King Fahd University of Petroleum & Minerals

Mechanical Engineering

Thermodynamics ME 204

BY

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My Office

- Office Hours: 12:00 – 01:00 am SMW
- 03:00 – 04:00 pm UT

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Outline

- Textbook
- Catalog Description
- Grading system
- Homework
- Attendance
- Exams

- What is thermodynamics
- Topics to be covered during the course
- Application Areas of Thermal-Fluid Sciences

Grading System

- 10% Homework / Design Project
- 20% Quizzes/ Class tests
- 20% Exam I
- 20% Exam II
- 30% Final Exam

(For unexcused absence, 0.5 mark will be deducted)

Homework

- Homework problems are 4-6 problems every week.
- All homework problems assigned during a given week are due in class one week later unless stated otherwise.
- Late Homework will NOT be accepted

Attendance

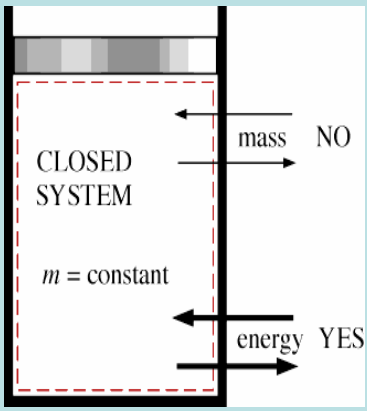
1. Attendance will be checked during each lecture.
2. Excuse should be authorized by the Deanship of Student Affairs and submitted one week later after resumption of class attendance.
3. For any unexcused absence, 0.5 marks will be deducted from the total grade.
4. Any student having more then 9 unexcused absences will receive a grade of DN for the course.

Review

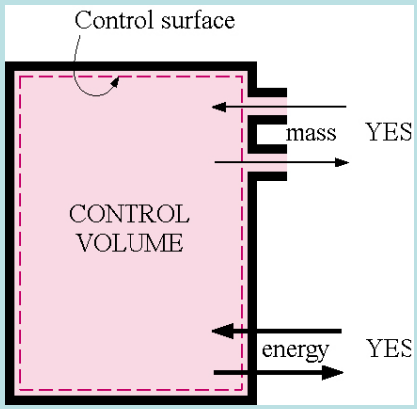
Basic Review of Thermodynamics I

Closed Systems vs. Open Systems

No mass can cross its boundary But energy can.

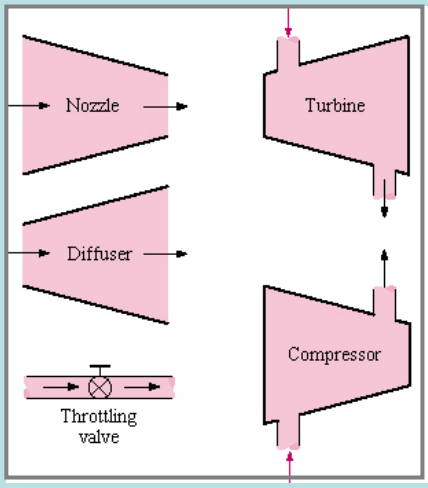


Both mass and energy can cross the boundaries of a control volume.

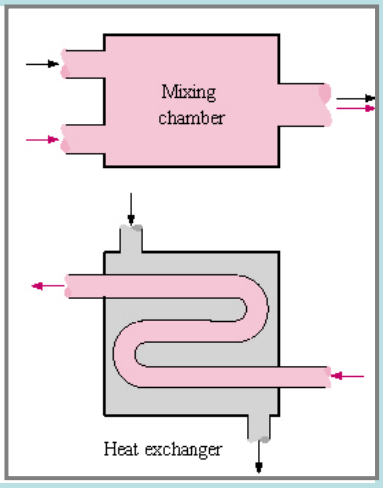


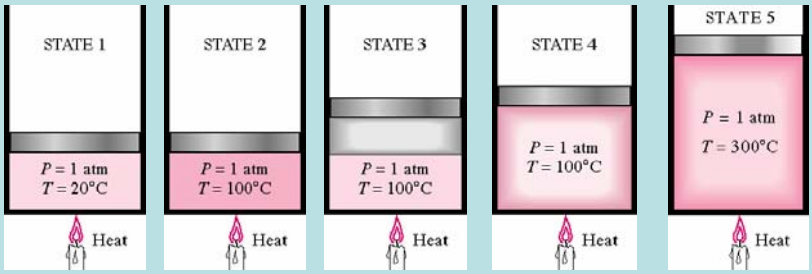
some common steady flow devices

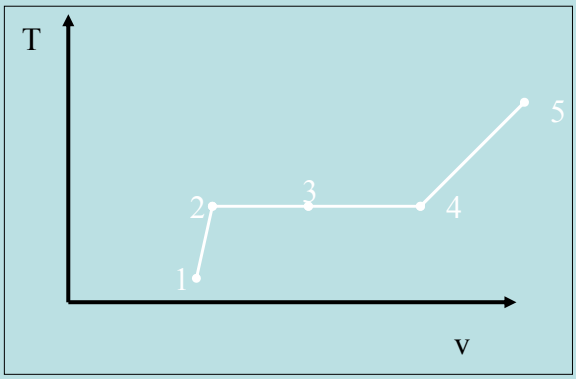
Only one in and one out



More than one inlet and exit



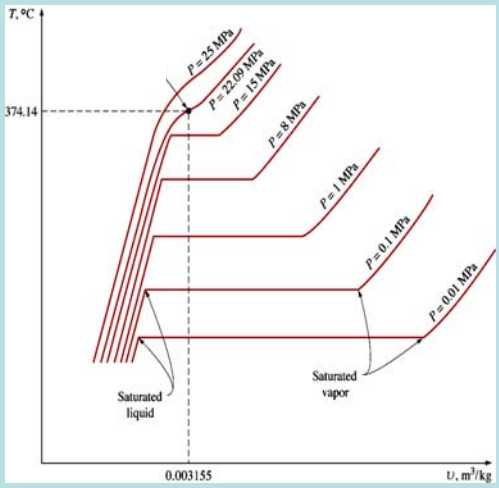




Phase Change Processes on a T-v diagram

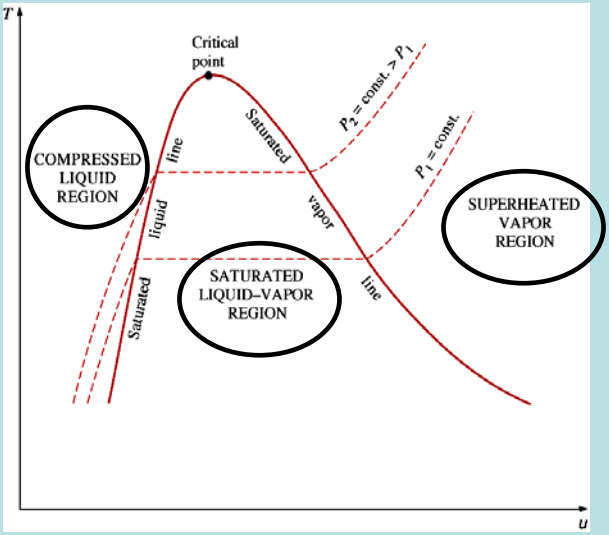
Phase Change at higher P on a T-v diagram

- Repeat this experiment for higher pressures.
- Similar curves will be obtained but at higher sat. temperature.
- Note that the sat. liquid specific volume ($v_{sat,f}$) will increase while the sat. vapor specific volume ($v_{sat,g}$) will decrease



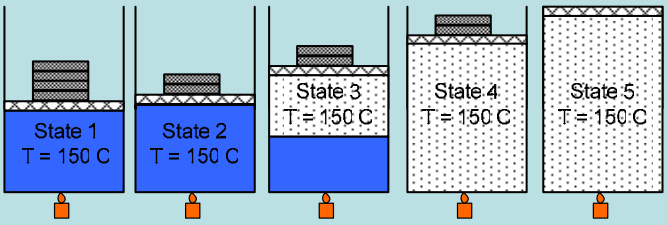
The phase dome on a T-v diagram

- **The saturated liquid states can be connected by a line called the *saturated liquid line*.**
- **The saturated vapor states can be connected by another line, called the saturated vapor line, to form a phase dome.**
- **Three main regions can be identified.**



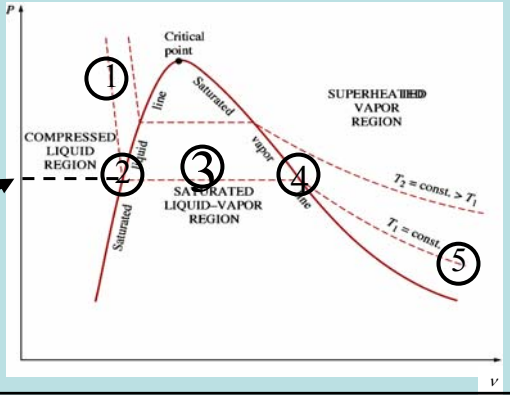
Phase Change Processes on a P-v diagram

Decrease P gradually but keep T constant.



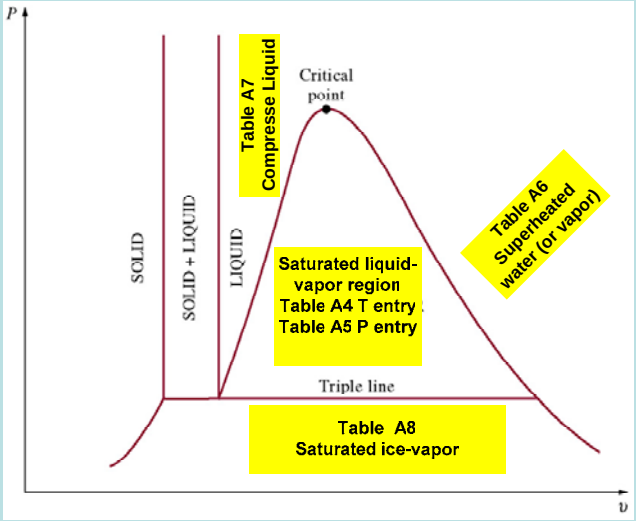
The pressure at which a pure substance changes phase is called the saturation pressure P_{sat}.

At P_{sat}, Liquid and vapor phases are in equilibrium.



From State 2 to 4, no weights are removed (P=constant) and T is kept constant but heating causes liquid to vaporize.

Thermodynamics Tables



Saturated Liquid-vapor mixture Table A-4

Saturated liquid-vapor mixture falls **under the P-v (or T-v) dome.**

Its properties can be obtained from Water Tables A-4 and A-5

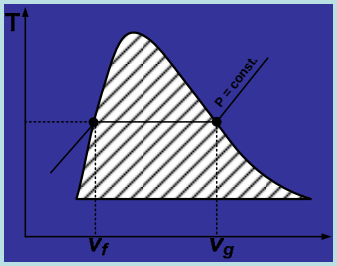


TABLE A–4

Saturated water—Temperature table

		Specific volume, m³/kg		*Internal energy, kJ/kg*		
Temp., T °C	Sat. press., P_{sat} kPa	Sat. liquid, v_f	Sat. vapor, v_g	Sat. liquid, u_f	Evap., u_{fg}	Sat. vapor, u_g
0.01	0.6113	0.001000	206.14	0.0	2375.3	2375.3
5	0.8721	0.001000	147.12	20.97	2361.3	2382.3
10	1.2276	0.001000	106.38	42.00	2347.2	2389.2
15	1.7051	0.001001	77.93	62.99	2333.1	2396.1
20	2.339	0.001002	57.79	83.95	2319.0	2402.9
25	3.169	0.001003	43.36	104.88	2304.9	2409.8
30	4.246	0.001004	32.89	125.78	2290.8	2416.6
35	5.628	0.001006	25.22	146.67	2276.7	2423.4
40	7.384	0.001008	19.52	167.56	2262.6	2430.1
45	9.593	0.001010	15.26	188.44	2248.4	2436.8
50	12.349	0.001012	12.03	209.32	2234.2	2443.5
55	15.758	0.001015	9.568	230.21	2219.9	2450.1
60	19.940	0.001017	7.671	251.11	2205.5	2456.6
65	25.03	0.001020	6.197	272.02	2191.1	2463.1
70	31.19	0.001023	5.042	292.95	2176.6	2469.6
75	38.58	0.001026	4.131	313.90	2162.0	2475.9
80	47.39	0.001029	3.407	334.86	2147.4	2482.2
85	57.83	0.001033	2.828	355.84	2132.6	2488.4
90	70.14	0.001036	2.361	376.85	2117.7	2494.5
95	84.55	0.001040	1.982	397.88	2102.7	2500.6

Saturated Liquid-vapor mixture Table A-5

In Table A-5 (page 832), Pressure is listed in the left column as the independent variable.

Use whichever table is convenient.

TABLE A–5

Saturated water—Pressure table

Press., P kPa	Sat. temp., T_{sat} °C	Specific volume, m³/kg: Sat. liquid, v_f	Specific volume, m³/kg: Sat. vapor, v_g	Internal energy, kJ/kg: Sat. liquid, u_f	Internal energy, kJ/kg: Evap., u_{fg}	Internal energy, kJ/kg: Sat. vapor, u_g
0.6113	0.01	0.001000	206.14	0.00	2375.3	2375.3
1.0	6.98	0.001000	129.21	29.30	2355.7	2385.0
1.5	13.03	0.001001	87.98	54.71	2338.6	2393.3
2.0	17.50	0.001001	67.00	73.48	2326.0	2399.5
2.5	21.08	0.001002	54.25	88.48	2315.9	2404.4
3.0	24.08	0.001003	45.67	101.04	2307.5	2408.5
4.0	28.96	0.001004	34.80	121.45	2293.7	2415.2
5.0	32.88	0.001005	28.19	137.81	2282.7	2420.5
7.5	40.29	0.001008	19.24	168.78	2261.7	2430.5
10	45.81	0.001010	14.67	191.82	2246.1	2437.9
15	53.97	0.001014	10.02	225.92	2222.8	2448.7
20	60.06	0.001017	7.649	251.38	2205.4	2456.7
25	64.97	0.001020	6.204	271.90	2191.2	2463.1
30	69.10	0.001022	5.229	289.20	2179.2	2468.4
40	75.87	0.001027	3.993	317.53	2159.5	2477.0
50	81.33	0.001030	3.240	340.44	2143.4	2483.9
75	91.78	0.001037	2.217	384.31	2112.4	2496.7

Superheated Vapor Table A-6

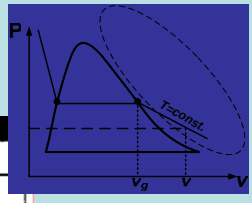


TABLE A–6

Superheated water

T °C	v m³/kg	u kJ/kg	h kJ/kg	s kJ/kg · K	v m³/kg	u kJ/kg	h kJ/kg	s kJ/kg · K
	P = 0.01 MPa (45.81°C)*				P = 0.05 MPa (81.33°C)			
Sat.†	14.674	2437.9	2584.7	8.1502	3.240	2483.9	2645.9	7.5939
50	14.869	2443.9	2592.6	8.1749				
100	17.196	2515.5	2687.5	8.4479	3.418	2511.6	2682.5	7.6947
150	19.512	2587.9	2783.0	8.6882	3.889	2585.6	2780.1	7.9401
200	21.825	2661.3	2879.5	8.9038	4.356	2659.9	2877.7	8.1580
250	24.136	2736.0	2977.3	9.1002	4.820	2735.0	2976.0	8.3556
300	26.445	2812.1	3076.5	9.2813	5.284	2811.3	3075.5	8.5373
400	31.063	2968.9	3279.6	9.6077	6.209	2968.5	3278.9	8.8642
500	35.679	3132.3	3489.1	9.8978	7.134	3132.0	3488.7	9.1546
600	40.295	3302.5	3705.4	10.1608	8.057	3302.2	3705.1	9.4178
700	44.911	3479.6	3928.7	10.4028	8.981	3479.4	3928.5	9.6599
800	49.526	3663.8	4159.0	10.6281	9.904	3663.6	4158.9	9.8852
900	54.141	3855.0	4396.4	10.8396	10.828	3854.9	4396.3	10.0967
1000	58.757	4053.0	4640.6	11.0393	11.751	4052.9	4640.5	10.2964
1100	63.372	4257.5	4891.2	11.2287	12.674	4257.4	4891.1	10.4859
1200	67.987	4467.9	5147.8	11.4091	13.597	4467.8	5147.7	10.6662
1300	72.602	4683.7	5409.7	11.5811	14.521	4683.6	5409.6	10.8382

In the region to the right of the saturated vapor line, a substance exists as *superheated vapor*.

Compressed liquid Table A-7

In the region to the left of the saturated liquid line, a substance exists as *compressed liquid*.

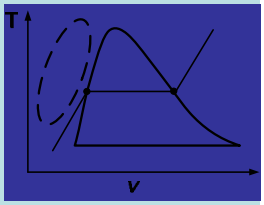


TABLE A–7

Compressed liquid water

T °C	v m³/kg	u kJ/kg	h kJ/kg	s kJ/kg · K	v m³/kg	u kJ/kg	h kJ/kg	s kJ/kg · K
	P = 5 MPa (263.99°C)				P = 10 MPa (311.06°C)			
Sat.	0.0012859	1147.8	1154.2	2.9202	0.0014524	1393.0	1407.6	3.3596
0	0.0009977	0.04	5.04	0.0001	0.0009952	0.09	10.04	0.0002
20	0.0009995	83.65	88.65	0.2956	0.0009972	83.36	93.33	0.2945
40	0.0010056	166.95	171.97	0.5705	0.0010034	166.35	176.38	0.5686
60	0.0010149	250.23	255.30	0.8285	0.0010127	249.36	259.49	0.8258
80	0.0010268	333.72	338.85	1.0720	0.0010245	332.59	342.83	1.0688
100	0.0010410	417.52	422.72	1.3030	0.0010385	416.12	426.50	1.2992
120	0.0010576	501.80	507.09	1.5233	0.0010549	500.08	510.64	1,5189
140	0.0010768	586.76	592.15	1.7343	0.0010737	584.68	595.42	1.7292
160	0.0010988	672.62	678.12	1.9375	0.0010953	670.13	681.08	1.9317
180	0.0011240	759.63	765.25	2.1341	0.0011199	756.65	767.84	2.1275
200	0.0011530	848.1	853.9	2.3255	0.0011480	844.5	856.0	2.3178
220	0.0011866	938.4	944.4	2.5128	0.0011805	934.1	945.9	2.5039
240	0.0012264	1031.4	1037.5	2.6979	0.0012187	1026.0	1038.1	2.6872
260	0.0012749	1127.9	1134.3	2.8830	0.0012645	1121.1	1133.7	2.8699
280					0.0013216	1220.9	1234.1	3.0548
300					0.0013972	1328.4	1342.3	3.2469
320								
340								

Quality (x), derivation

$$V = V_f + V_g$$

$$mv = m_f v_f + m_g v_g$$

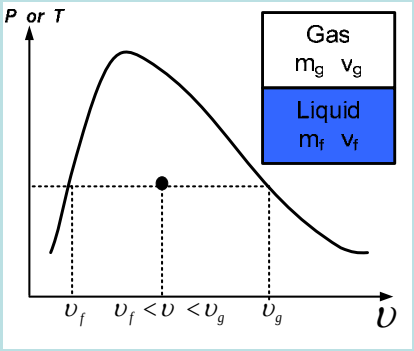
$$mv = (m - m_g) v_f + m_g v_g$$

$$\therefore \quad v = (1 - x) v_f + x v_g$$

$$v = v_f + x (v_g - v_f)$$

$$\boxed{\Rightarrow v = v_f + x v_{fg}}$$

$$\text{where} \quad v_{fg} = v_g - v_f$$



Linear Interpolation

A	B
100	5
130	y
200	10

$$\frac{130-100}{200-100}=\frac{y-5}{10-5}$$

General Equations

The general mass balance equation

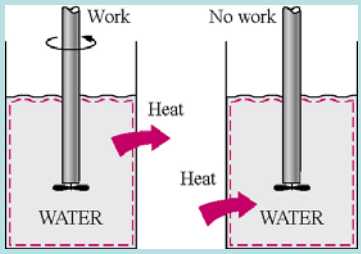
$$\sum m_{in}-\sum m_{exit}=\Delta m_{system}=m_2-m_1$$

The general energy balance equation

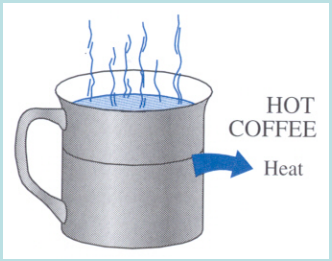
$$Q-W+\sum m_i\left(h_i+\frac{V_i^2}{2}+gz_i\right)-\sum m_e\left(h_e+\frac{V_e^2}{2}+gz_e\right)=m_2u_2-m_1u_1+\Delta KE+\Delta PE$$

Case 1

$Q \rightarrow W$



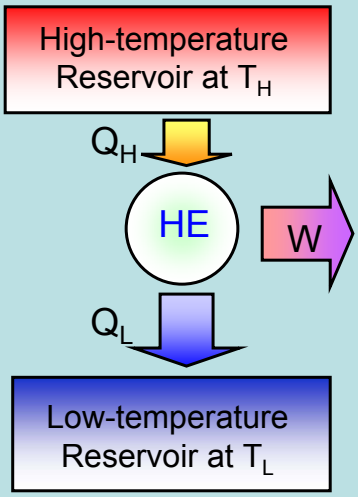
Case 2



$Q_L \rightarrow Q_H$

Characteristics of Heat Engines..

- **They receive heat from high-temperature source.**
- **They convert part of this heat to work.**
- **They reject the remaining waste heat to a low-temperature sink.**
- **They operate on (a thermodynamic) cycle.**



Thermal efficiency

$$Performance = \frac{Desired\ output}{Required\ input}$$

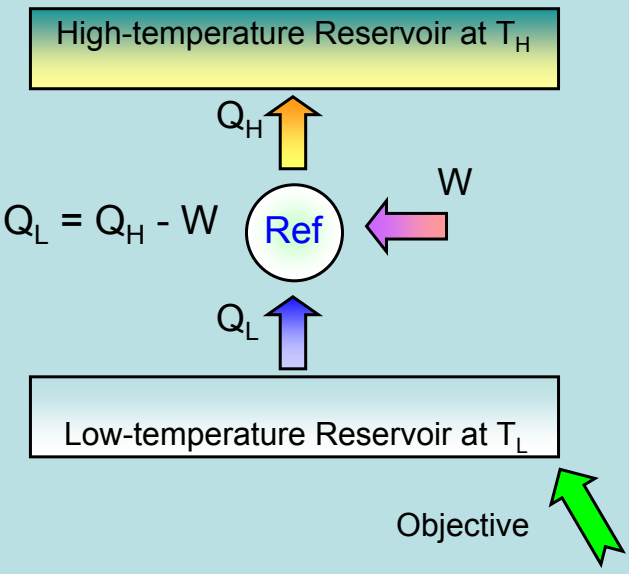
Thermal Efficiency

$$\eta_{th} = \frac{W_{net,out}}{Q_{in}} = \frac{Q_{in} - Q_{out}}{Q_{in}}$$

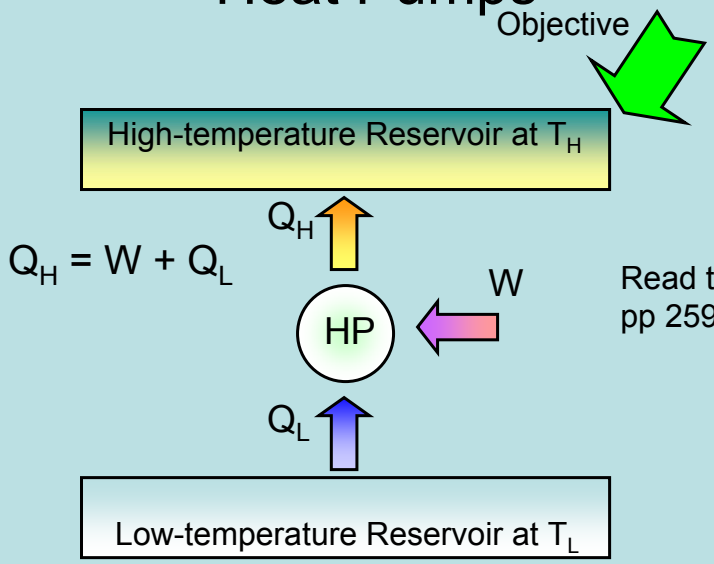
$$= 1 - \frac{Q_{out}}{Q_{in}}$$

< 100 %

Refrigerators



Heat Pumps



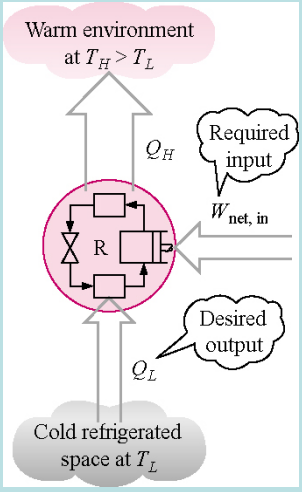
Read to parts of pp 259 and 260

Coefficient of Performance of a Refrigerator

The efficiency of a refrigerator is expressed in term of the *coefficient of performance* (COP_R).

$$COP_R = \frac{\text{Desired output}}{\text{Required input}}$$

$$= \frac{Q_L}{W_{net,in}} = \frac{Q_L}{Q_H - Q_L} = \frac{1}{\frac{Q_H}{Q_L} - 1}$$

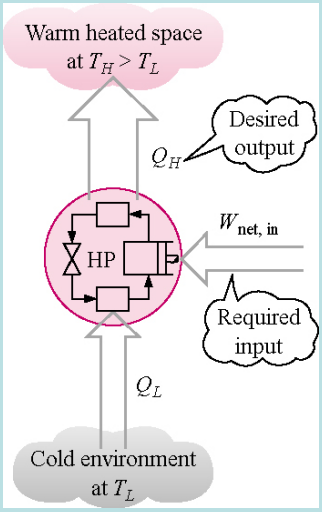


Coefficient of Performance of a Heat Pump

The efficiency of a heat pump is expressed in term of the *coefficient of performance* (COP_{HP}).

$$COP_{HP} = \frac{\text{Desired output}}{\text{Required input}}$$

$$= \frac{Q_H}{W_{net,in}} = \frac{Q_H}{Q_H - Q_L} = \frac{1}{1 - \frac{Q_L}{Q_H}}$$



●A ***reversible process*** is defined as a process that can be reversed without leaving any trace on either system or surroundings.

- **Reversible processes**
- **Ideal processes**
- **Irreversible processes**
- **Actual processes**

Heat transfer process and finite temperature difference process

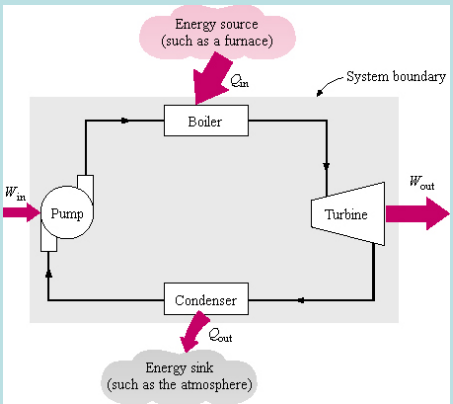
1. **For a Heat transfer process to be revisable process it has to be an Isothermal process.**

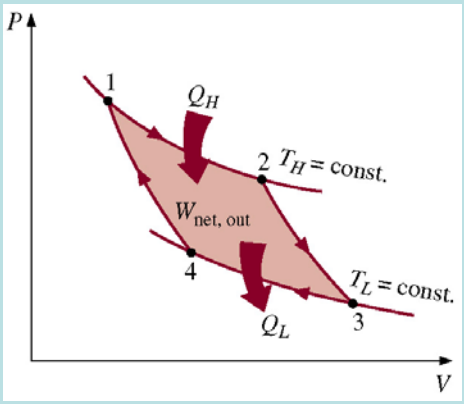
$$Q \neq 0$$
$$\Delta T = 0$$

2. **For a finite temperature difference process to be revisable process it has to be an adiabatic process.**

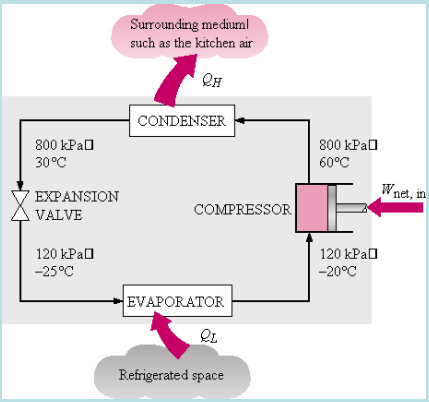
$$\Delta T \neq 0$$
$$Q = 0$$

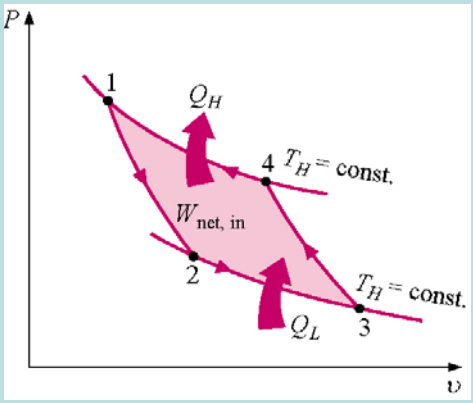
Carnot cycle can be executed in many different ways





Reversed Carnot Cycle





How do Reversible Carnot Heat Engine compare with real engines?

$$\eta_{thermal} \equiv \eta_{th}$$

$$\eta_{th} \begin{cases} < \eta_{th,rev} & \textit{irreversible heat engine} \\ = \eta_{th,rev} & \textit{reversible heat engine} \\ > \eta_{th,rev} & \textit{impossible heat engine} \end{cases}$$

How do Carnot Refrigerator compare with real Refrigerator?

COP of Refrigerator

$$COP_R = \frac{1}{\frac{Q_H}{Q_L} - 1}$$

COP of Carnot Refrigerator

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

$$COP_R \begin{cases} < COP_{R,rev} & irreversible\ refrigerator \\ = COP_{R,rev} & reversible\ refrigerator \\ > COP_{R,rev} & impossible\ refrigerator \end{cases}$$

How do Carnot Heat Pump compare with real one?

COP of real Heat Pump

$$COP_{HP} = \frac{1}{1 - \frac{Q_L}{Q_H}}$$

COP of Carnot Heat Pump

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

$$COP_{HP} \begin{cases} < COP_{HP,rev} & irreversible\ Heat\ Pump \\ = COP_{HP,rev} & reversible\ Heat\ Pump \\ > COP_{HP,rev} & impossible\ Heat\ Pump \end{cases}$$

Derivation of Clausius Inequality

$$\oint \frac{\delta Q}{T} \leq 0$$

$\oint \frac{\delta Q}{T}$	Reversible	Irreversible
Heat Engine	= ٠	< 0
Refrigeration	= ٠	< 0

The equality in the Clausius inequality holds for totally or just internally reversible cycles and the inequality for the irreversible ones.

The Entropy Balance (closed system)

There is some entropy generated during an irreversible process such that

$$S_2 - S_1 = \int_1^2 \frac{\delta Q}{T} + S_{gen}$$

Entropy change

Entropy transfer with heat

Entropy generation due to irreversibility

This is the entropy balance for a closed system.

Summary of the increase of entropy principle

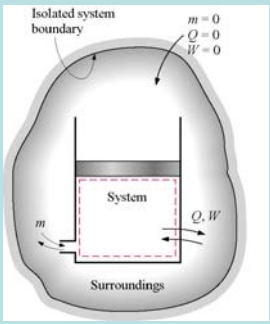
$$S_{gen}\begin{cases} > 0 & irreversible\ \ process \\ = 0 & reversible\ \ \ process \\ < 0 & imposible\ \ \ process \end{cases}$$

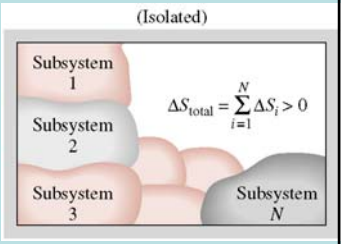
Let us now have an example on this concept.

The increase of entropy principle

- Now suppose the system is not adiabatic.
- We can make it adiabatic by extending the surrounding until no heat, mass, or work are crossing the boundary of the surrounding.
- This way, the system and its surroundings can be viewed again as an isolated system.
- The entropy change of an isolated system is the sum of the entropy changes of its components (the system and its surroundings), and is never less than zero.
- Now, let us apply the entropy balance for an isolated system:

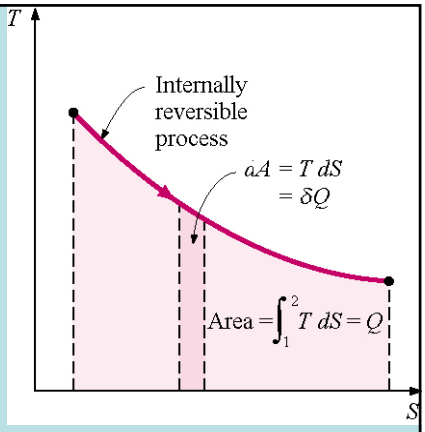
$$S_{gen} = \Delta S_{total} = \Delta S_{sys} + \Delta S_{surr} \geq 0$$





Thus

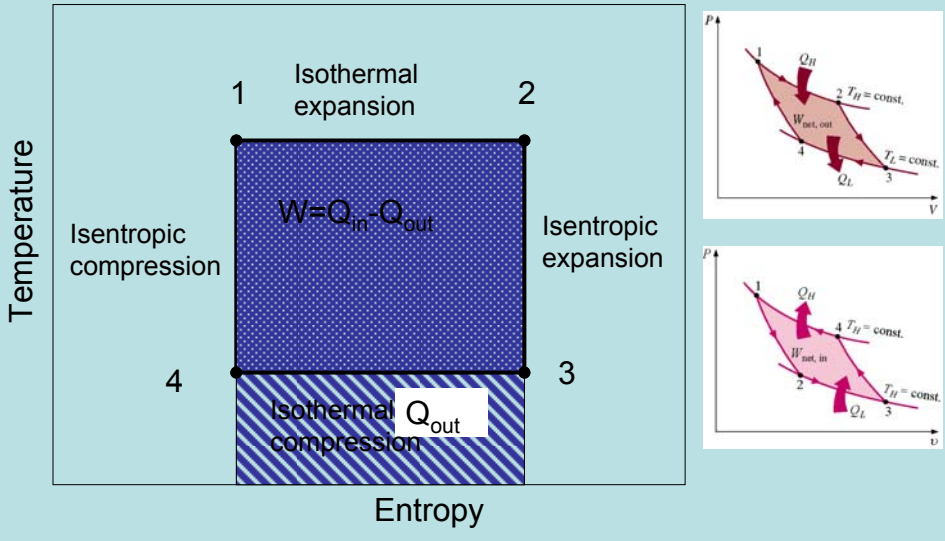
$$Q_{\text{int},rev} = \int_1^2 T dS$$



This area has no meaning for irreversible processes!

It can be done only for a reversible process for which you know the *relationship between T and s* during a process. Let us see some of them.

T-s Diagram for the Carnot Cycle



The T-ds relations:

Gibbs equations or Tds relationship

$$Tds = du + Pdv \qquad Tds = dh - vdP$$

A- Entropy Change of Liquids and Solids

$$\Delta s = C \ln\left(\frac{T_2}{T_1}\right)$$

B- The Entropy Change of Ideal Gases
B1-Constant specific heats

$$\Delta s = C_v \ln\left(\frac{T_2}{T_1}\right) + R \ln\left(\frac{v_2}{v_1}\right) \qquad \Delta s = C_p \ln\left(\frac{T_2}{T_1}\right) - R \ln\left(\frac{P_2}{P_1}\right)$$

B2-Variable specific heats

$$\Delta s = s_2^0 - s_1^0 - R \ln\frac{P_2}{P_1}$$

C-The Isentropic processes of Ideal Gases
C1-Constant specific heats

$$Pv^{k} = \text{constant} \qquad Tv^{k-1} = \text{constant} \qquad TP^{\frac{1-k}{k}} = \text{constant}$$

C2-Variable specific heats

$$\frac{v_2}{v_1} = \frac{v_{r2}}{v_{r1}} \qquad \frac{P_2}{P_1} = \frac{P_{r2}}{P_{r1}}$$

Entropy balance for Open Systems

$$\begin{pmatrix}\text{Total}\\ \text{Entropy}\\ \text{In}\end{pmatrix} - \begin{pmatrix}\text{Total}\\ \text{Entropy}\\ \text{Out}\end{pmatrix} + \begin{pmatrix}\text{Total}\\ \text{Entropy}\\ \text{Generated}\end{pmatrix} = \begin{pmatrix}\text{Change in the}\\ \text{total entropy}\\ \text{of the system}\end{pmatrix}$$

$$S_{in} - S_{out} + S_{gen} = \Delta S_{system} = S_2 - S_1$$

$$\underbrace{\sum \frac{Q}{T}}_{\text{1- Heat transfer (in or out)}} + \underbrace{\sum m_i s_i - \sum m_e s_e}_{\text{2 –mass (in or out)}} \underbrace{+ S_{gen}}_{\text{3- Entropy generation}} = \Delta S_{cv}$$

Isentropic Efficiency of Turbines

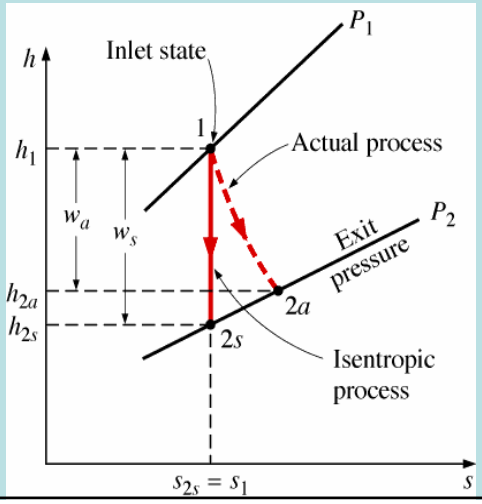
Remember, if KE and PE are ignored in the energy balance equation, then the work is

$$w = h_1 - h_2$$

$$\eta_{Turbine} = \frac{\text{actual turbine work}}{\text{isentropic turbine work}}$$

$$\eta_{Turbine} = \frac{w_a}{w_s}$$

$$\eta_{Turbine} = \frac{h_1 - h_{2a}}{h_1 - h_{2s}}$$



Isentropic Efficiency of Compressors

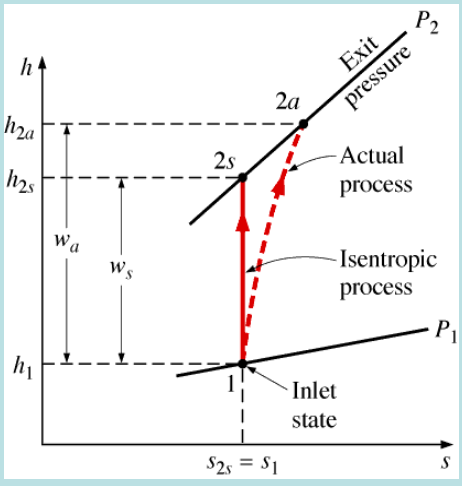
$$\eta_{isen,comp} \equiv \frac{\text{Isentropic compressor work}}{\text{Actual compressor work}} = \frac{w_s}{w_a}$$

Remember, if KE and PE are ignored in the energy balance equation, then the work is

$$w = h_2 - h_1$$

$$\eta_{isen,comp} \cong \frac{h_{2s} - h_1}{h_{2a} - h_1}$$

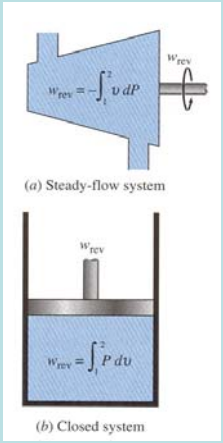
$0.75 < \eta_{isen,comp} \cong 0.85$ for Well-designed compressors.

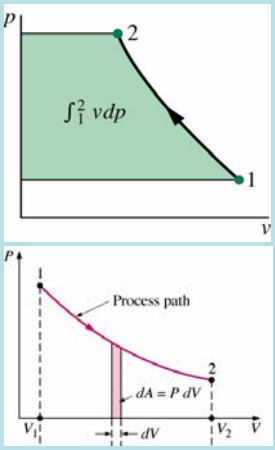


Reversible steady-flow work Vs. Boundary work

$$w_{rev,in} = \int_1^2 v dP$$

$$W_b = \int_1^2 P dv$$





Summary

General Equations

The general mass balance equation

$$\sum m_{in} - \sum m_{exit} = \Delta m_{system} = m_2 - m_1$$

The general energy balance equation

$$Q - W + \sum m_i \left(h_i + \frac{V_i^2}{2} + g z_i \right) - \sum m_e \left(h_e + \frac{V_e^2}{2} + g z_e \right) = m_2 u_2 - m_1 u_1 + \Delta KE + \Delta PE$$

The general entropy balance equation

$$\sum \frac{Q}{T} + \sum m_i s_i - \sum m_e s_e + S_{gen} = (S_2 - S_1)_{CV}$$