ME 200 – Thermodynamics 1
Chapter 3 In-Class Notes
for Spring 2023

Properties of Pure Substances

- Phases of a pure substance
- T-v and P-v diagrams
- Properties tables for “real” fluids
- Ideal liquid & solid properties
- Ideal gas property models

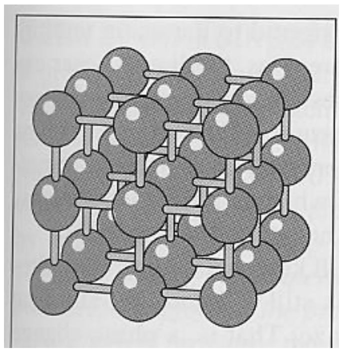
Lecture 7
Phase Changes and Diagrams

Pure Substance

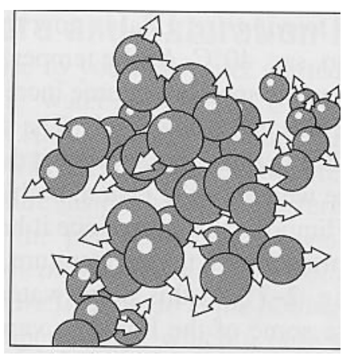
- A substance with fixed chemical composition throughout i.e. water, N_2, He, CO_2, etc.
- A mixture of chemical elements or compounds is treated as a pure substance as long as mixture is homogeneous i.e. Air
- A mixture of two or more phases is still a pure substance as long as chemical composition of each phase is same i.e. ice and liquid water but not liquid and gaseous air

Phases of a Pure Substance

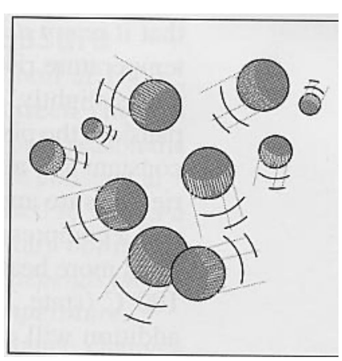
Solid: molecules oscillate about "fixed" positions



Liquid: groups of molecules float about each other



Gas: gas molecules move randomly

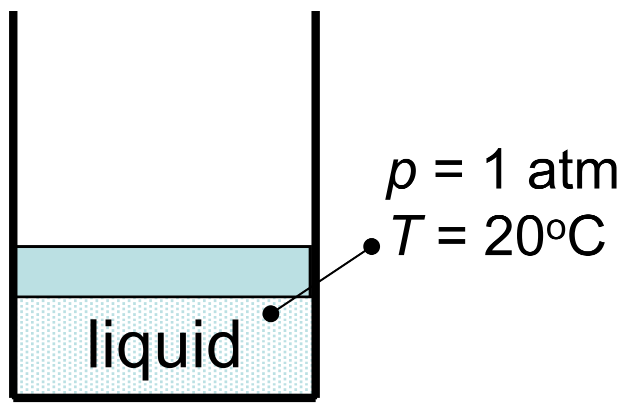


Phase Change Process for Pure Substances

1. Phase change at constant pressure

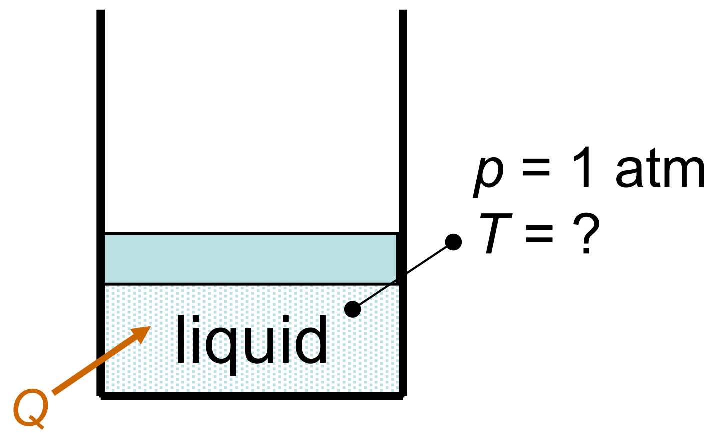
- Consider pure water in a sealed container with a floating top having no mass (atmosphere exerts constant pressure)

Initially at room conditions



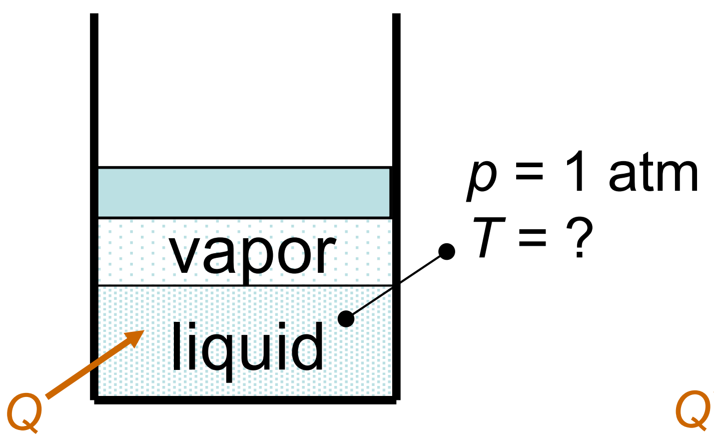
(a) “compressed liquid”

Add heat until water just begins to “boil”



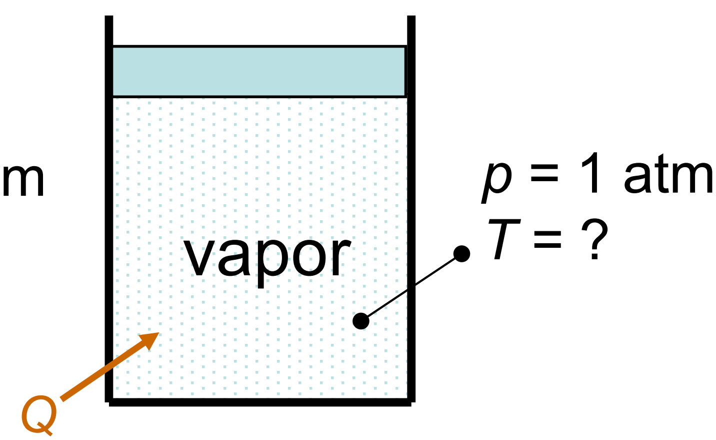
(b) “saturated liquid”

Keep adding heat as liquid vaporizes”



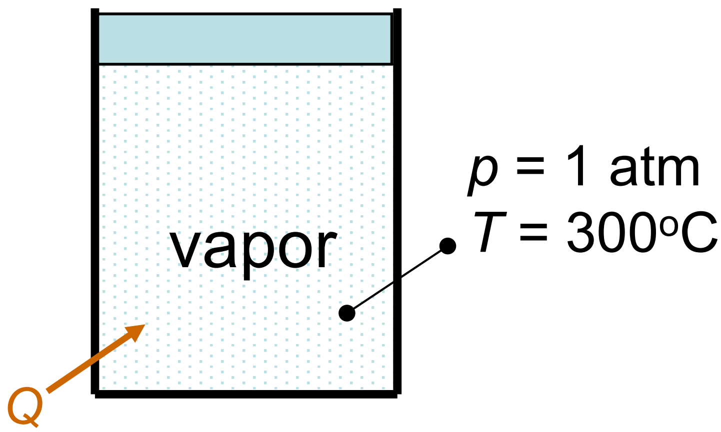
(c) “liquid-vapor mixture”

Keep adding heat until liquid is just gone”



(d) “saturated vapor”

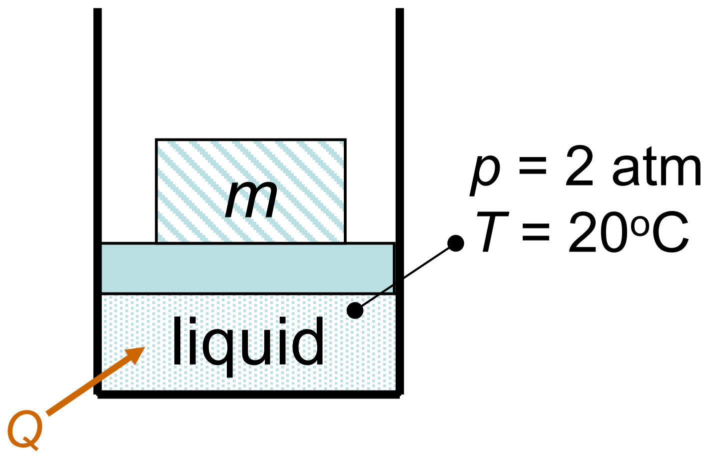
Keep adding heat



(e) "superheated vapor"

Temperature vs. specific volume (T vs. v)

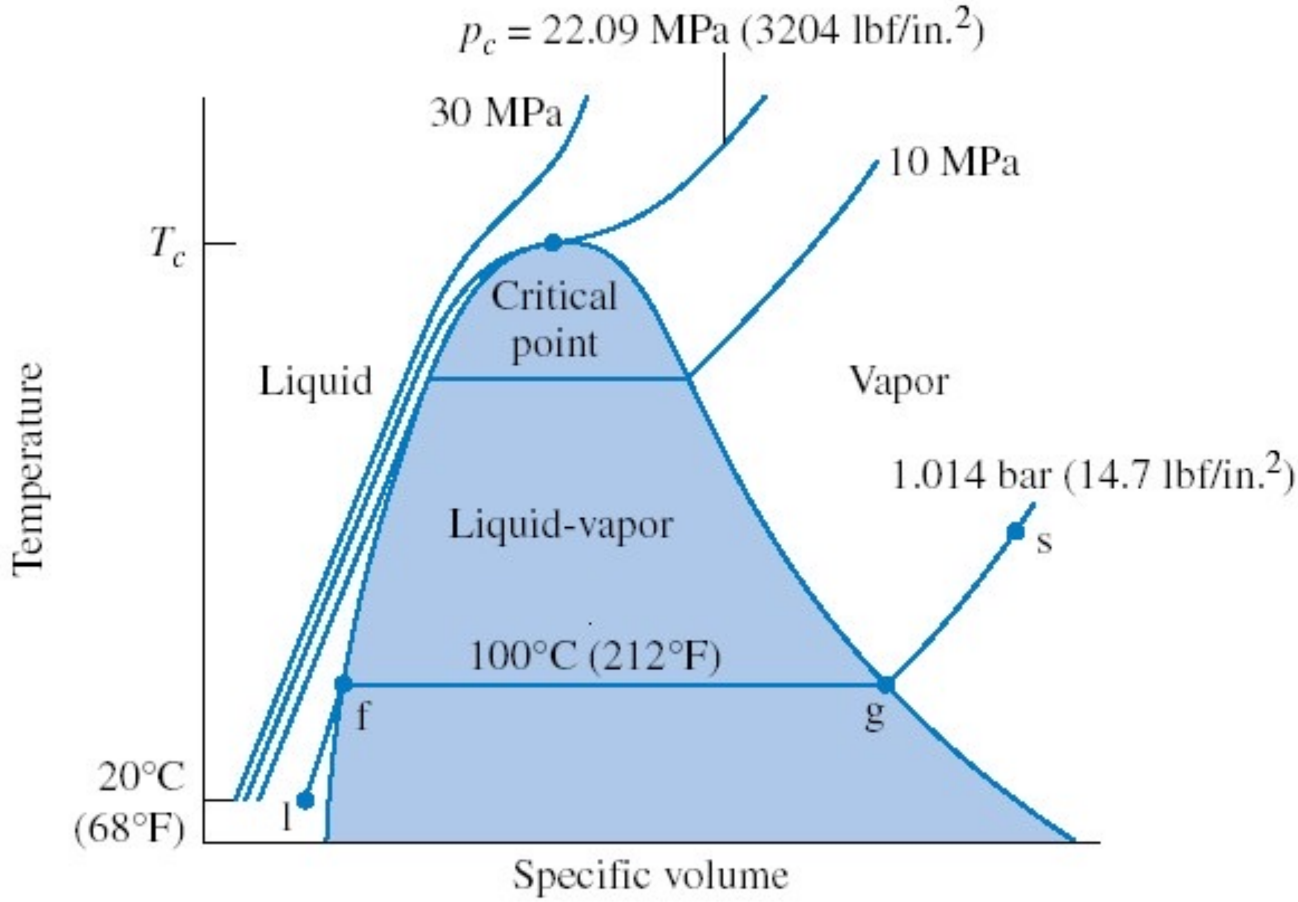
Suppose that mass is added above the piston and the experiment is repeated!



Does the initial specific volume change?

Does the saturation temperature change?

T-v diagram for water



<u>Property</u>: Any characteristic of a system

- Extensive: Depends on the size (extent) of the system, such as volume, mass
- Intensive: Does not depend on the size of the system, such as specific volume, density

<u>State</u>: The "condition" of a system as described by its properties

<u>State Principle</u>: The equilibrium state of a simple homogeneous substance is fixed by any two independent, intensive properties.

Q-1 A butane lighter contains a mixture of liquid and vapor butane at room temperature. What are the minimum properties necessary to determine the pressure of the butane mixture?

A. Temperature only

B. Temperature and specific volume

C. Mass and specific volume

D. None of the above

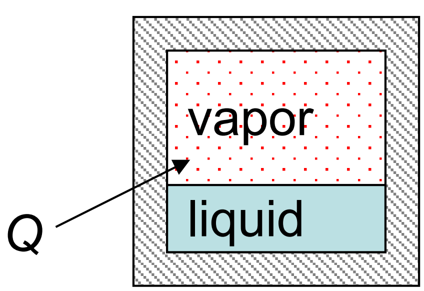
Q-2 A saturated mixture of liquid and vapor water is contained within a rigid tank at the condition depicted as Point A on the T-v diagram below. Heat is then added until only one phase is present. Which phase is it?

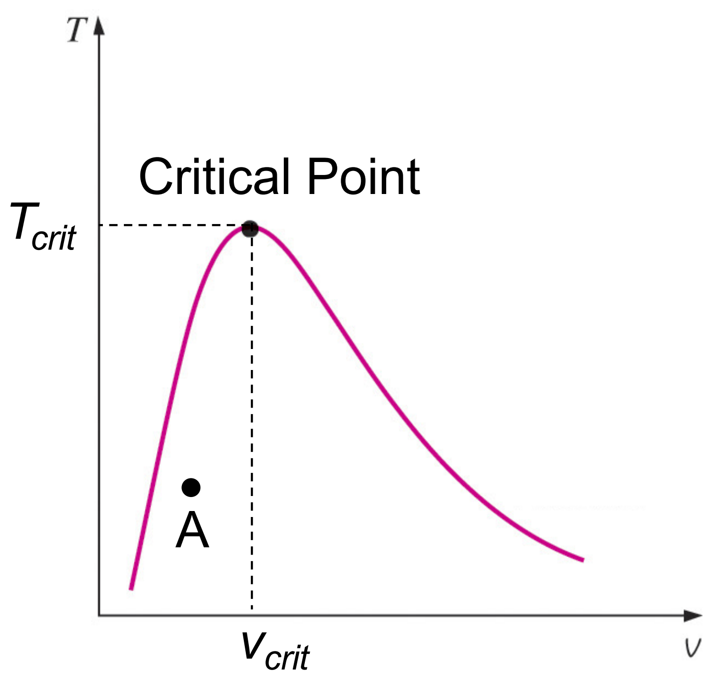
A. Solid

B. Liquid

C. Vapor

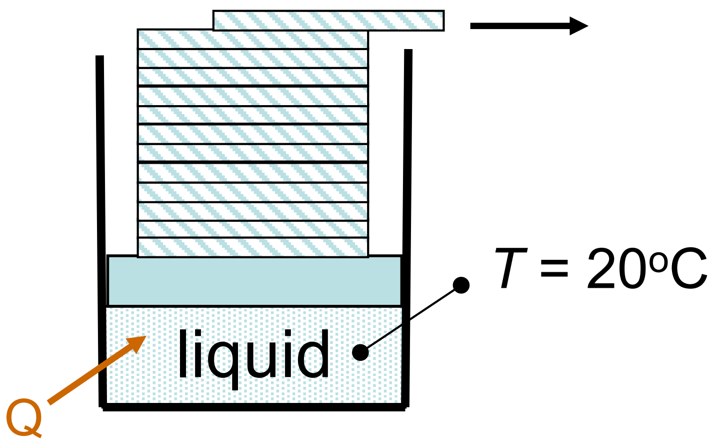
D. Not enough information

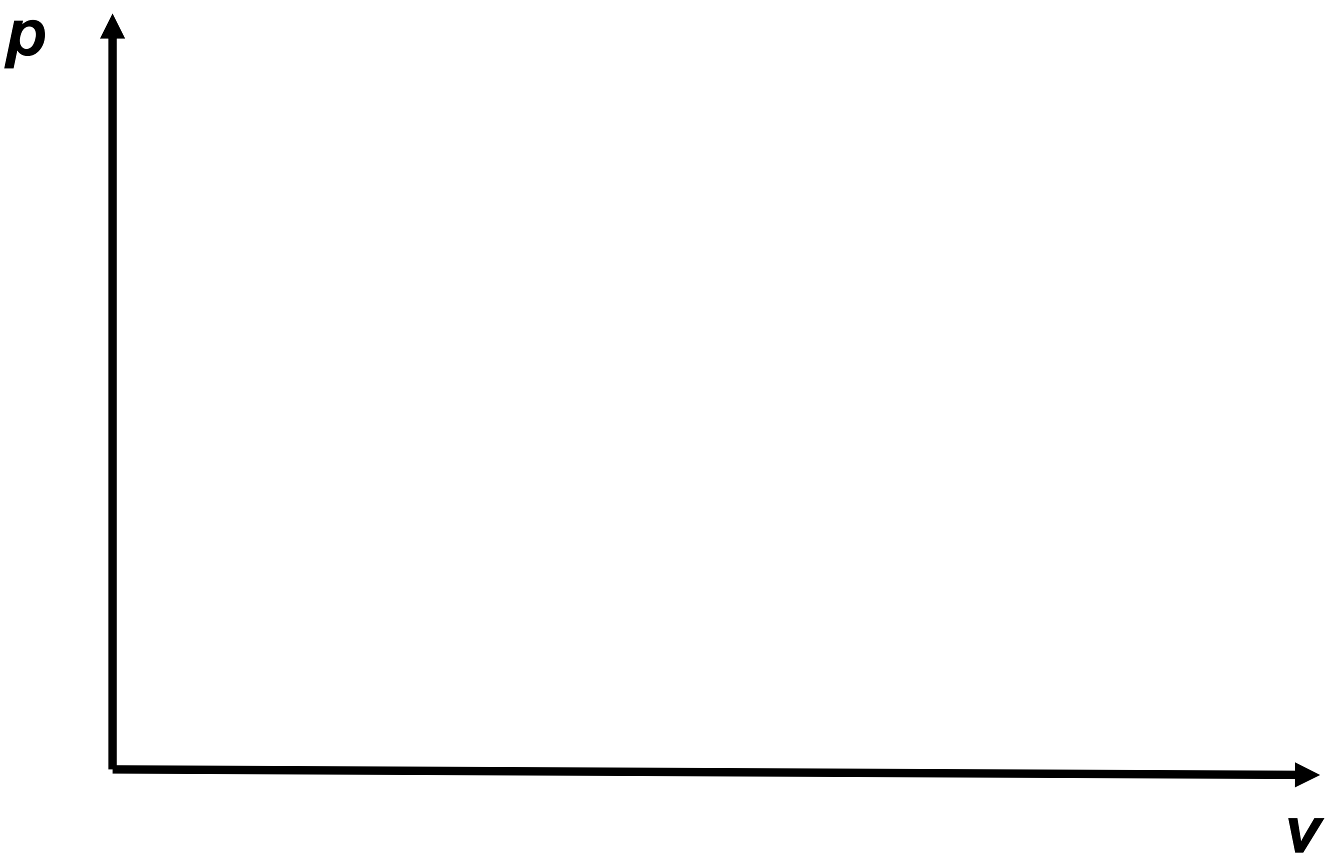




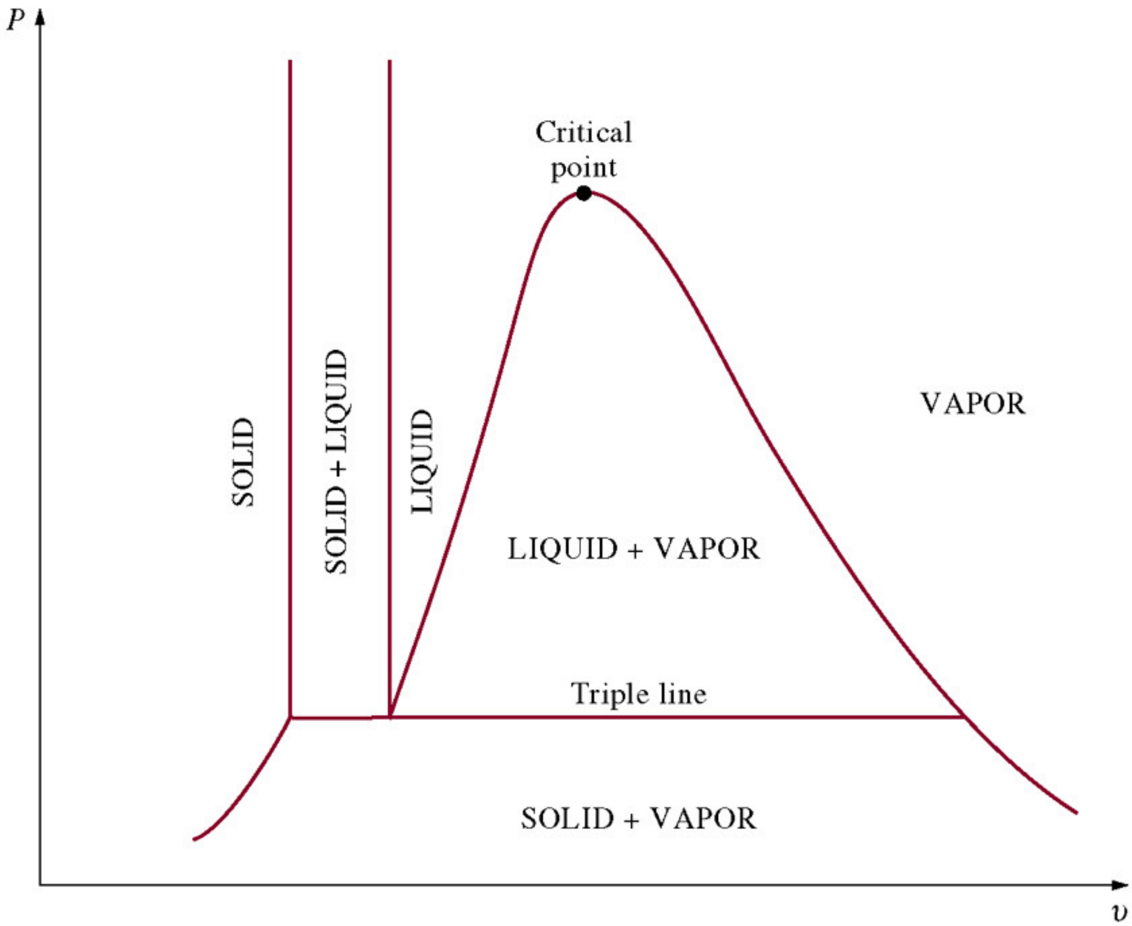
2. Now consider phase change at constant temperature

- Consider pure water in a sealed container with a floating top with weights above
- Remove weights to reduce pressure (*p*)
- Add heat to keep constant temperature

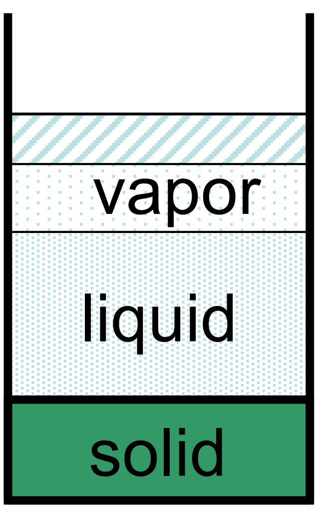




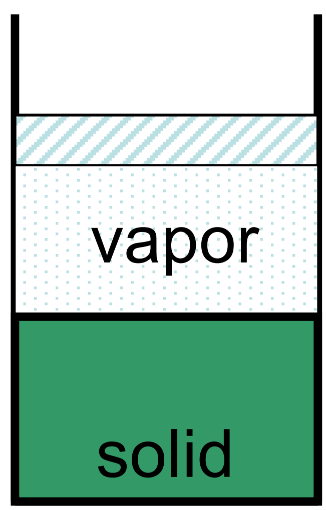
P-*v* diagram of a substance that contracts on freezing.



<u>Triple point</u>: all 3 phases coexist



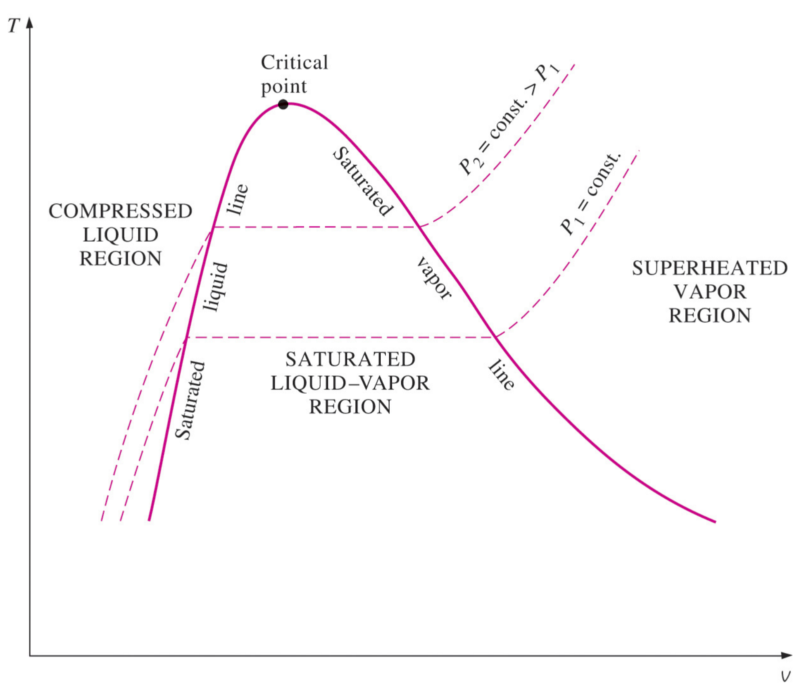
<u>Sublimation</u>: at pressures below triple point



Lecture 8
Property Tables for "Real" Fluids

- Properties are listed in the form of tables, e.g. steam tables
- They list property information for each region of interest, such as SHV, CL, and SLVM regions
- Looking at steam tables you find enthalpy, *h*, and entropy, *s*, which we have not discussed yet
- Entropy later, enthalpy now . . .
- *H=U+PV* (kJ) or *h=u+pv* (kJ/kg)
- *P, T, v, u, h*, and *s* data are tabulated

Phases of a Pure Substance



- Compressed liquid (CL)
- Saturated liquid
  - Uses subscript "f"
- Saturated liquid-vapor mixture (SLVM)
- Saturated vapor
  - Uses subscript "g"
- Superheated vapor (SHV)

$$s_{fg} = s_g - s_f$$

$$h_{fg} = h_g - h_f \qquad u_{fg} = u_g - u_f$$

Saturated water tables (*T* table, *P* table)

Saturated Temperature Table for Water

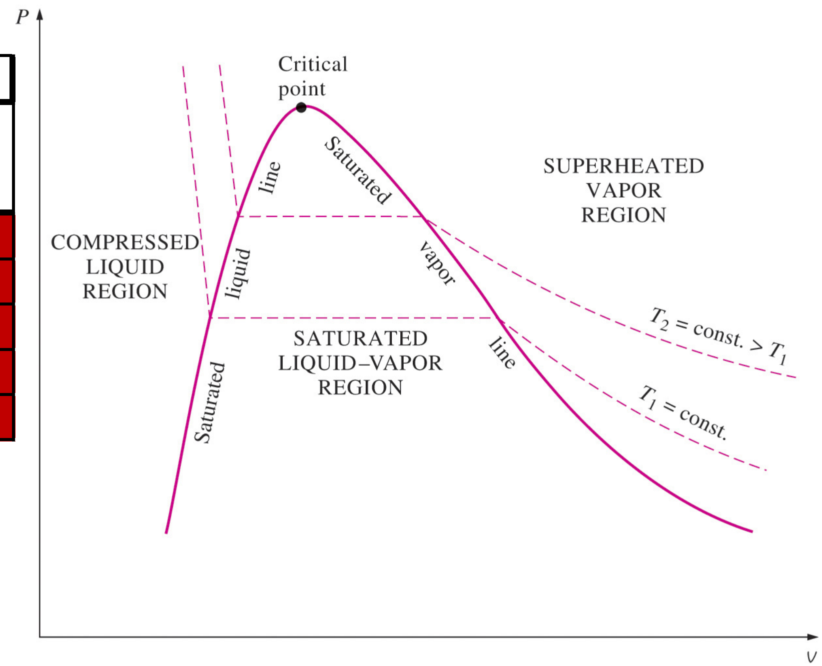
		Liquid	Vapor
Temp. (C)	Press. (bar)	Volume (v_f, m^3/kg)	Volume (v_g, m^3/kg)
0.01	0.0061165	0.0010002	205.99
4	0.0081355	0.0010001	157.12
5	0.0087258	0.0010001	147.01
6	0.0093536	0.0010001	137.63
8	0.010730	0.0010002	120.83

Temperature

Corresponding saturation pressure

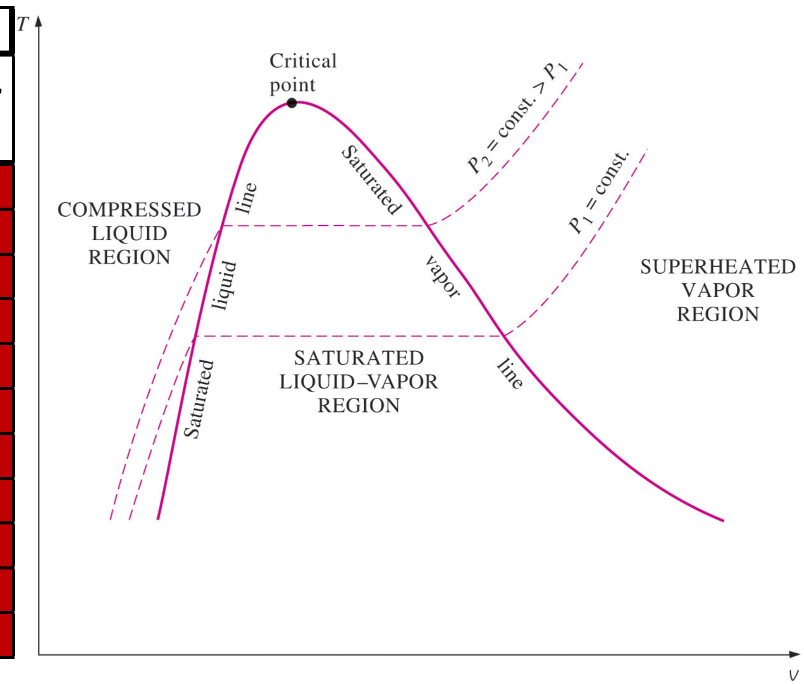
Specific volume of saturated liquid

Specific volume of saturated vapor



Saturated Pressure Table for Water

		Liquid	Vapor
Press. (bar)	Temp. (C)	Volume (v_f, m^3/kg)	Volume (v_g, m^3/kg)
0.01	6.970	0.0010001	129.18
0.02	17.50	0.0010014	66.987
0.03	24.08	0.0010028	45.653
0.04	28.96	0.0010041	34.791
0.05	32.87	0.0010053	28.185
0.06	36.16	0.0010065	23.733
0.07	39.00	0.0010075	20.524
0.08	41.51	0.0010085	18.099
0.09	43.76	0.0010094	16.199
0.1	45.81	0.0010103	14.670
0.2	60.06	0.0010172	7.6480

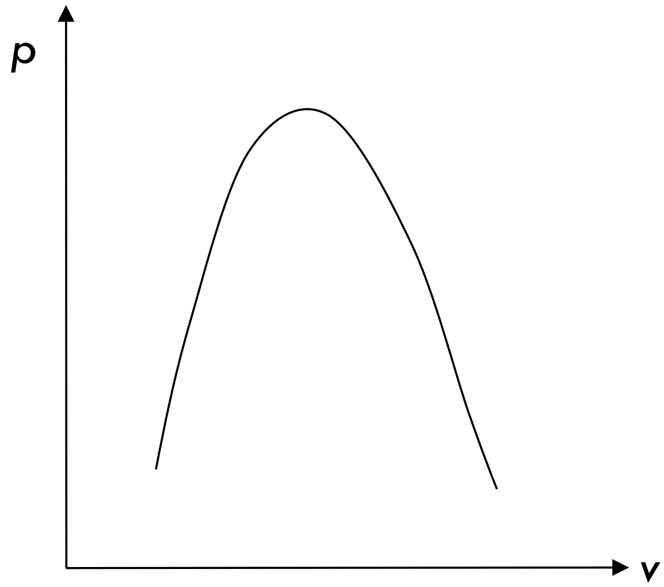


v

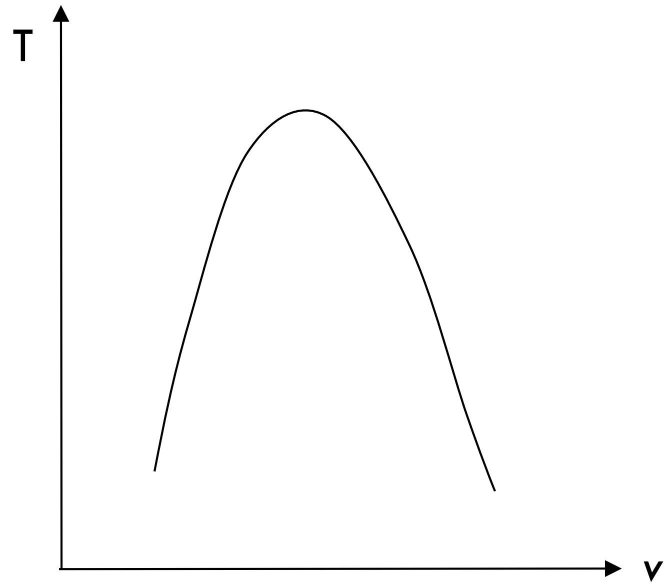
Examples

What is the phase of water at the following states?

State 1: p = 350 kPa and T = 178 ^oC



State 2: p = 9 kPa and T = 50 ^oC



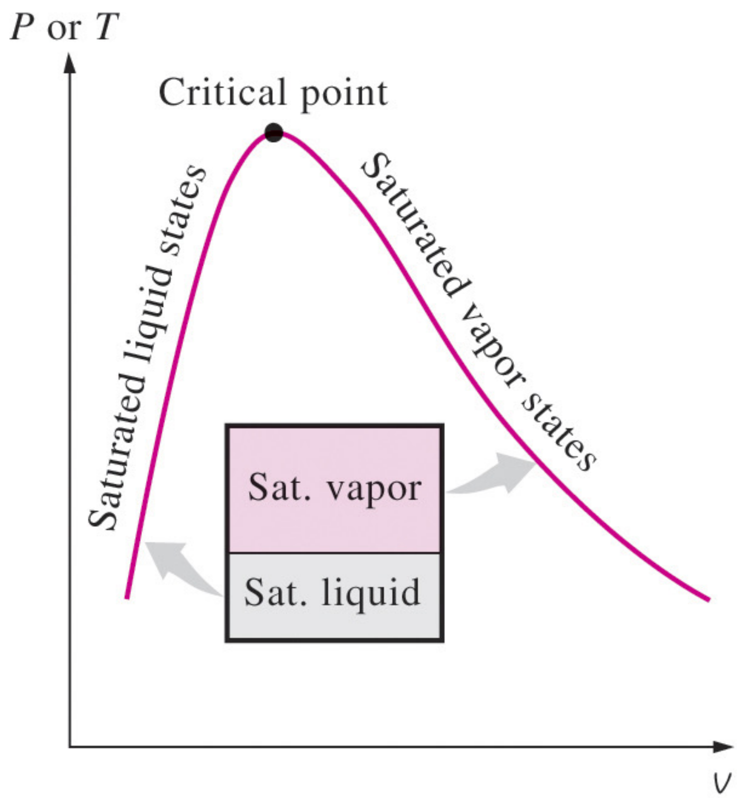
Examples

A rigid tank contains 50 kg of saturated liquid water at 90 C. Determine the pressure in the tank and volume in the tank.

A piston-cylinder device contains 50 liters of saturated water vapor at 3 bar. Determine *T* of vapor and mass of vapor inside the cylinder.

Saturated Liquid-Vapor Mixture (SLVM)

- During vaporization or condensation substance exists as part liquid and part vapor i.e. mixture of SL and SV



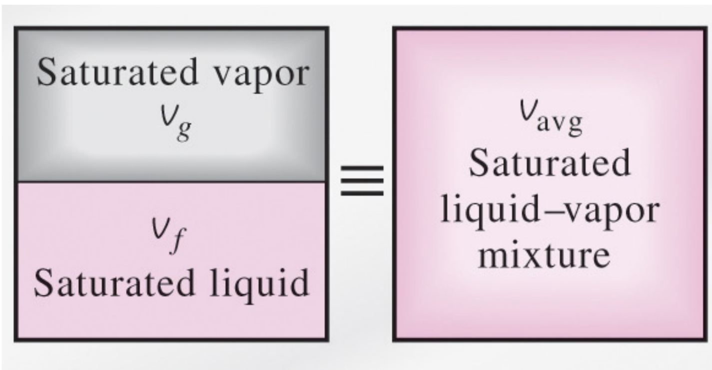
- We need to know proportions of each phase in mixture
- We define quality, x, as ratio of mass of vapor to total mass of mixture

$$x \equiv \frac{m_{vap}}{m_{total}} \qquad m_{total} = m_{liq} + m_{vap} = m_f + m_g$$

- x always between 0 and 1, i.e. *x*=0 for SL and x=1 for SV
- *x* can be used as one of two independent, intensive properties to fix state
- Properties of SL and SV are same in mixture as if alone

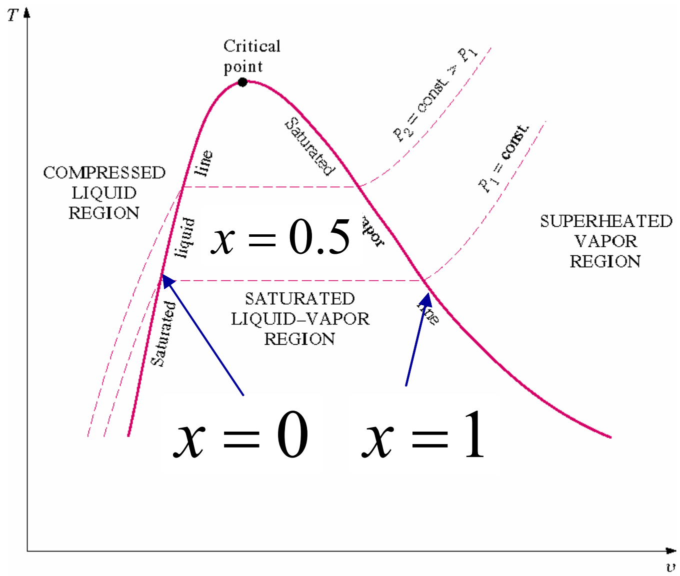
SLVM Properties

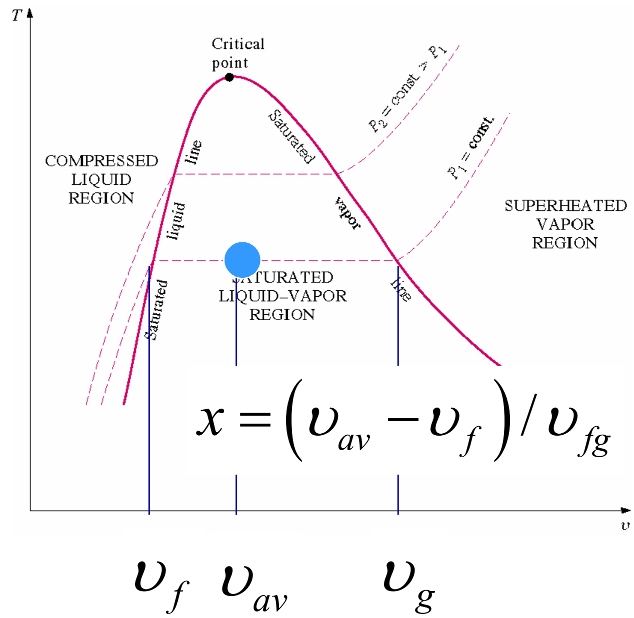
- We normally pretend SLVM is homogeneous mixture



- x has no meaning outside of the wet dome

Quality on the Wet Dome





Example

A rigid tank contains 10 kg of water at 90 C. If 8 kg of water is in liquid form and the rest is in vapor form, determine (a) *p* in tank, (b) *V* of tank.

Superheated Vapor (SHV)

- Single phase region to right of SV line
- *T*, *p* are independent and fix state
- $p<p_{sat}$ at given T
- $T>T_{sat}$ at given p
- *v*, *u*, *h* > SV values at given *p* or *T*

Superheated Water Vapor

Temp. (C)	Volume (m^3/kg)	Internal Energy (kJ/kg)	Enthalpy (kJ/kg)	Entropy (kJ/kg/K)
	p = 0.06 bar, T_{sat} = 36.16°C			
Sat.	23.733	2424.2	2566.6	8.3290
80	27.133	2487.2	2650.0	8.5811
120	30.220	2544.7	2726.0	8.7850
160	33.303	2602.7	2802.5	8.9703
200	36.383	2661.5	2879.8	9.1409
240	39.463	2721.1	2957.9	9.2994

Temp. (C)	Volume (m^3/kg)	Internal Energy (kJ/kg)	Enthalpy (kJ/kg)	Entropy (kJ/kg/K)
	p = 0.7 bar = 0.07 MPa, T_{sat} = 89.93°C			
Sat.	2.3648	2493.9	2659.4	7.4790
100	2.4343	2509.4	2679.8	7.5344
120	2.5710	2539.7	2719.7	7.6385
160	2.8409	2599.5	2798.4	7.8292
200	3.1083	2659.3	2876.8	8.0024

Example

- Find internal energy (u) of water at 5 bar and 240 C.

- Find temperature of water at p=0.5 MPa and h=2890 kJ/kg

Linear Interpolation

- Assumes any two data points connected by straight line (set slopes equal to find missing value)

A	B
100	5
130	X
200	10

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

Compressed Liquid (CL)

- Not much data due to relative independence of CL properties with pressure
  - Only for water at high pressure (2.5 to 30 MPa)
- $p>p_{sat}$ at given T (CL) and $T<T_{sat}$ at given p (SC)

Water Compressed Liquid Data

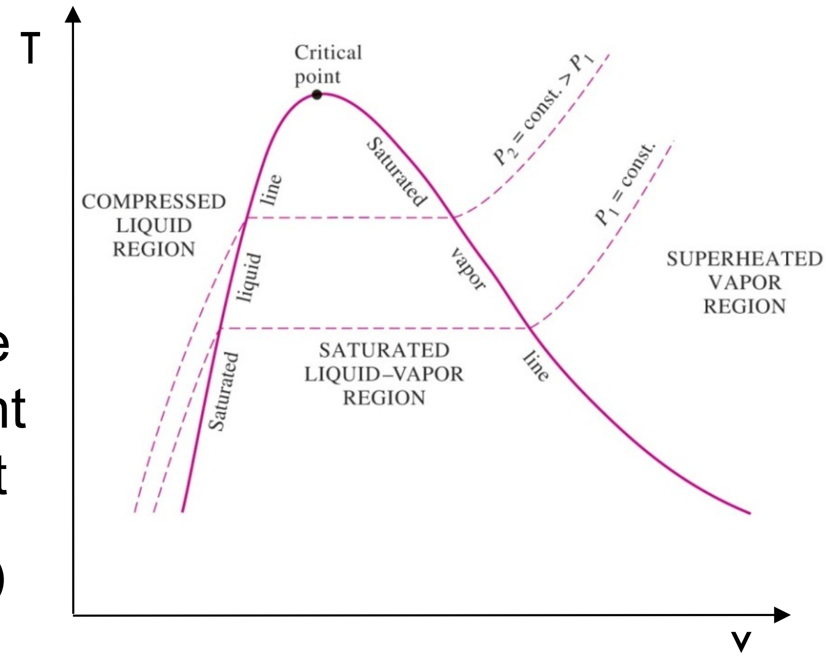
Temp. (C)	Volume (m^3/kg)	Internal Energy (kJ/kg)	Enthalpy (kJ/kg)	Entropy (kJ/kg/K)	Volume (m^3/kg)	Internal Energy (kJ/kg)	Enthalpy (kJ/kg)	Entropy (kJ/kg/K)
	p = 25 bar, T_{sat} = 223.95°C				p = 50 bar = 5.0 MPa, T_{sat} = 263.94°C			
20	1.0007E-03	83.76	86.26	0.29596	9.9956E-04	83.61	88.61	0.29543
40	1.0068E-03	167.22	169.74	0.57143	1.0057E-03	166.92	171.95	0.57046
80	1.0279E-03	334.39	336.96	1.0740	1.0267E-03	333.82	338.95	1.0723
100	1.0422E-03	418.36	420.97	1.3053	1.0410E-03	417.64	422.85	1.3034
140	1.0784E-03	587.85	590.55	1.7370	1.0769E-03	586.79	592.18	1.7344
180	1.1261E-03	760.99	763.81	2.1372	1.1240E-03	759.46	765.08	2.1338
200	1.1556E-03	849.76	852.65	2.3290	1.1531E-03	847.91	853.68	2.3251
220	1.1899E-03	940.65	943.63	2.5173	1.1868E-03	938.39	944.32	2.5127
Sat.	1.1974E-03	958.91	961.91	2.5543	1.2864E-03	1148.20	1154.60	2.9210

Compressed Liquid (CL)

- Liquid can be considered incompressible if change in pressure barely changes *v* and *u*
- Good approximation for *v* and *u* of CL is to treat as SL at same *T* (properties of CL do vary with *T*)

$$v \cong v_{f@T}$$

$$u \cong u_{f@T}$$



- Enthalpy of CL has a pressure dependence that may be significant at high pressures, but

$$h \cong h_{f@T} + v_f(P - P_{sat})$$

Example

Determine internal energy of CL water at 80 C and 5 MPa using (a) data from CL table and (b) SL data. Error?

Reference State and Values

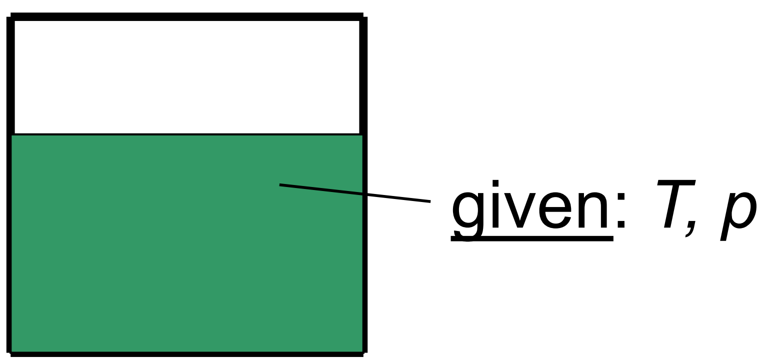
- *u, h, s* cannot be measured directly
- *p, T, v* can be measured directly
- Changes in *u, h, s* computed using derived relations with *p, T, v*
- Note: only changes can be computed, not *u, h, s*, at a specific state
- But fortunately in 1st and 2nd laws only changes in these properties are needed
- We choose a convenient reference state and set properties to zero at that state
- For water, $u = 0$, $s = 0$, at 0.01°C for SL state: Note that: 1) $h=u+pv$; 2) u and h could have negative values relative to reference; 3) different ref. state for different substances; 4) ref. state cancels out

$$\left(u_2 - u_{ref}\right) - \left(u_1 - u_{ref}\right) = u_2 - u_1 = \Delta u$$

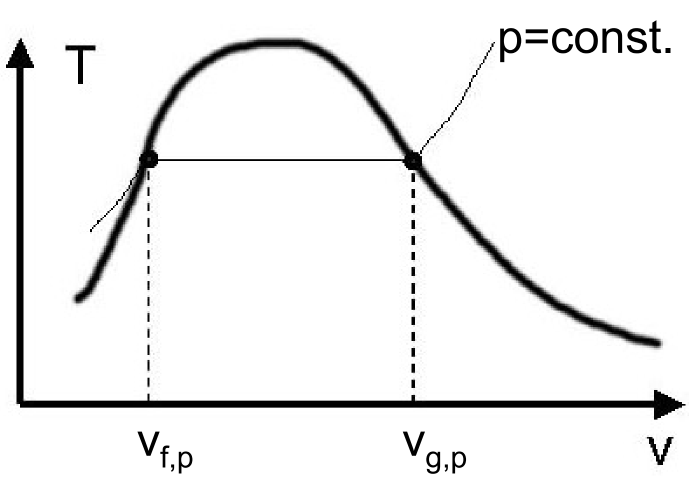
Lecture 9
Examples with Properties

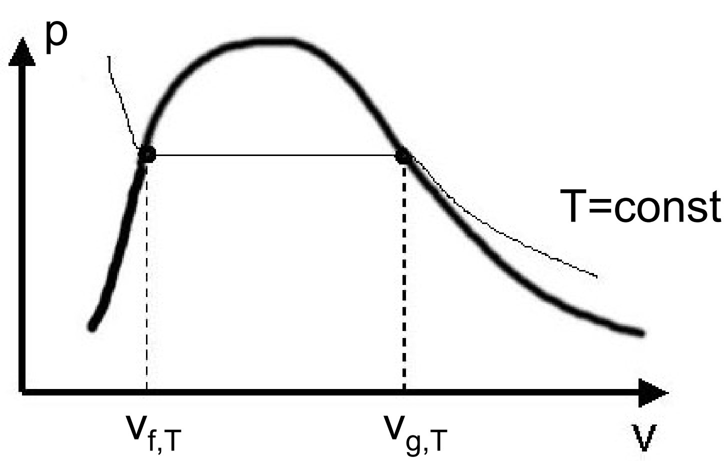
Condition of a Substance

Suppose we have a rigid tank containing a pure substance, how do we determine the state?

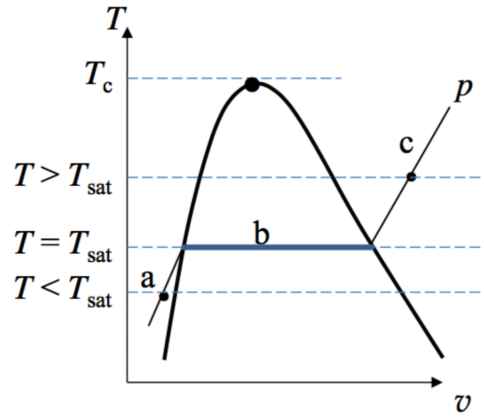
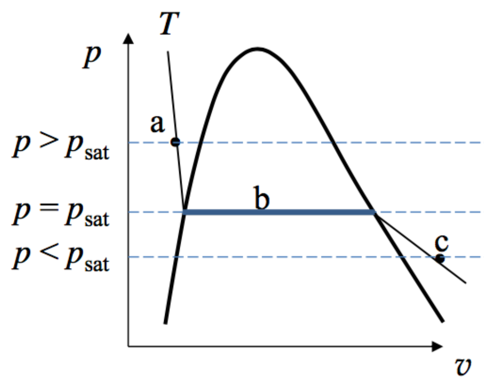
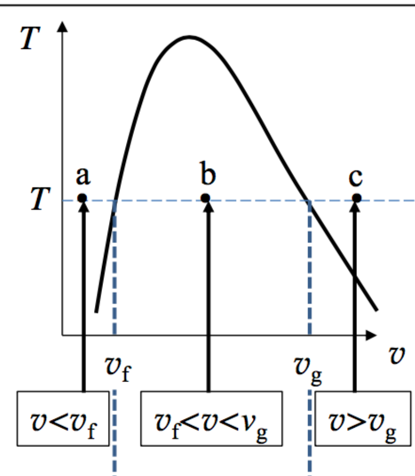


Look at the saturated conditions

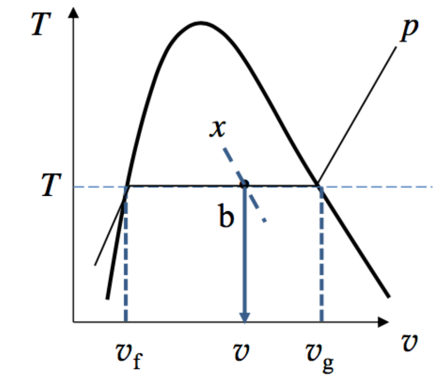
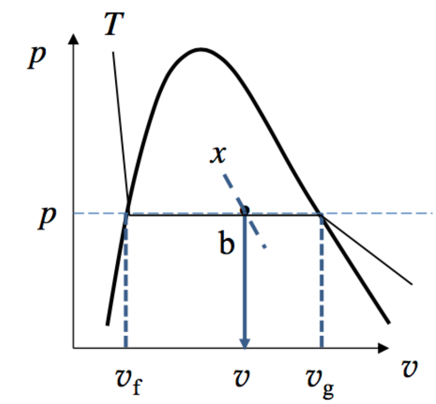




General Rules

Given Properties	Test to Determine Region of Vapor Dome	Vapor Dome Diagram
1. p 2. T	**Look up *p* in Saturation Properties - P tables:** a. If $T < T_{sat}$, Compressed liquid b. If $T = T_{sat}$, Two-phase, liquid-vapor mixture c. If $T > T_{sat}$, Superheated vapor d. If T > T_c, Superheated vapor	
1. p 2. T	**Look up *T* in Saturation Properties - T tables:** a. If $p > p_{sat}$, Compressed liquid b. It $p = p_{sat}$, Two-phase, liquid-vapor mixture c. If $p < p_{sat}$, Superheated vapor	
1. T 2. v, u, h, or s	**Look up *T* in Saturation Property - T tables:** a. If $v < v_f$, Compressed liquid b. If $v_f < v < v_g$, Two-phase, liquid-vapor mixture c. If $v > v_g$, Superheated vapor **Apply the same procedure if *u*, *h*, or *s* is given.**	

General Rules

Given Properties	Test to Determine Region of Vapor Dome	Vapor Dome Diagram
1. T 2. x	b. Two-phase, liquid vapor mixture	
1. p 2. x	b. Two-phase, liquid vapor mixture	

Quality Calculations:

$x = \dfrac{v - v_f}{v_g - v_f}$	$x = \dfrac{u - u_f}{u_g - u_f}$
$v = v_f + x(v_g - v_f)$	$u = u_f + x(u_g - u_f)$

$x = \dfrac{h - h_f}{h_g - h_f} = \dfrac{h - h_f}{h_{fg}}$	$x = \dfrac{s - s_f}{s_g - s_f}$
$h = h_f + x(h_g - h_f) = h_f + xh_{fg}$	$s = s_f + x(s_g - s_f)$

Example

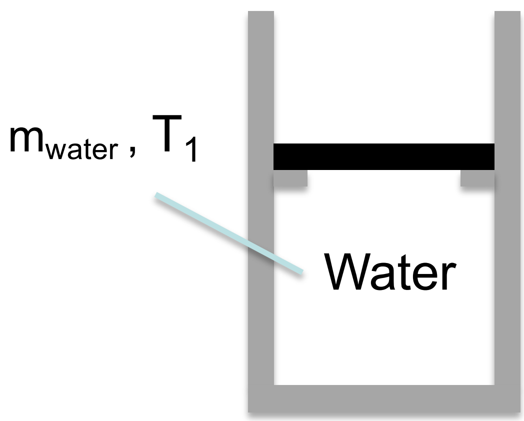
Given: Piston cylinder containing water; floating piston with negligible mass, sitting on stops & exposed to ambient pressure

V_1 = 1 m^3, m_{water} = 5 kg, T_1 = 50^{o}C, P_{atm} = 100 kPa

Find: P_1, u_1

System: P_{atm} = 100 kPa

Assumptions:



Suppose the mixture is heated until piston just begins to move. Determine P_2, u_2, and Q_{12}. Show the process on a P-v diagram

The process continues until all the water is a saturated vapor. Show the process on a P-v diagram. Determine P_3, u_3, and Q_{23}.

Heat continues to be added until the water temperature is 200 C. Show the process on a P-v diagram. Determine u_4, and Q_{34}.

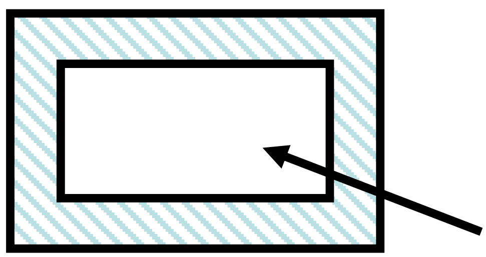
Another Example

An insulated tank is divided into two parts by a partition. One part of the tank contains 2.5 kg of compressed liquid water at 60°C and 600 kPa while the other part is evacuated. The partition is now removed, and the water expands to fill the entire tank. Determine the final temperature of the water and the volume of the tank for a final pressure of 10 kPa.

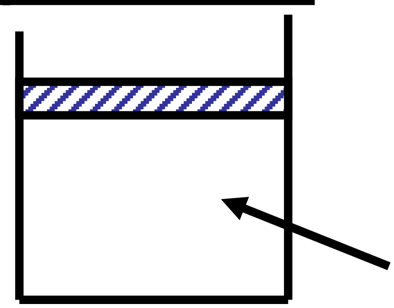
Lecture 10
Specific Heats

- Definitions
- Application to evaluating incompressible substance properties
  - Compressed liquids and solids

Constant Volume Specific Heat



Constant Pressure Specific Heat



- Intensive properties
- Measure of the energy required to raise the temperature of a substance at constant volume or constant pressure
- Defined for liquid, gases, and solids, **but <u>not</u> for two-phase mixtures**

Compressed Liquid Properties

Three ways to evaluate:

1. Use compressed liquid tables
    - they're not typically available

2. Neglect pressure dependence on specific volume and internal energy
    - Excellent assumption under most circumstances

3. Assume incompressible
    - Also works well in most cases

1. Compressed Liquid Tables

Water Compressed Liquid Data

Temp. (C)	Volume (m^3/kg)	Internal Energy (kJ/kg)	Enthalpy (kJ/kg)	Entropy (kJ/kg/K)	Volume (m^3/kg)	Internal Energy (kJ/kg)	Enthalpy (kJ/kg)	Entropy (kJ/kg/K)
	p = 25 bar, T_{sat} = 223.95°C				p = 50 bar = 5.0 MPa, T_{sat} = 263.94°C			
20	1.0007E-03	83.76	86.26	0.29596	9.9956E-04	83.61	88.61	0.29543
40	1.0068E-03	167.22	169.74	0.57143	1.0057E-03	166.92	171.95	0.57046
80	1.0279E-03	334.39	336.96	1.0740	1.0267E-03	333.82	338.95	1.0723
100	1.0422E-03	418.36	420.97	1.3053	1.0410E-03	417.64	422.85	1.3034
140	1.0784E-03	587.85	590.55	1.7370	1.0769E-03	586.79	592.18	1.7344
180	1.1261E-03	760.99	763.81	2.1372	1.1240E-03	759.46	765.08	2.1338
200	1.1556E-03	849.76	852.65	2.3290	1.1531E-03	847.91	853.68	2.3251
220	1.1899E-03	940.65	943.63	2.5173	1.1868E-03	938.39	944.32	2.5127
Sat.	1.1974E-03	958.91	961.91	2.5543	1.2864E-03	1148.20	1154.60	2.9210

Temp. (C)	Volume (m^3/kg)	Internal Energy (kJ/kg)	Enthalpy (kJ/kg)	Entropy (kJ/kg/K)	Volume (m^3/kg)	Internal Energy (kJ/kg)	Enthalpy (kJ/kg)	Entropy (kJ/kg/K)
	p = 75 bar = 7.5 MPa, T_{sat} = 290.54°C				p = 100 bar = 10.0 MPa, T_{sat} = 311.00°C			
20	9.9843E-04	83.46	90.95	0.29489	9.9731E-04	83.31	93.28	0.29435
40	1.0046E-03	166.63	174.16	0.56949	1.0035E-03	166.33	176.36	0.56851
80	1.0256E-03	333.25	340.95	1.0707	1.0244E-03	332.69	342.94	1.0691
100	1.0397E-03	416.93	424.73	1.3015	1.0385E-03	416.23	426.62	1.2996
140	1.0753E-03	585.75	593.81	1.7319	1.0738E-03	584.71	595.45	1.7293
180	1.1220E-03	757.96	766.37	2.1304	1.1200E-03	756.48	767.68	2.1271
220	1.1838E-03	936.17	945.05	2.5082	1.1809E-03	934.00	945.81	2.5037
260	1.2703E-03	1125.00	1134.50	2.8775	1.2653E-03	1121.60	1134.30	2.8710
Sat.	1.3682E-03	1282.70	1292.90	3.1662	1.4526E-03	1393.50	1408.10	3.3606

Temp. (C)	Volume (m^3/kg)	Internal Energy (kJ/kg)	Enthalpy (kJ/kg)	Entropy (kJ/kg/K)	Volume (m^3/kg)	Internal Energy (kJ/kg)	Enthalpy (kJ/kg)	Entropy (kJ/kg/K)
	p = 150 bar = 15.0 MPa, T_{sat} = 342.16°C				p = 200 bar = 20.0 MPa, T_{sat} = 365.75°C			
20	9.9510E-04	83.01	97.93	0.29323	9.9292E-04	82.71	102.57	0.29207
40	1.0013E-03	165.75	180.77	0.56656	9.9923E-04	165.17	185.16	0.56461
80	1.0221E-03	331.59	346.92	1.0659	1.0199E-03	330.50	350.90	1.0627
100	1.0361E-03	414.85	430.39	1.2958	1.0337E-03	413.50	434.17	1.2920
140	1.0708E-03	582.69	598.75	1.7243	1.0679E-03	580.71	602.07	1.7194
180	1.1160E-03	753.58	770.32	2.1206	1.1122E-03	750.77	773.02	2.1143
220	1.1752E-03	929.80	947.43	2.4951	1.1697E-03	925.77	949.16	2.4867
260	1.2560E-03	1115.10	1134.00	2.8586	1.2472E-03	1109.00	1134.00	2.8469
300	1.3783E-03	1317.60	1338.30	3.2279	1.3611E-03	1307.10	1334.40	3.2091
Sat.	1.6570E-03	1585.30	1610.20	3.6846	2.0400E-03	1786.40	1827.20	4.0156

2. Neglect P Dependence for v and u

$$v(T,P) \approx v_f(T)$$

$$u(T,P) \approx u_f(T)$$

Saturated Liquid Water Properties

		Liquid			
Temp. (C)	Press. (bar)	Volume (v_f, m^3/kg)	Internal Energy (u_f, kJ/kg)	Enthalpy (h_f, kJ/kg)	Entropy (s_f, kJ/kg/K)
0.01	0.0061165	0.0010002	0.0000	0.00061178	0.000000
4	0.0081355	0.0010001	16.812	16.813	0.061103
5	0.0087258	0.0010001	21.019	21.020	0.076254
6	0.0093536	0.0010001	25.223	25.224	0.091342
8	0.010730	0.0010002	33.626	33.627	0.121330
10	0.012282	0.0010003	42.020	42.021	0.151090
11	0.013130	0.0010004	46.215	46.216	0.165870
12	0.014028	0.0010005	50.408	50.409	0.180610
13	0.014981	0.0010007	54.600	54.601	0.195280
14	0.015990	0.0010008	58.790	58.792	0.209900
15	0.017058	0.0010009	62.980	62.981	0.224460

3. Incompressible Assumption

$$v = \text{constant}$$

$$u = u(T) \quad \text{only}$$

Specific Heats of Some Solids and Liquid Water

Substance	Temperature [K]	c_p [kJ/(kgK)]
Copper	300	0.3894
Lead	300	0.129
Water (saturated liquid)	275	4.214
	300	4.181
	325	4.182
	350	4.195
	375	4.218
	400	4.255

Example

During a picnic on a hot summer day, all the cold drinks disappeared quickly, and the only available drinks were those at the ambient temperature of 75°F (23.9°C). To cool a 12-fluid-oz (0.35 liter) drink in a can, a person puts the warm can in the iced water of the chest at 32°F (0°C). Using the properties of water for the drink, determine the mass of ice that will melt by the time the canned drink cools to 45°F (7.2°C).

Lectures 11 & 12
Ideal Gas Model and Applications

- Ideal gas equation of state
- Application of specific heats to evaluating ideal gases properties
- Polytropic processes

Ideal Gas Equation of State

- Equation of state relates *P, v*, and *T*
- Ideal gas law is valid at "low" pressures

$$pV = n\bar{R}T$$

p: pressure [N/m^2] or [psi]

V: volume [m^3] or [ft^3]

n: number of moles [kmol] or [lb_{mol}]

$\bar{R}$: universal gas constant [8.314 kJ/kmol-K or 10.73 psi ft^3/lb_{mol}-R]

T: temperature [K] or [R]

Note: 1 mole contains 6.023×10^{23} molecules

Can rewrite as

$$\frac{pV}{n} = \bar{R}T \qquad \text{or} \qquad p\bar{v} = \bar{R}T$$

$\bar{v}$: molar specific volume [m^3/kmol] or [ft^3/lbmol]

Can express on a mass basis by introducing the gas molar mass, *M*

M = molar mass [kg/kmol] or [lbm/lbmol]

$$pV = M \cdot n \frac{\bar{R}}{M} T \qquad \text{or} \qquad pV = mRT$$

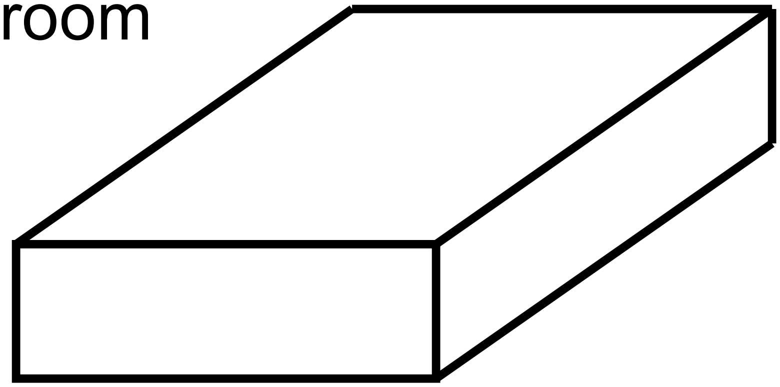
or

$$pv = RT$$

$R = \bar{R} / M$: specific gas constant [kJ/kg-K] or [Btu/lbm-R]

Example

Given: Large Classroom
(3m x 6m x 10m)
$T = 25^oC$
p = 100 kPa



Find: Mass of air inside the classroom

Assumptions:

Solution:

Ideal Gas Processes for a Closed System

m = constant and R = constant

Therefore, for a process from state 1 to 2

$$\frac{p_1 V_1}{T_1} = mR \quad = \frac{p_2 V_2}{T_2}$$

or

$$\frac{V_2}{V_1} = \frac{v_2}{v_1} = \frac{T_2}{T_1}\frac{p_1}{p_2}$$

Special Cases

1. Constant volume process (isochoric, $V_2 = V_1$) ⇨ $\frac{T_2}{T_1} = \frac{p_2}{p_1}$

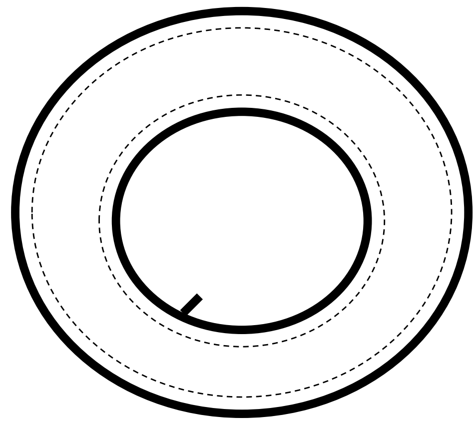
2. Constant temperature process (isothermal, $T_1 = T_2$) ⇨ $\frac{p_2}{p_1} = \frac{V_1}{V_2}$

3. Constant pressure process (isobaric, $P_1 = P_2$): ⇨ $\frac{T_2}{T_1} = \frac{V_2}{V_1}$

Example

Given: automotive tire, initially at T_1 = 75°F (23.9°C) & P_1 = 32 psi_g (221 kPa gauge); after driving for a while, T_2 =105°F (40.6°C)

Find: the effect of increased temperature on tire pressure?

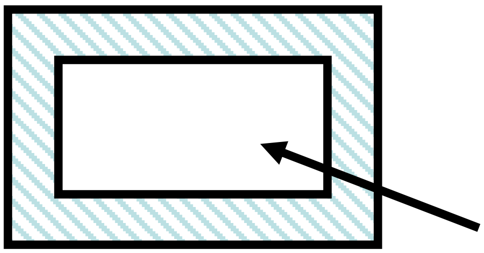


Assumptions:

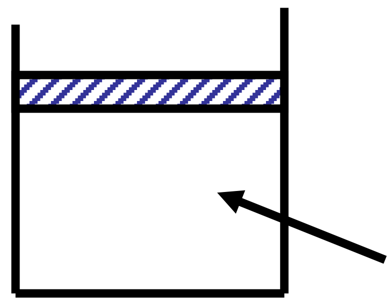
Solution:

Applying Specific Heats for Evaluating Ideal Gases Properties

Constant Volume Specific Heat



Constant Pressure Specific Heat



- Intensive properties
- Measure of the energy required to raise the temperature of a substance at constant volume or constant pressure
- Defined for liquid, gases, and solids, **but not for two-phase mixtures**

Specific Heats for Ideal Gases

From experiments, it is known that for gases that exhibit ideal gas behavior (Z ~ 1)

$$u = f(T) \quad \text{only}$$

Then

Property Changes for Ideal Gases

Consider an ideal gas undergoing a process from state 1 to 2. Then

$$\Delta u = u_2 - u_1 = \int_{u_1}^{u_2} du \quad = \int_{T_1}^{T_2} C_v dT$$

$$\Delta h = h_2 - h_1 = \int_{h_1}^{h_2} dh \quad = \int_{T_1}^{T_2} C_p dT$$

Three ways to evaluate integrals:

1. Assume constant specific heats

2. Use empirical functions for C_v and C_p that can be analytically integrated (see Table A-21)

3. Tabulated integrals (see ideal gas tables)

1. Assuming Constant Specific Heats

$$\Delta u = c_v\,(T_2 - T_1)$$

$$\Delta h = c_p\,(T_2 - T_1)$$

Specific Heats of Some Gases

Substance	Formula	MW	R [kJ/(kgK)]	c_P (300 K) [kJ/(kgK)]	c_v (300 K) [kJ/(kgK)]	T_{crit} [K]	P_{crit} [MPa]
Air	-	28.97	0.28700	1.005	0.7177	132.5	3.786
Ammonia	NH_3	17.031	0.48817	2.095	1.607	405.4	11.333
Carbon dioxide	CO_2	44.010	0.18892	0.8435	0.6546	304.1	7.377
Nitrogen	N_2	28.013	0.29680	1.038	0.7409	126.2	3.396
Oxygen	O_2	31.999	0.25983	0.9143	0.6544	154.6	5.043
Propane	C_3H_8	44.094	0.18855	1.666	1.478	369.8	4.247
R134a	CH_2F_4	102.03	0.08149	0.8367	0.7552	374.2	4.059
Water	H_2O	18.015	0.46152	1.868	1.407	647.1	22.064

How do handle temperature dependence?

Substance	Temperature [K]	c_p [kJ/(kgK)]
Air (ideal gas)	275	1.004
	300	1.005
	325	1.006
	350	1.008
	375	1.010
	400	1.013
	500	1.029
	600	1.051
	700	1.075
	800	1.099
	900	1.121
	1000	1.141

At what temperature should C_p be evaluated?

2. Empirical Specific Heat Relations

Given in Table A-21 using the form

$$\overline{C}_p = \overline{R} \cdot \left(\alpha + \beta T + \gamma T^2 + \delta T^3 + \varepsilon T^4\right)$$

Then

$$\Delta h = \frac{\overline{R}}{M} \int_{T_1}^{T_2} (\alpha + \beta T + \gamma T^2 + \delta T^3 + \varepsilon T^4)\, dT$$

$$\Delta u = \Delta h - \Delta(pv)$$

$$= \Delta h - R \Delta T$$

TABLE A-21

Variation of $\bar{c}_p$ with Temperature for Selected Ideal Gases

$$\frac{\bar{c}_p}{\bar{R}} = \alpha + \beta T + \gamma T^2 + \delta T^3 + \varepsilon T^4$$

T is in K, equations valid from 300 to 1000 K

Gas	α	$\beta \times 10^3$	$\gamma \times 10^6$	$\delta \times 10^9$	$\varepsilon \times 10^{12}$
CO	3.710	−1.619	3.692	−2.032	0.240
CO_2	2.401	8.735	−6.607	2.002	0
H_2	3.057	2.677	−5.810	5.521	−1.812
H_2O	4.070	−1.108	4.152	−2.964	0.807
O_2	3.626	−1.878	7.055	−6.764	2.156
N_2	3.675	−1.208	2.324	−0.632	−0.226
Air	3.653	−1.337	3.294	−1.913	0.2763
SO_2	3.267	5.324	0.684	−5.281	2.559
CH_4	3.826	−3.979	24.558	−22.733	6.963
C_2H_2	1.410	19.057	−24.501	16.391	−4.135
C_2H_4	1.426	11.383	7.989	−16.254	6.749
Monatomic gases[a]	2.5	0	0	0	0

[a]For monatomic gases, such as He, Ne, and Ar, $\bar{c}_p$ is constant over a wide temperature range and is very nearly equal to $5/2\,\bar{R}$.

3. Tabulated Integrals

Tabulated values determined from

$$u(T) = u_{ref} + \int_{T_{ref}}^{T} c_v dT$$

$$h(T) = h_{ref} + \int_{T_{ref}}^{T} c_p dT$$

Reference point
$h_{ref} = 0$ @ $T_{ref} = 0$ K

Determine changes as

$$\Delta u = u(T_2) - u(T_1) \qquad \Delta h = h(T_2) - h(T_1)$$

Ideal Gas Properties for Air

Temp. [K]	h [kJ/kg]	u [kJ/kg]	s° [kJ/kg/K]
200	200.0	142.5	1.309
210	210.0	149.7	1.352
220	220.0	156.8	1.395
230	230.0	164.0	1.437
240	240.0	171.1	1.479
250	250.0	178.3	1.520
260	260.0	185.4	1.559
270	270.0	192.6	1.597
280	280.1	199.8	1.633

Other Ideal Gas Relations

1st Law Example with Ideal Gas

Given: air in piston-cylinder device
initially: $V_1 = 0.02\ m^3$, $T_1 = 298\ K$
after heating: $V_2 = 0.04\ m^3$
piston exposed to atmosphere

System:

Find: final temperature, T_2 & heat transfer, Q

Assumptions:

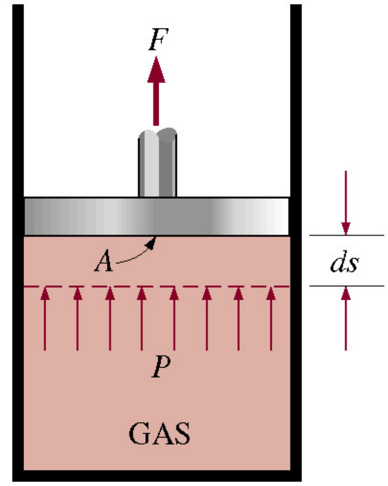
Analysis:

Polytropic Processes with Ideal Gases

A process where

$$pV^n = \text{constant} = C$$

where n is the polytropic coefficient



Then, the boundary work for a quasistatic process is

$$W = pdV = \int_{V_1}^{V_2} \frac{C}{V^n} dV = \frac{CV_2^{1-n} - CV_1^{1-n}}{1-n}$$

$$But\ C = p_1V_1^n = p_2V_2^n \Rightarrow$$

$$W = \frac{(p_2V_2^n)V_2^{1-n} - (p_1V_1^n)V_1^{1-n}}{1-n} = \frac{p_2V_2 - p_1V_1}{1-n}$$

- **Valid for any fluid undergoing a quasistatic, polytropic process except:**
  - **Not valid for *n* = 1**

For *n* = 1

$$pV = C \Rightarrow$$

$$W = \int_{V_1}^{V_2} p\,dV = \int_{V_1}^{V_2} \frac{C}{V} dV = C \ln\frac{V_2}{V_1}$$

$$W = (p_1 V_1) \ln\frac{V_2}{V_1}$$

Polytropic Processes with an Ideal Gas

For closed system with $n \neq 1$

$$W = \frac{mR\left(T_2 - T_1\right)}{1-n}$$

For closed system with $n = 1$

$$W = (mRT_1) \ln\frac{V_2}{V_1}$$