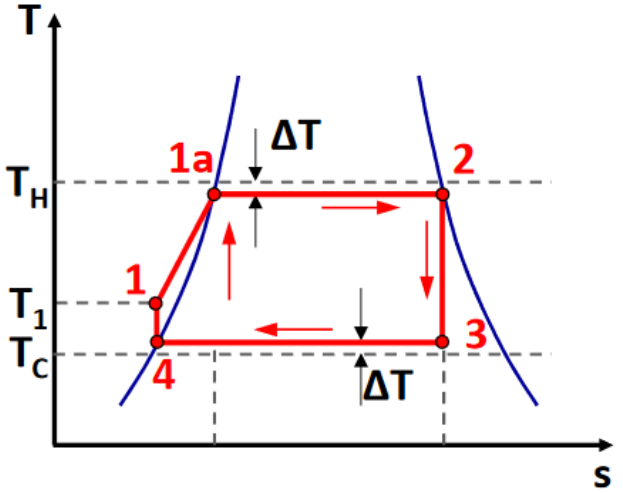
(a) *T*-*s* diagram

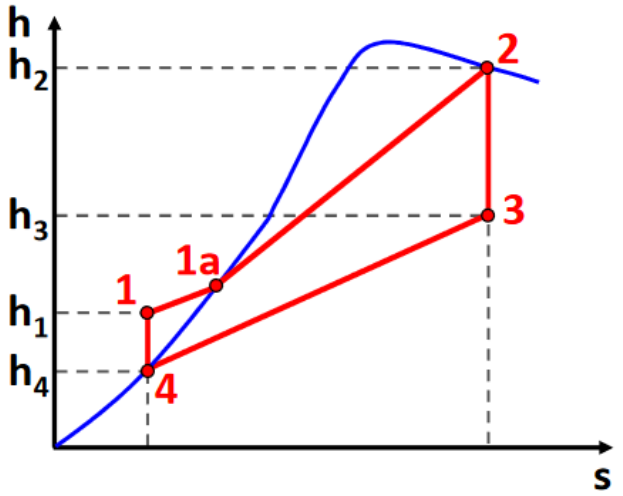
Note - All processes *reversible*

INTERNALLY REVERSIBLE RANKINE STEAM CYCLE

Let us overcome the issues with the compression by doing it in the liquid phase. Transformation 1-4 is now a pumping. The cycle is not any longer bi-thermal → loss of efficiency.



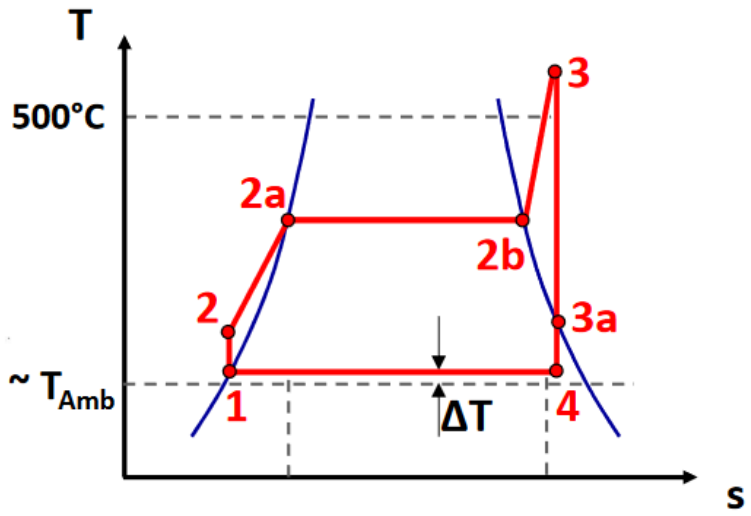


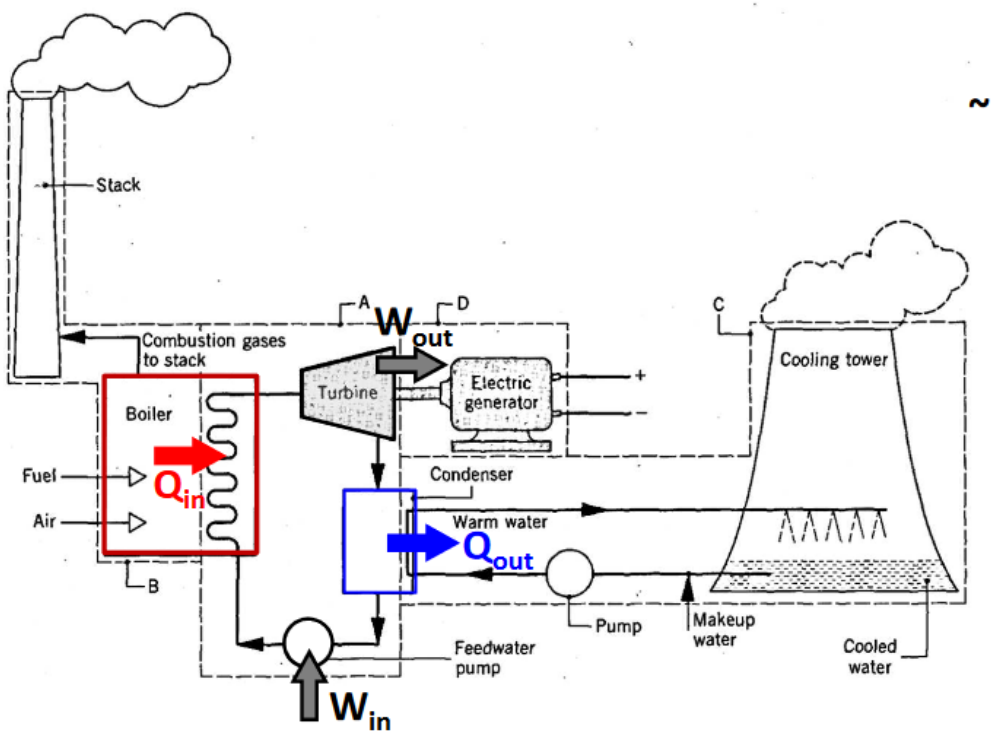


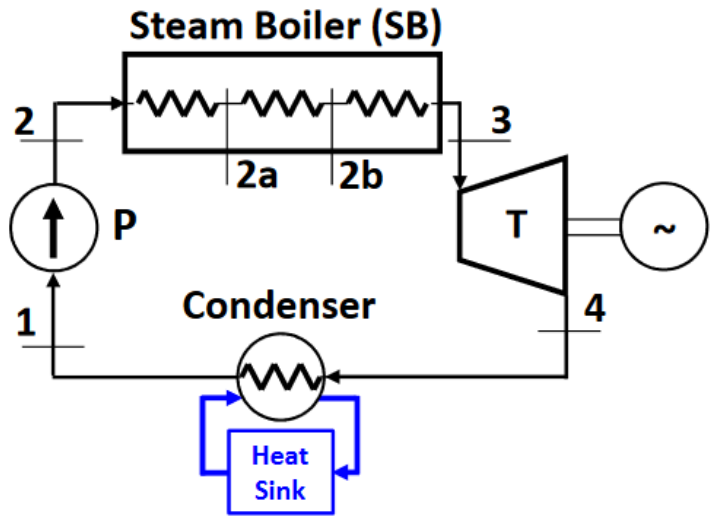
NOTE: A process is *internally reversible* if no irreversibilities occur within the boundaries of the system during the process.
A process is *externally reversible* if no irreversibilities occur outside the boundaries of the system during the process.

HIRN CYCLE OR SUPERHEATED-VAPOUR RANKINE CYCLE

The Hirn Cycle solves also the issues with the liquid expansion in the turbine.

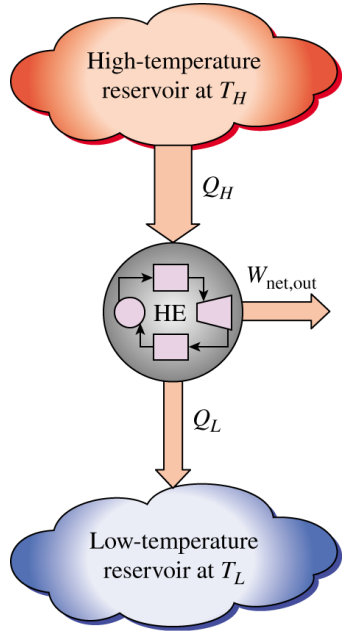




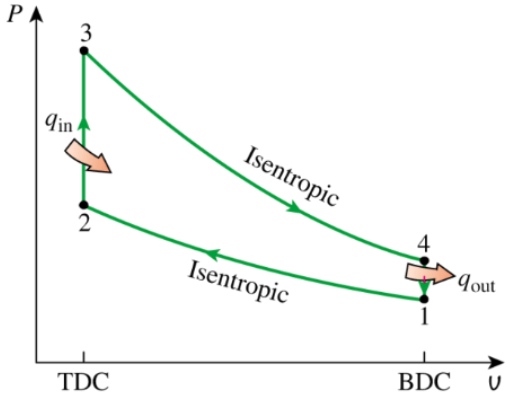


Cycle Performance

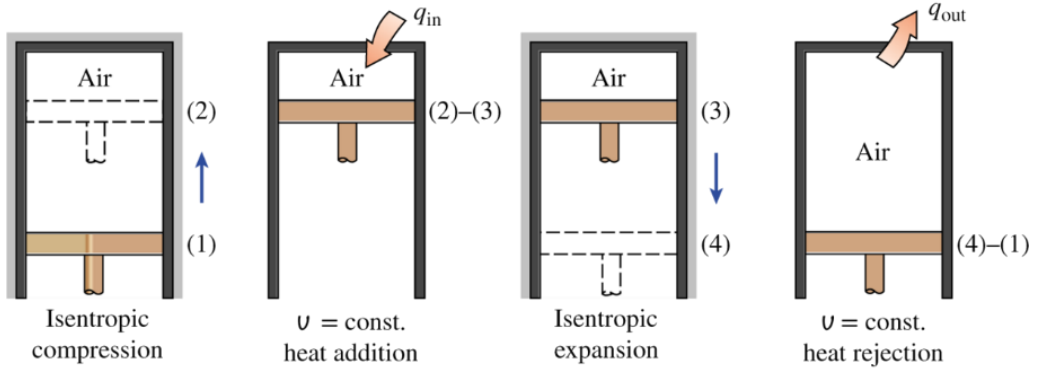
- Efficiency = what you want / what you pay for
- For heat engine, Brayton and Rankine cycles, etc…
- WORK output is desired
- Efficiency:
  - $\eta_{th} = \frac{\dot{W}_{net,\,out}}{\dot{Q}_{in}}$
  - $\eta_{th} < 100\%$



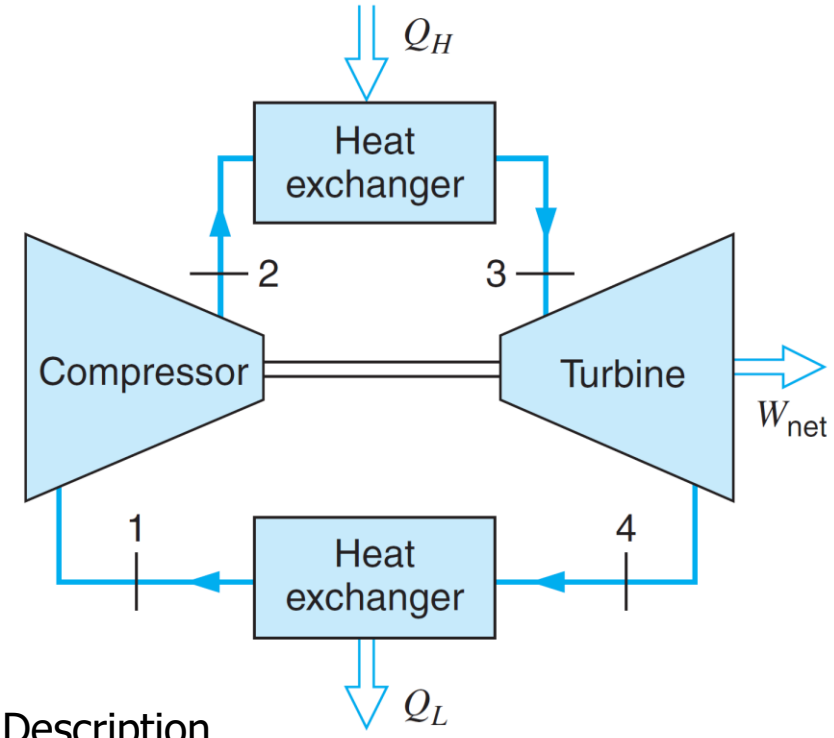
Schematic of a heat engine

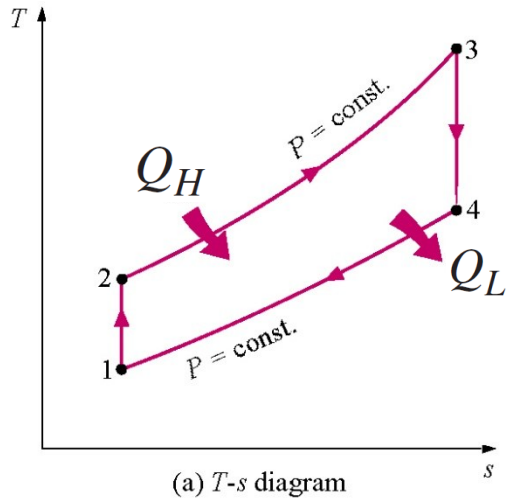


Ideal Otto cycle

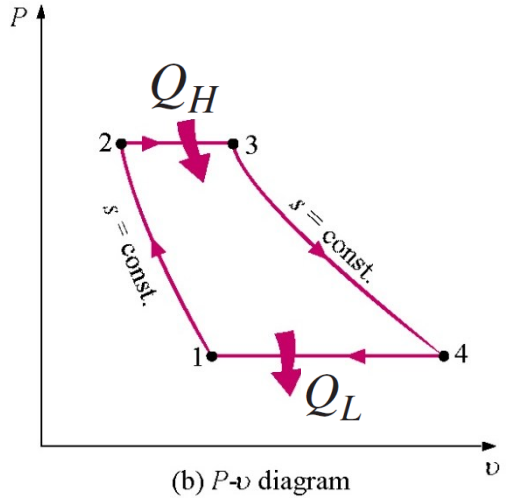


Closed Brayton Cycle (example)





(a) T-s diagram



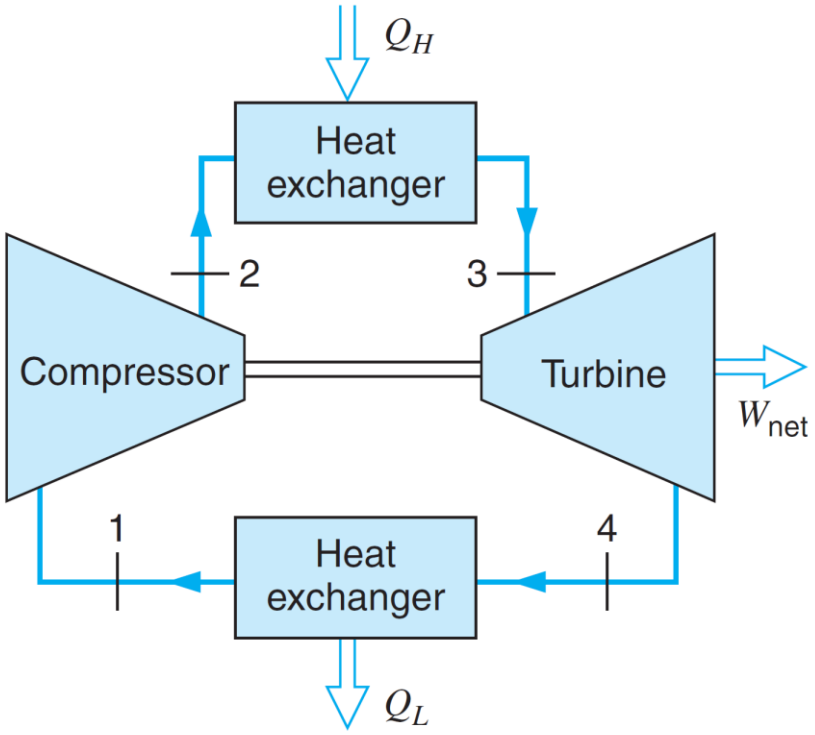
(b) P-υ diagram

Process	Description
1-2	Isentropic compression (in a compressor)
2-3	Constant pressure heat addition (in a heat exchanger)
3-4	Isentropic expansion (in a turbine)
4-1	Constant pressure heat rejection (in a heat exchanger)

Processes 1-2 and 3-4 are isentropic, and $P_2 = P_3$ and $P_4 = P_1$. The **ideal gas isentropic relations** are

$$\frac{T_2}{T_1} = \left(\frac{P_2}{P_1}\right)^{(k-1)/k} = \left(\frac{P_3}{P_4}\right)^{(k-1)/k} = \frac{T_3}{T_4}$$

Closed Brayton Cycle



To find Q_H (or Q_{in})

Apply the conservation of energy to process 2-3 for *P* = constant (no work), steady-flow, and neglect changes in kinetic and potential energies.

$$\dot{E}_{in} = \dot{E}_{out} \Rightarrow \dot{m}_2 h_2 + \dot{Q}_{in} = \dot{m}_3 h_3$$

The conservation of mass gives,

$$\dot{m}_{in} = \dot{m}_{out} \Rightarrow \dot{m}_2 = \dot{m}_3 = \dot{m}$$

$$\dot{Q}_{in} = \dot{m}(h_3 - h_2) = \dot{m}(C_{p,3}T_3 - C_{p,2}T_2)$$

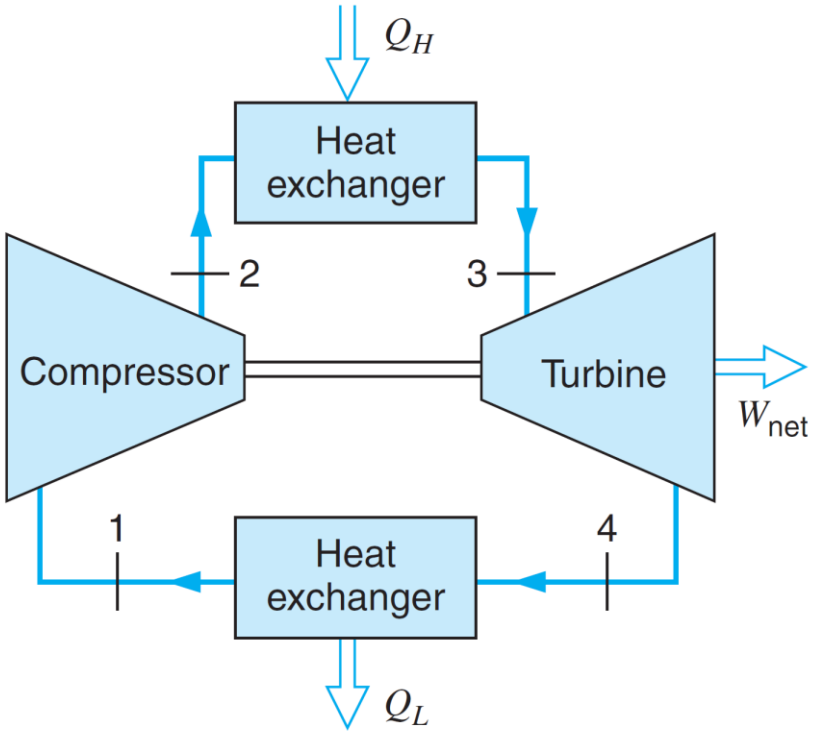
For constant specific heats,

$$\dot{Q}_{in} = \dot{m}C_p(T_3 - T_2)$$

The heat added per unit mass flow is

$$q_{in} = \frac{\dot{Q}_{in}}{\dot{m}} = C_p(T_3 - T_2)$$

Closed Brayton Cycle



$$q_{in} = \frac{\dot{Q}_{in}}{\dot{m}} = C_p(T_3 - T_2)$$

Numerical example:

P_1 = 1 bar and T_1 = 297 K

Maximum temperature (T_3) = 1400 K and P_2 = 12 bar

1 kg/s of air (C_p = 1.005 kJ/kg·K; k = 1.4)

$$T_2 := T_1 \cdot \left(\frac{P_2}{P_1}\right)^{\frac{k-1}{k}} = 604\,K$$

$$T_3 = 1400\,K \qquad \text{given in the data}$$

$$q_{in} := 1.005\,\frac{kJ}{kg \cdot K}(1400K - 604K)$$

$$q_{in} = 800\,\frac{kJ}{kg}$$

To find Q_L (or Q_{out})

The conservation of energy for process 4-1 with constant specific heats gives:

$$\dot{Q}_{out} = \dot{m}(h_4 - h_1) = \dot{m}C_p(T_4 - T_1)$$

$$q_{out} = \frac{\dot{Q}_{out}}{\dot{m}} = C_p(T_4 - T_1)$$

$$q_{out} := 1.005\,\frac{kJ}{kg\cdot K}\cdot(688K - 297K)$$

$$q_{out} = 393\,\frac{kJ}{kg}$$

Numerical example continued:

$$T_4 = T_3\cdot\left(\frac{P_4}{P_3}\right)^{\frac{k-1}{k}}$$

$$P_4 := P_1 = 1\,bar \qquad T_4 := 1400K\cdot\left(\frac{1bar}{12bar}\right)^{\frac{1.4-1}{1.4}}$$

$$P_3 := P_2 = 12\,bar \qquad T_4 = 688\,K$$

The net thermal efficiency can then be calculated

$$\eta_{th,\,Brayton} = 1 - \frac{\dot{Q}_{out}}{\dot{Q}_{in}} = 1 - \frac{q_{out}}{q_{in}}$$

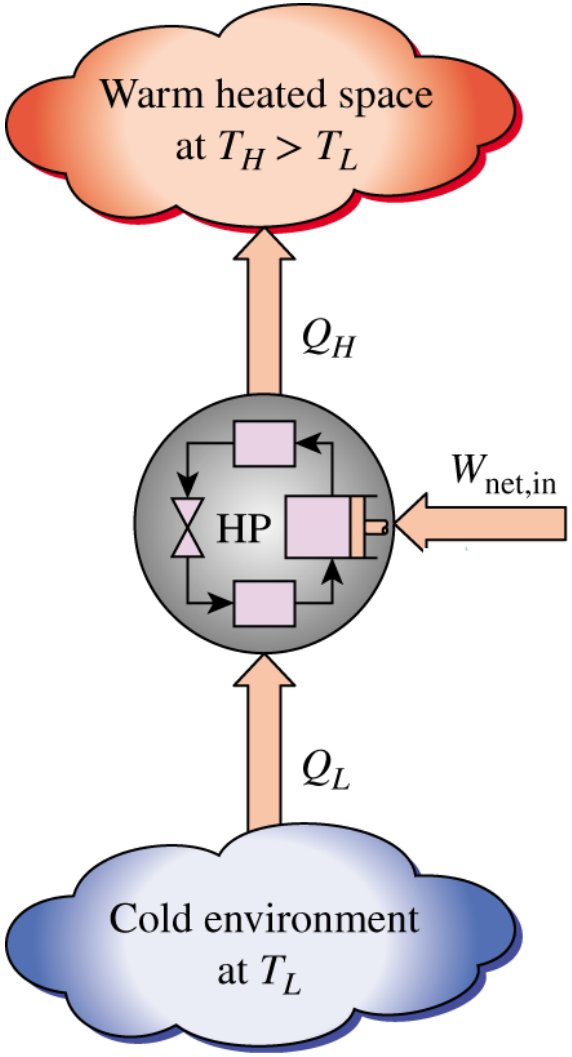
$$\eta_{th_Brayton} := 1 - \frac{393\,\frac{kJ}{kg}}{800\,\frac{kJ}{kg}}$$

$$\eta_{th_Brayton} = 0.509$$

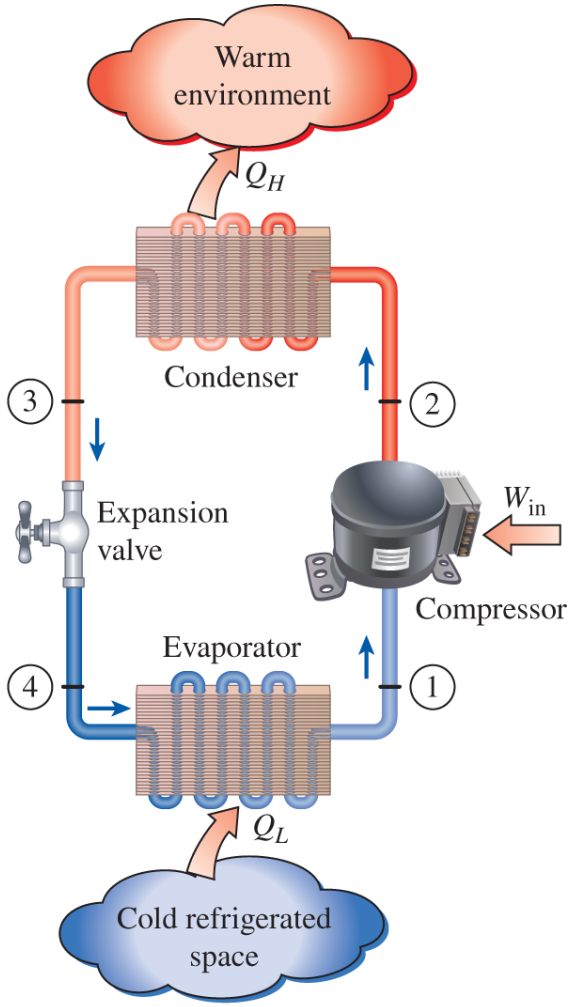
Heat Pumps/Refrigerators

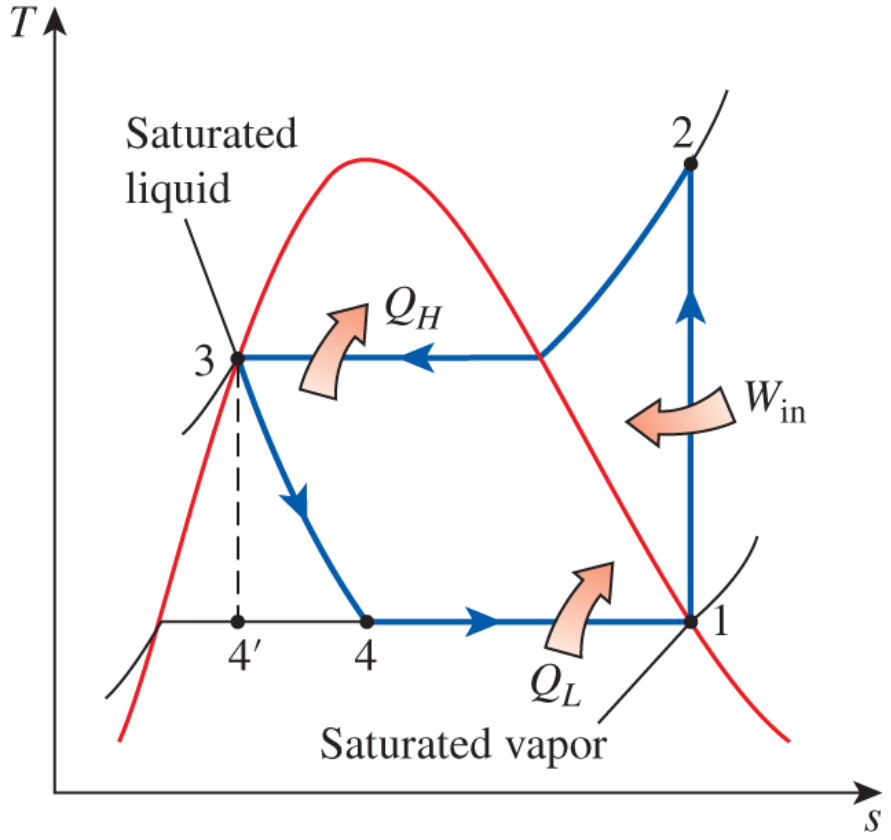
- HEAT transfer is desired
  - Either gain heat or remove heat

- Measure performance using COP:
  - $COP = \frac{\dot{Q}_{H,out}}{\dot{W}_{in}}$, heating mode
  - $COP = \frac{\dot{Q}_{L,in}}{\dot{W}_{in}}$, refrigeration mode
  - $COP > 1$



Ideal Vapour Compression Cycle





1-2 Isentropic compression in a compressor

2-3 Constant-pressure heat rejection in a condenser

3-4 Throttling in an expansion device

4-1 Constant-pressure heat absorption in an evaporator

Ideal Vapour Compression Cycle

Steady-flow energy balance

$$(q_{\text{in}} - q_{\text{out}}) + (w_{\text{in}} - w_{\text{out}}) = h_e - h_i$$

$$\text{COP}_R = \frac{q_L}{w_{\text{net, in}}} = \frac{h_1 - h_4}{h_2 - h_1}$$

$$\text{COP}_{HP} = \frac{q_H}{w_{\text{net, in}}} = \frac{h_2 - h_3}{h_2 - h_1}$$

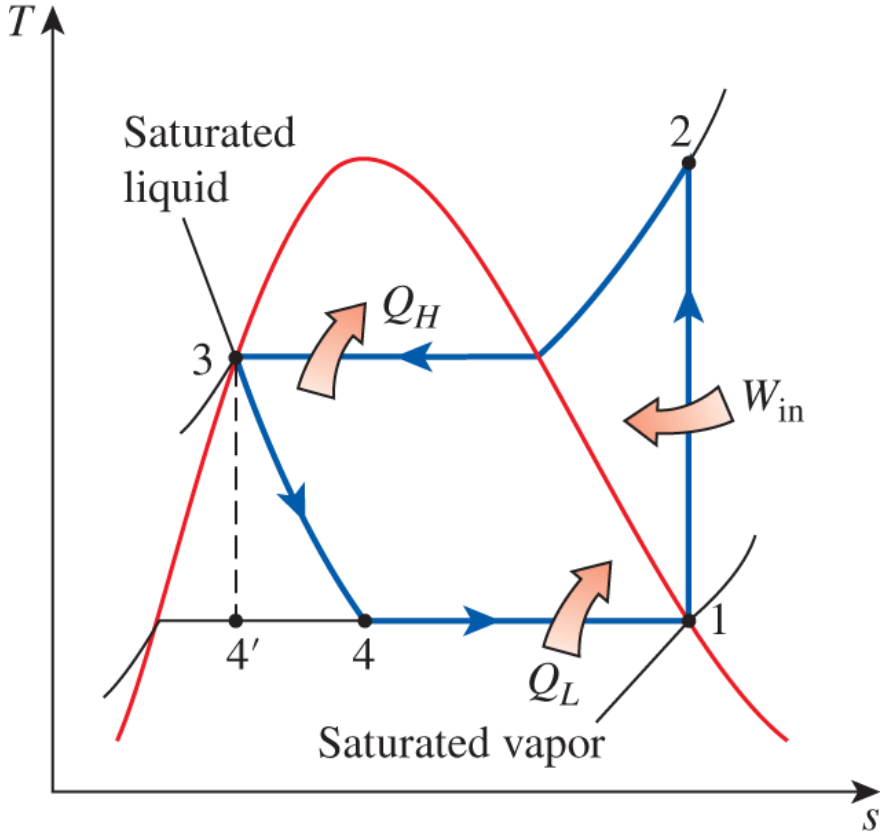
Note:

$$h_1 = h_{g\ @\ P_1}$$

$$h_3 = h_{f\ @\ P_3}$$

$$\dot{Q}_H = \dot{m}(h_2 - h_3)$$

$$\Rightarrow q_H = \frac{\dot{Q}_H}{\dot{m}} = (h_2 - h_3)$$

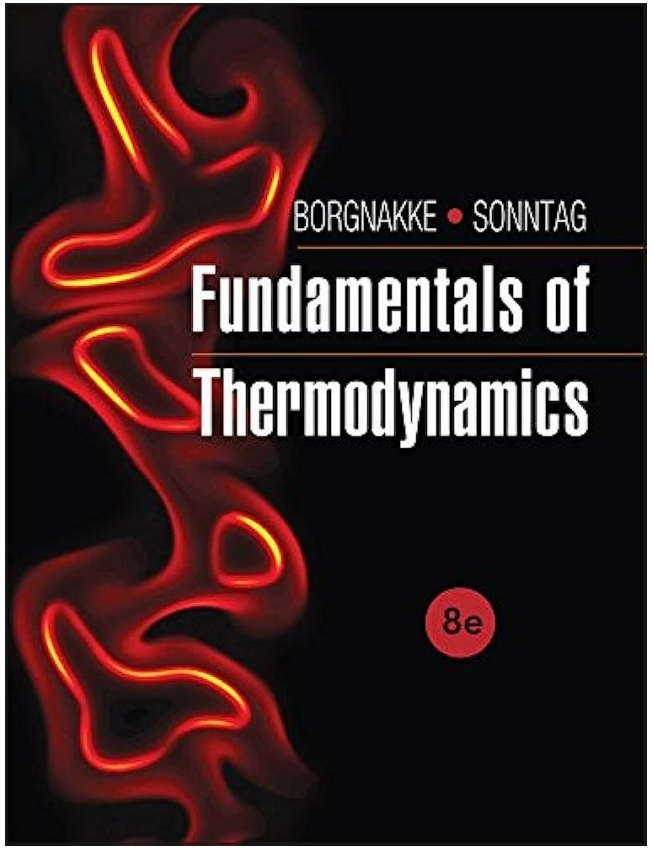


The ideal vapor-compression refrigeration cycle involves an irreversible (throttling) process to make it a more realistic model for the actual systems.

Replacing the expansion valve by a turbine is not practical since the added benefits cannot justify the added cost and complexity.

SUMMARY

- Course overview
- Strategies to succeed at Thermodynamics 4
- Revision of key concepts from Thermodynamics 2
  - Relevant chapters in Borgnakke and Sonntag (8th ed)
    - Chapters **1–7**
    - Sections **9.1–9.3** and **9.8–9.10**
    - Sections **10.1** and **10.2**
- What to do next
  - Go to Thermodynamics 2 on Learn and revise lecture slides on Thermodynamics 2
  - **Attempt tutorial sheet #1 of Thermodynamics 4**



NEXT: Gas turbines and Brayton cycle

Thanks for listening

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