

# INTRODUCTION

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## OBJECTIVES

- provide reasons for why thermo is relevant
- describe/review some fundamental concepts
  - » thermodynamic systems
  - » equilibrium and steady state
  - » thermodynamic properties
  - » processes and cycles
  - » work and energy
  - » describe thermodynamic heat and heat transfer
  - » develop the principle of conservation of energy
  - » Introduce enthalpy and heat capacity

## First Law of Thermodynamics

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“Although energy assumes many forms, the total quantity of energy is constant and when energy disappears in one form, it appears simultaneously in other forms.”

$$\Delta E_{\text{system}} + \Delta E_{\text{surroundings}} = 0$$

Consider a fixed position, closed system, at rest :

$$\Delta U = Q + W \quad \text{finite changes}$$

$$dU = \delta Q + \delta W \quad \text{differential changes}$$

## Energy Analysis of Cyclic Processes

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Many applications (e.g. power generation, refrigeration) require cyclic processes.

The energy balance for a cyclic process is :

$$dE_{\text{cycle}} = \delta Q_{\text{cycle}} + \delta W_{\text{cycle}}$$

For ideal fluid

$$\Delta U_{\text{cyc}} = 0$$

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3

## Enthalpy

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In the analysis of certain processes, certain combinations of thermodynamic properties are encountered. One such is **enthalpy**.

Consider the reversible expansion of a gas at constant pressure in a piston-cylinder assembly :

$$H \equiv U + PV$$

enthalpy is a defined property because it occurs often

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4

## Heat capacity, C

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Materials have an ability to absorb or liberate a specific quantity of heat. This is called heat capacity.

$$C \equiv \frac{\delta Q}{\delta T}$$

Consider a closed system of n moles undergoing reversible, mechanical work.

- for a constant volume process :

$$C_v = \left( \frac{\delta U}{\delta T} \right)_v$$

- for a constant pressure process :

$$C_p = \left( \frac{\delta H}{\delta T} \right)_p$$

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5

## Pure Fluids

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To apply the energy balance to a system requires knowledge of the properties of the system and how these properties are related.

### OBJECTIVES

- Describe properties of pure fluids using phase diagrams
- Review the concept of an ideal gas
- Develop work equations for processes involving ideal gases

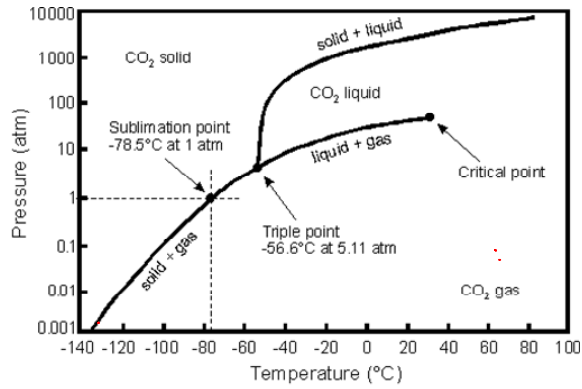
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6

## Properties of Real Fluids

Experimental measurements have been made of pure substances over a range of P, V and T



P-T diagram for CO<sub>2</sub>

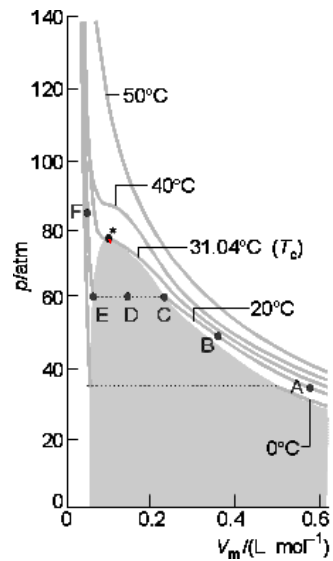
Pressure-Temperature phase diagram for CO<sub>2</sub>.

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## Properties of Real Fluids - PV diagram



isotherms of CO<sub>2</sub>

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## Equations of State

In order to calculate properties such as internal energy and enthalpy, an accurate relationship between readily measurable properties such as P, V, T is necessary

### OBJECTIVES

- Introduce the virial equations (pg. 70-71)
- Introduce the compressibility factor (pg. 72, 87-90)
- Discuss cubic equations of state
  - » Van der Waals, Redlich-Kwong (pg. 91-94)
- Introduce the generalized compressibility factor and principle of corresponding states (pg 95-100)
- Discuss generalized equations of state (pg 101-110)

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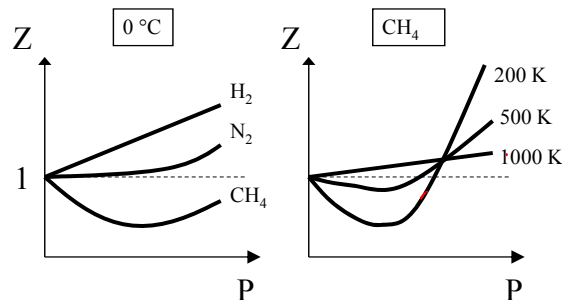
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## Compressibility Factor, Z

- used to describe degree of deviation of gas from ideal behavior

$$Z = \frac{V_{\text{real}}}{V_{\text{IG}}} \quad Z = \frac{PV}{RT} = 1 + B'P + C'P^2 + \dots$$



$$\lim_{P \rightarrow 0} Z = 1, \quad \lim_{P \rightarrow 0} Z = 1$$

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10

## Cubic Equations of State (p. 90-98)

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Redlich-Kwong Equation (1949)

$$P = \frac{RT}{V-b} - \frac{a}{T^{0.5}V(V+b)}$$

There have been many equations of state published. In general :

$$P = \frac{RT}{V-b} - \frac{a}{V^2 + cbV + db^2}$$

## Generalized Redlich-Kwong

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$$P = \frac{RT}{V-b} - \frac{a}{V(V+b)}$$

$$a(T) = 0.42748 \frac{R^2 T_c^2}{T_r^{0.5} P_c}$$

$$b = 0.08664 \frac{RT_c}{P_c}$$

## Generalized Virial Equation

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Based on the use of the **acentric factor**,  $\omega$ , and is only applicable to gases.

$Z = Z^0 + \omega Z^1$   $Z^0$  and  $Z^1$  can be found in tables or :

$$Z^0 = 1 + \frac{B^0 P_r}{T_r} \quad B^0 = 0.083 - \frac{0.422}{T_r^{1.6}}$$

$$Z^1 = \frac{B^1 P_r}{T_r} \quad B^1 = 0.139 - \frac{0.172}{T_r^{4.2}}$$

$$\omega = -1.0 - \log \left[ P_r^{\text{sat}} \right]_{T_r=0.7}$$

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13

## Other Thermodynamic Relations

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### OBJECTIVES

- to introduce several other useful thermodynamic relations that are defined in terms of partial derivatives of some other property
  - » specifically heat capacity, isothermal compressibility, and volume expansivity

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14

## A Few More Thermodynamic Properties

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Recall that if 2 state variables are known, then all other state variables for a single component system can be determined.

Consider  $V$  :  $V=V(T,P)$

• Expansion coefficient : 
$$\beta = \frac{1}{V} \left( \frac{\partial V}{\partial T} \right)_P$$

• Isothermal compressibility 
$$\kappa = -\frac{1}{V} \left( \frac{\partial V}{\partial P} \right)_T$$

## Second Law of Thermodynamics

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Some processes occur spontaneously and some don't (nonspontaneous).

- heat flows from hot to cold
- gas expands to fill its container
- reaction proceeds in one direction rather than another

There must be something that determines whether a process will occur spontaneously.

### OBJECTIVES (AND READING)

- To introduce the second law of thermodynamics (pgs 159-160)
- To review the concept of the Carnot cycle (pgs 161-163)
- Introduce the concept of thermal efficiency (pgs 163-166)
- Introduce entropy,  $S$ , and derive equations to calculate changes in  $S$  (pgs 167-180)

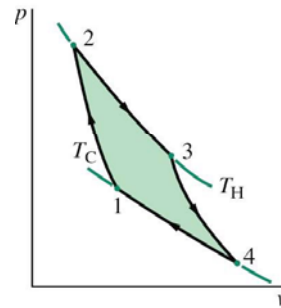
## Carnot Engine

The maximum amount of mechanical work is done via a reversible process. A heat engine operating in a reversible manner is called a Carnot engine and consists of 4 steps:

- reversible adiabatic compression from  $T_C$  to  $T_H$  (step 1-2)
- reversible isothermal expansion at  $T_H$  (step 2-3)
- reversible adiabatic expansion from  $T_H$  to  $T_C$  (step 3-4)
- reversible isothermal compression at  $T_C$  (step 4-1)

For any working fluid :

$$\eta = 1 - \frac{T_C}{T_H}$$



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17

## ENTROPY

- Entropy represents the energy in the system that cannot be converted into useful work

$$dS \equiv \left( \frac{\delta Q}{T} \right)_{\text{rev}} \quad \oint \left( \frac{\delta Q}{T} \right)_{\text{rev}} = 0$$

- $\Delta S_{\text{total}} \geq 0$
- This statement of the second law affirms that every process proceeds in such a direction that the total entropy change associated with the process is positive, the limiting value of zero is only obtained for a reversible process.
- NO PROCESS IS POSSIBLE FOR WHICH THE TOTAL ENTROPY DECREASES.
- Fluids spontaneously flow from high pressure to low pressure!! (Never the other way around.)
- Goldilocks porridge always spontaneously gets colder with time!

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18

## Thermodynamic Relations

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By combining the 1st Law with the 2nd Law we can derive the following :

$$TdS = dH - VdP$$

$$TdS = dU + PdV$$

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19

## ENTROPY CHANGES

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Consider an ideal gas undergoing a mechanically reversible process in a closed system.

$$\frac{\Delta S}{R} = \int_{T_1}^{T_2} \frac{C_p^{ig}}{R} \frac{dT}{T} - \ln\left(\frac{P_2}{P_1}\right)$$

The entropy change for a solid or liquid at constant P is :

$$\frac{\Delta S}{R} = \int_{T_1}^{T_2} \frac{C_p}{R} \frac{dT}{T}$$

For a phase change at constant T and P :

$$\Delta S = \frac{\Delta H_{\text{transition}}}{T_{\text{transition}}}$$

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20

## More on Entropy

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### OBJECTIVES

- To derive a means of predicting spontaneous processes
- To demonstrate that entropy represents heat energy that cannot be converted into work
- To illustrate the relationship between entropy and equilibrium

## Thermodynamic Properties of Real Gases

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### OBJECTIVES

- To define the Gibbs and Helmholtz energies (pp 199-201)
- Introduce the Maxwell Equations (p 201)
- Use the Maxwell equations to develop enthalpy and entropy relationships (pp. 202-208)
- Introduce residual properties (pp. 208-211)
- Use residual properties to develop expressions of H and S for real gases (pp. 212-220)

## Fundamental Property Relationships

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For closed systems with changes occurring between equilibrium states :

$$dU = TdS - PdV$$

$$dH = TdS + VdP$$

$$dA = -PdV - SdT$$

$$dG = VdP - SdT$$

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23

## Maxwell's Equations

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These equations form the basis of other equations relating thermodynamic properties

$$\left(\frac{\partial T}{\partial V}\right)_S = -\left(\frac{\partial P}{\partial S}\right)_V$$

$$\left(\frac{\partial T}{\partial P}\right)_S = \left(\frac{\partial V}{\partial S}\right)_P$$

$$\left(\frac{\partial P}{\partial T}\right)_V = \left(\frac{\partial S}{\partial V}\right)_T$$

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

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## Thermodynamic Properties of Fluids

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Real gases

- we want to know H, S as a function of T and P
- recall Gibbs free energy

$$dG = VdP - SdT$$

- from this we can derive

$$\frac{H}{RT} = -T \left[ \frac{\partial \left( \frac{G}{RT} \right)}{\partial T} \right]_P \quad \frac{S}{R} = \frac{H}{RT} - \frac{G}{RT}$$

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25

## Residual Properties

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departure from ideal behavior

$$G^R = G - G^{ig}$$

$G^R$  = residual Gibbs free energy

- note that residual properties can be written for other thermodynamic properties (V, H, S)

$$\frac{H^R}{RT} = -T \left[ \frac{\partial \left( \frac{G^R}{RT} \right)}{\partial T} \right]_P \quad \frac{S^R}{R} = \frac{H^R}{RT} - \frac{G^R}{RT}$$

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26

## How do you find $G^R$ ?

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recall for non-ideal gases

$$PV = ZRT$$

from which we can derive

$$\frac{G^R}{RT} = \int_0^P \frac{(Z-1)}{P} dP \qquad \frac{H^R}{RT} = -T \int_0^P \left( \frac{\partial Z}{\partial T} \right)_P \frac{dP}{P}$$

$$\frac{S^R}{R} = -T \int_0^P \left( \frac{\partial Z}{\partial T} \right)_P \frac{dP}{P} - \int_0^P \frac{(Z-1)}{P} dP$$

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27

## Real Gases : Residual Properties

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Redlich-Kwong Equation :

$$\frac{H^R}{RT} = Z - 1 - \frac{7.4}{T_r^{1.5}} \ln \left( 1 + \frac{0.08664 P_r}{Z T_r} \right)$$

$$\frac{S^R}{R} = \ln \left( Z - \frac{0.08664 P_r}{T_r} \right) - \frac{2.467}{T_r^{1.5}} \ln \left( 1 + \frac{0.08664 P_r}{Z T_r} \right)$$

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28

## Real Gases : Residual Properties

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Generalized Virial Correlations for Gases :

$$\frac{H^R}{RT_c} = P_r \left[ B^0 - \frac{0.675}{T_r^{1.6}} + \omega \left( B^1 - \frac{0.722}{T_r^{4.2}} \right) \right]$$

$$\frac{S^R}{R} = -P_r \left[ \frac{0.675}{T_r^{2.6}} + \omega \left( \frac{0.722}{T_r^{5.2}} \right) \right]$$

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## Other Sources for H and S

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The enthalpy and entropy values for many gases of interest can also be found in tabulated or figure format

### OBJECTIVES

- To illustrate the use of T-S and H-S figures (p226-227, inside back cover)
- To illustrate the use of tables (e.g. steam table p715-787)
- To introduce the Clausius-Clapeyron and Antoine equations (p222-223)
- To introduce the concept of quality (p 225)

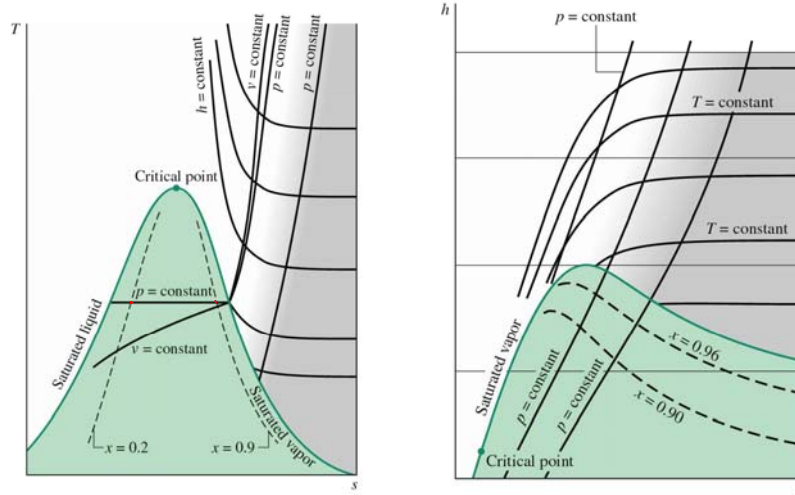
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# Where Else do You Find H and S?

thermodynamic diagrams



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31

# Steam Tables

Table F.1. Saturated Steam, SI Units (Continued)

t °C	T K	P kPa	SPECIFIC VOLUME V			INTERNAL ENERGY U			ENTHALPY H			ENTROPY S		
			sat. liq.	sat. evap.	sat. vap.	sat. liq.	sat. evap.	sat. vap.	sat. liq.	sat. evap.	sat. vap.	sat. liq.	sat. evap.	sat. vap.
75	348.15	38.55	1.026	4133.1	4134.1	313.9	2162.1	2476.0	313.9	2321.5	2635.4	1.0154	6.6681	7.6835
76	349.15	40.19	1.027	3974.6	3975.7	318.1	2159.2	2477.3	318.1	2318.9	2637.1	1.0275	6.6418	7.6693
77	350.15	41.89	1.027	3823.3	3824.3	322.3	2156.3	2478.5	322.3	2316.4	2638.7	1.0395	6.6159	7.6551
78	351.15	43.65	1.028	3678.6	3679.6	326.5	2153.3	2479.8	326.5	2313.9	2640.4	1.0514	6.5896	7.6410
79	352.15	45.47	1.029	3540.3	3541.3	330.7	2150.4	2481.1	330.7	2311.4	2642.1	1.0634	6.5637	7.6271
80	353.15	47.36	1.029	3408.1	3409.1	334.9	2147.4	2482.3	334.9	2308.8	2643.8	1.0753	6.5380	7.6132
81	354.15	49.31	1.030	3281.6	3282.6	339.1	2144.5	2483.5	339.1	2306.3	2645.4	1.0871	6.5123	7.5995
82	355.15	51.33	1.031	3161.6	3161.6	343.3	2141.5	2484.8	343.3	2303.8	2647.1	1.0990	6.4868	7.5858
83	356.15	53.42	1.031	3044.8	3045.8	347.5	2138.6	2486.0	347.5	2301.2	2648.7	1.1108	6.4615	7.5722
84	357.15	55.57	1.032	2933.9	2933.0	351.7	2135.6	2487.3	351.7	2298.6	2650.4	1.1225	6.4362	7.5587
85	358.15	57.80	1.033	2827.8	2828.8	355.9	2132.6	2488.5	355.9	2296.1	2652.0	1.1343	6.4111	7.5454
86	359.15	60.11	1.033	2726.1	2727.2	360.1	2129.7	2489.7	360.1	2293.5	2653.6	1.1460	6.3861	7.5321
87	360.15	62.49	1.034	2628.8	2629.8	364.3	2126.7	2490.9	364.3	2290.9	2655.3	1.1577	6.3612	7.5189
88	361.15	64.95	1.035	2535.4	2536.5	368.5	2123.7	2492.2	368.5	2288.4	2656.9	1.1693	6.3365	7.5058
89	362.15	67.49	1.035	2446.0	2447.0	372.7	2120.7	2493.4	372.7	2285.8	2658.5	1.1809	6.3119	7.4928
90	363.15	70.11	1.036	2360.3	2361.3	376.9	2117.7	2494.6	376.9	2283.2	2660.1	1.1925	6.2873	7.4799
91	364.15	72.81	1.037	2278.0	2279.1	381.1	2114.7	2495.8	381.1	2280.6	2661.7	1.2041	6.2629	7.4670
92	365.15	75.61	1.038	2199.2	2200.2	385.3	2111.7	2497.0	385.3	2278.0	2663.4	1.2156	6.2387	7.4543
93	366.15	78.49	1.038	2123.5	2124.5	389.5	2108.7	2498.2	389.5	2275.4	2665.0	1.2271	6.2145	7.4416
94	367.15	81.46	1.039	2050.9	2051.9	393.7	2105.7	2499.4	393.7	2272.8	2666.6	1.2386	6.1905	7.4291
95	368.15	84.53	1.040	1981.2	1982.2	397.9	2102.7	2500.6	397.9	2270.2	2668.1	1.2501	6.1665	7.4166
96	369.15	87.69	1.041	1914.3	1915.3	402.1	2099.7	2501.8	402.1	2267.5	2669.7	1.2615	6.1427	7.4042
97	370.15	90.94	1.041	1850.0	1851.0	406.3	2096.6	2503.0	406.3	2264.9	2671.3	1.2729	6.1190	7.3919
98	371.15	94.30	1.042	1788.3	1789.3	410.5	2093.6	2504.1	410.5	2262.2	2672.9	1.2842	6.0954	7.3796
99	372.15	97.76	1.043	1729.0	1730.0	414.7	2090.6	2505.3	414.7	2259.6	2674.4	1.2956	6.0719	7.3675
100	373.15	101.33	1.044	1672.0	1673.0	419.0	2087.5	2506.5	419.0	2256.9	2676.0	1.3069	6.0485	7.3554
102	375.15	108.79	1.045	1564.5	1565.5	427.4	2081.4	2508.8	427.4	2251.6	2679.1	1.3294	6.0021	7.3315
104	377.15	116.68	1.047	1465.1	1466.2	435.8	2075.3	2511.1	435.8	2246.3	2682.2	1.3518	5.9560	7.3078
106	379.15	125.04	1.049	1373.1	1374.2	444.3	2069.2	2513.4	444.3	2240.9	2685.3	1.3742	5.9104	7.2845
108	381.15	133.90	1.050	1287.9	1288.9	452.7	2063.0	2515.7	452.7	2235.4	2688.3	1.3964	5.8651	7.2615
110	383.15	143.27	1.052	1208.9	1209.9	461.2	2056.8	2518.0	461.2	2230.0	2691.3	1.4185	5.8203	7.2388
112	385.15	153.16	1.054	1135.6	1136.6	469.6	2050.6	2520.2	469.6	2224.5	2694.3	1.4405	5.7758	7.2164
114	387.15	163.62	1.055	1067.5	1068.5	478.1	2044.3	2522.4	478.1	2219.0	2697.2	1.4624	5.7318	7.1942
116	389.15	174.65	1.057	1004.2	1005.2	486.6	2038.1	2524.6	486.6	2213.4	2700.2	1.4842	5.6881	7.1723
118	391.15	186.28	1.059	945.3	946.3	495.0	2031.8	2526.8	495.0	2207.9	2703.1	1.5060	5.6447	7.1507
120	393.15	198.54	1.061	890.5	891.5	503.5	2025.4	2529.0	503.5	2202.2	2706.0	1.5276	5.6017	7.1293
122	395.15	211.45	1.062	839.4	840.5	512.0	2019.1	2531.1	512.0	2196.6	2708.8	1.5491	5.5590	7.1082
124	397.15	225.04	1.064	791.8	792.8	520.5	2012.7	2533.2	520.5	2190.9	2711.6	1.5706	5.5167	7.0873
126	399.15	239.33	1.066	747.3	748.4	529.0	2006.3	2535.3	529.0	2185.2	2714.4	1.5919	5.4747	7.0666
128	401.15	254.35	1.068	705.8	706.9	537.5	1999.9	2537.4	537.5	2179.4	2717.2	1.6132	5.4330	7.0462

32

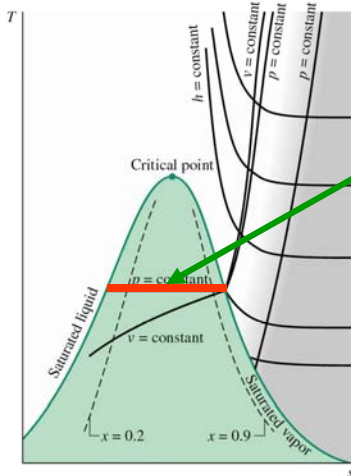
# Steam Tables

Table F.2. Superheated Steam, SI Units (Continued)

P/kPa ( $t^{\text{sat}}$ /°C)	sat. liq.	sat. vap.	TEMPERATURE: $t$ °C (TEMPERATURE: $T$ kelvins)									
			150 (423.15)	175 (448.15)	200 (473.15)	220 (493.15)	240 (513.15)	260 (533.15)	280 (553.15)	300 (573.15)		
325 (136.29)	V U H S	1.076 572.847 573.197 1.7004	561.75 2545.7 2728.3 6.9640	583.58 2568.7 2758.4 7.0363	622.41 2609.6 2811.9 7.1592	660.33 2649.6 2864.2 7.2729	690.22 2681.2 2905.6 7.3585	719.81 2712.7 2946.6 7.4400	749.18 2744.0 2987.5 7.5181	778.39 2775.3 3028.2 7.5933	807.47 2806.6 3069.0 7.6657	
350 (138.87)	V U H S	1.079 583.892 584.270 1.7273	524.00 2548.2 2731.6 6.9392	540.58 2567.1 2756.3 6.9982	576.90 2608.3 2810.3 7.1222	612.31 2648.6 2853.0 7.2366	640.18 2680.4 2904.5 7.3226	667.75 2712.0 2945.7 7.4045	695.09 2743.4 2986.7 7.4828	722.27 2774.8 3027.6 7.5581	749.33 2806.2 3068.4 7.6307	
375 (141.31)	V U H S	1.081 594.332 594.737 1.7526	491.13 2550.6 2734.7 6.9160	503.29 2565.4 2754.1 6.9624	537.46 2607.1 2808.6 7.0875	570.69 2647.7 2861.7 7.2027	596.81 2679.6 2903.4 7.2891	622.62 2711.3 2944.8 7.3713	648.22 2742.8 2985.9 7.4499	673.64 2774.3 3026.9 7.5254	698.94 2805.7 3067.8 7.5981	
400 (143.62)	V U H S	1.084 604.237 604.670 1.7764	462.22 2552.7 2737.6 6.8943	470.66 2563.7 2752.0 6.9285	502.93 2605.8 2807.0 7.0548	534.26 2646.7 2860.4 7.1708	558.85 2678.8 2902.3 7.2576	583.14 2710.6 2943.9 7.3402	607.20 2742.2 2985.1 7.4190	631.09 2773.7 3026.2 7.4947	654.85 2803.3 3067.2 7.5675	
425 (145.82)	V U H S	1.086 613.667 614.128 1.7990	436.61 2554.8 2740.3 6.8739	441.85 2562.0 2749.8 6.8965	472.47 2604.5 2805.3 7.0239	502.12 2645.7 2859.1 7.1407	525.36 2678.0 2901.2 7.2280	548.30 2709.9 2942.9 7.3108	571.01 2741.6 2984.3 7.3899	593.54 2773.2 3025.5 7.4657	615.95 2804.8 3066.6 7.5388	
450 (147.92)	V U H S	1.088 622.672 623.162 1.8204	413.75 2556.7 2742.9 6.8547	416.24 2560.3 2747.7 6.8660	445.38 2603.2 2803.7 6.9946	473.55 2644.7 2857.8 7.1121	495.59 2677.1 2900.2 7.1999	517.33 2709.2 2942.0 7.2831	538.83 2741.0 2983.5 7.3624	560.17 2772.7 3024.8 7.4384	581.37 2804.4 3066.0 7.5116	
475 (149.92)	V U H S	1.091 631.294 631.812 1.8408	393.22 2558.5 2745.3 6.8365	393.31 2558.6 2745.5 6.8369	421.14 2601.9 2802.0 6.9667	447.97 2643.7 2856.5 7.0850	468.95 2676.3 2899.1 7.1732	489.62 2708.5 2941.1 7.2567	510.05 2740.4 2982.7 7.3363	530.30 2772.2 3024.1 7.4125	550.43 2803.9 3065.4 7.4858	
500 (151.84)	V U H S	1.093 639.569 640.116 1.8604	374.68 2560.2 2747.5 6.8192	..... ..... ..... .....	399.31 2600.6 2800.3 6.9400	424.96 2642.7 2855.1 7.0592	444.97 2675.5 2898.0 7.1478	464.67 2707.8 2940.1 7.2317	484.14 2739.8 2981.9 7.3115	503.43 2771.7 3023.4 7.3879	522.58 2803.5 3064.8 7.4614	

## A few words on quality ...

thermodynamic diagrams



This line represents a constant pressure and constant temperature line during phase change.

It should be obvious if you recall that water at atmospheric pressure boils at 100 C and steam at 1 atm condenses at 100 C. Quality is just a measure of the fraction of vapour that has not yet turned to liquid.

$$S = x (S_{\text{vap}}) + (1-x)(S_{\text{liq}})$$

## Energy/Entropy Balances

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Our global objective is to develop means by which we can assess the design and efficiency of chemical processes. One means of doing this is through energy and entropy balances

### OBJECTIVES

- To derive the general energy balance equation for a control volume (Section 2.12 pg 44-52)
- To derive the general entropy balance for a control volume (Section 5.7 pg 176-180)
- To simplify these equations for a steady-state process (pg 51-52 and pg 177)

## Energy Balance

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total rate of energy entering c.v.

$$\dot{X}_T = \dot{Q} + \dot{W} - \Delta \left[ \left( H + \frac{u^2}{2} + zg \right) \dot{m} \right]_{fs}$$

accumulated energy within c.v.

$$\frac{dX_{cv}}{dt} = \frac{d(mU)_{cv}}{dt}$$

Putting it all together :

$$\frac{d(mU)_{cv}}{dt} = \dot{Q} + \dot{W} - \Delta \left[ \left( H + \frac{u^2}{2} + zg \right) \dot{m} \right]_{fs}$$

## Energy Balance : Steady State Flow

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- no changes in mass of the system *and* no changes with time in the properties of the fluid within the c.v. or its entrances and exits
- only shaft work is possible
- the rates at which heat and work cross the control surface is constant

$$\dot{Q} + \dot{W} = \Delta \left[ \left( H + \frac{u^2}{2} + zg \right) \dot{m} \right]_{fs}$$

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37

## Entropy Balance

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$$\frac{dS_{cv}}{dt} = \dot{S}_T + \dot{S}_{gen}$$

$$\dot{S}_T = \sum_j \frac{\dot{Q}_j}{T_{\sigma,j}} - \Delta(\dot{m}S)_{fs}$$

$$\frac{dS_{cv}}{dt} = \sum_j \frac{\dot{Q}_j}{T_{\sigma,j}} - \Delta(\dot{m}S)_{fs} + \dot{S}_{gen}$$

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38

## Entropy Balance

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invoking second law

$$\frac{dS_{cv}}{dt} - \sum_j \frac{\dot{Q}_j}{T_{\sigma,j}} + \Delta(\dot{m}S)_{fs} = \dot{S}_{gen} \geq 0$$

### Steady-state

- mass and entropy within c.v. are constant

$$\Delta(\dot{m}S)_{fs} = \sum_j \frac{\dot{Q}_j}{T_{\sigma,j}} + \dot{S}_{gen}$$

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39

## Components of Flow Processes

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Equipment used to extract/provide work and/or heat from a process

- turbines - generate electricity (pg 268-273)
- compressors and pumps - move fluid, change pressures (pg 273-280)
- heat exchangers - change temperature of fluid
- throttles - change pressure (p260-267)

### OBJECTIVES

- evaluate performance of components of flow processes through appropriate mass, energy, entropy balances

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40

## Turbines

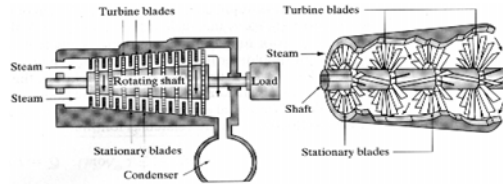
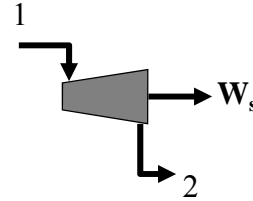


Figure 3.3-3 Sketch of a steam turbine. (Adapted from *The World Book Encyclopedia*, Field Educational Enterprises, New York, 1976.)

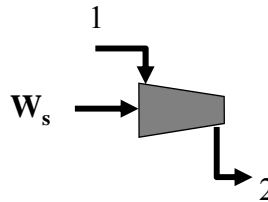
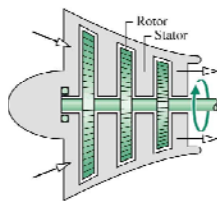


convert gas kinetic energy into work,  $W_s$

$$\Delta H = T_\sigma (\Delta S_{fs} - S_{gen}) + W_s$$

$$\eta_{\text{turbine}} = \frac{W}{W_s} = \frac{\Delta H}{(\Delta H)_s} \quad \text{efficiency}$$

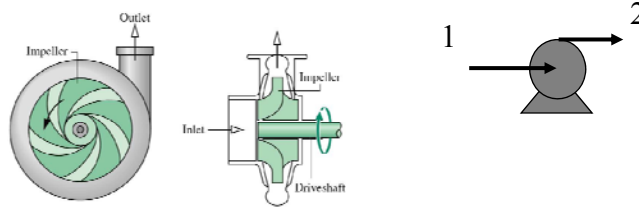
## Compressors



used to transport gases

$$\eta_{\text{comp}} = \frac{W_s}{W} = \frac{(\Delta H)_s}{\Delta H}$$

# Pumps



used to transport **liquids**

$$\eta_{\text{pump}} = \frac{W_s}{W} = \frac{(\Delta H)_s}{\Delta H} \quad (\Delta H)_s = V(P_e - P_i)$$

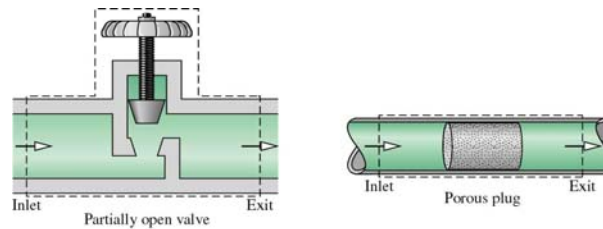
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43

# Throttle

Fluid flowing in a pipe suddenly encounters a restriction. Result is a pressure drop at constant enthalpy.



Some velocity change but typically not significant

Occurs quickly so adiabatic ( $Q=0$ )

No change in  $z$  and no shaft work

From energy balance:  $\Delta(H)_{fs}=0$

For an ideal gas  $H = \text{function of } T$  only so there will be no change in temperature.

For real gases there will be a small change in temperature

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44

## Power Generation

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The review of power plant analysis was the subject of the second last lecture.

The review notes from class will be published on the course website.

Responsible for Rankine Cycle and variations for increasing efficiency (p. 290 – 302).

Basic efficiency equations for gas turbine efficiency (Brayton). (p. 306-310)

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## Tutorial

(Date to be confirmed by class email)

Probably Dupuis 215 or 217 (or maybe the auditorium if the group is big.

***BRING QUESTIONS!***