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Lecture 6

Topic 2

First Law of Thermodynamics

Topic 2.4
- Introduction to enthalpy
- Specific Heat

Reading:
Ch 3.7-3.11 Borgnakke & Sonntag Ed. 8
Ch 4-3 & 4-4 Cengel and Boles Ed. 5

Lecture material

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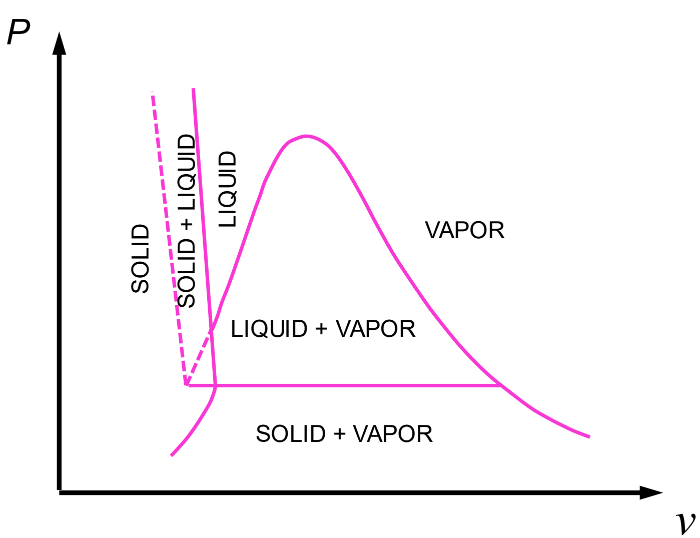
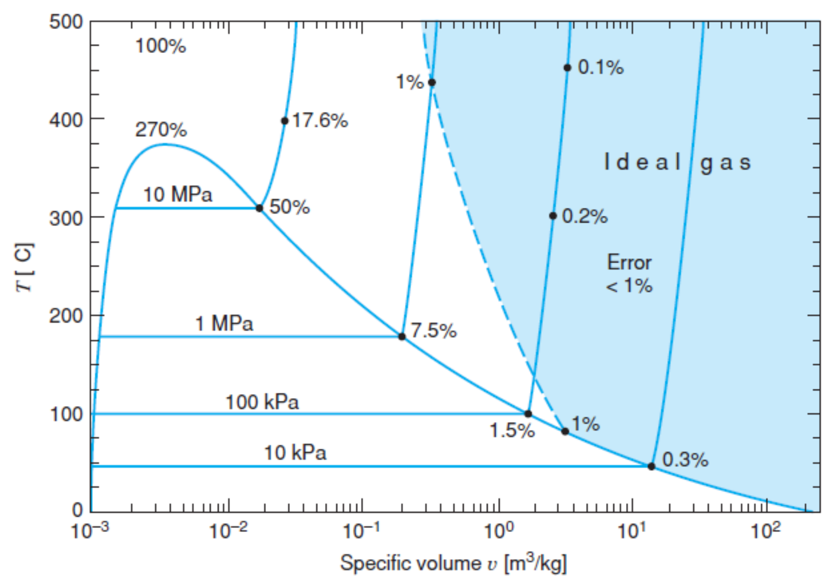
- Definition of Enthalpy (thermodynamic property)
  - $H = U + PV \quad OR \quad h = u + Pv$

- Specific heats C_v & C_P to determine ΔU & ΔH

$$\Delta U + \Delta KE + \Delta PE = Q_{process} - W_{process} + \Delta E_{mass}$$

- Focus on the following substances
  - Ideal gases (e.g. air, N_2, CO_2)
  - Liquids
  - Solids





2.3.4 Enthalpy

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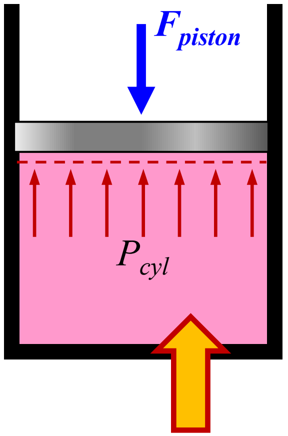
- Example: Heat addition under constant pressure process
  - Work: $W_{21} = \int_1^2 PdV = P(V_2 - V_1)$
  - 1st Law: $Q_{21} - W_{21} = U_2 - U_1$
  - $\rightarrow Q_{21} = U_2 - U_1 + P(V_2 - V_1) \quad OR \quad (U_2 + P_2V_2) - (U_1 + P_1V_1)$
  - U, P and V are all thermodynamic properties



- Thermodynamic property <u>Enthalpy</u>
  - $H = U + PV \quad OR \quad h = u + Pv$

- Heat transfer for constant pressure moving boundary system:
  - $Q_{21} = H_2 - H_1 = m(h_2 - h_1)$

- Specific enthalpy (h) is an intensive variable
  - Thermodynamic tables

TABLE B.1.1 *(continued)*
Saturated Water

		Enthalpy, kJ/kg		
Temp. (°C)	Press. (kPa)	Sat. Liquid h_f	Evap. h_{fg}	Sat. Vapor h_g
0.01	0.6113	0.00	2501.35	2501.35
5	0.8721	20.98	2489.57	2510.54
10	1.2276	41.99	2477.75	2519.74

2.4 Specific heats

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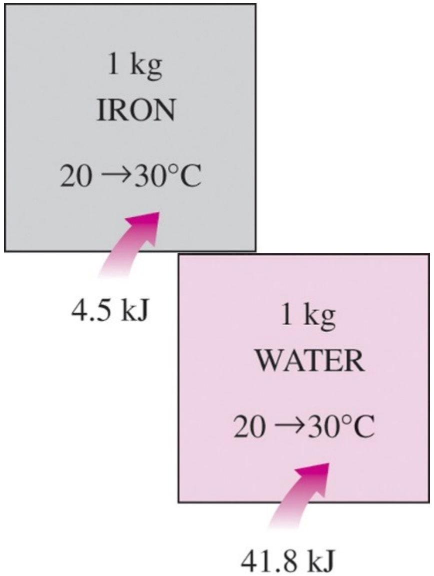
It takes different amounts of energy to increase the temperature of identical masses of different substances by 1°C.



Example:

- Takes 4.5 kJ to raise the temp. of 1kg iron from 20°→30°C
- Takes 41.8 kJ to raise the temp. of 1kg water from 20°→30°C

<u>Specific heat</u>: energy required to raise the temperature of a substance (unit mass) by one degree.

Specific heats for two cases:

- **Specific heat at constant volume (C_V):** energy required to raise the temp. of a substance (unit mass) by one degree as the <u>volume is maintained constant</u>.

- **Specific heat at constant pressure (C_P):** energy required to raise the temp. of a substance (unit mass) by one degree as the <u>pressure is maintained constant</u>.

2.4.1 C_p, C_v, U and H

- Relating C_p and C_v to other thermodynamic properties.

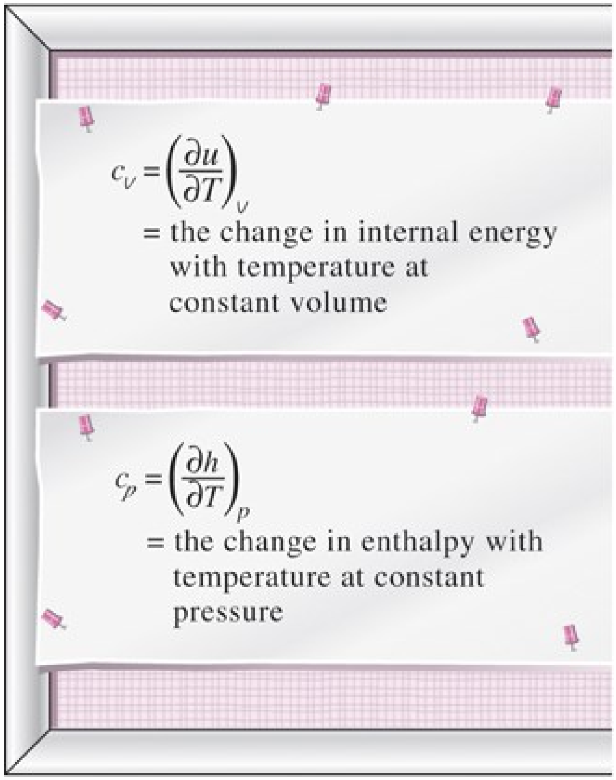
- Consider a fixed mass in a stationary, closed system undergoing a <u>constant-volume process</u>.
  - 1st law gives:
    - $\delta Q - \delta W = dU \quad \rightarrow \quad \delta Q = dU$
    - Definition of specific heat: $mC_v dT = \delta Q \quad \rightarrow mC_v dT = dU$

- Consider a fixed mass in a stationary, closed system undergoing a <u>constant-pressure process</u>.
  - 1st law gives:
    - $\delta Q - \delta W = dU \quad \rightarrow \quad \delta Q = dU + PdV = dH$
    - Definition of specific heat: $mC_p dT = \delta Q \quad \rightarrow mC_p dT = dH$

- Specific heats:

$$C_V = \left(\frac{\partial u}{\partial T}\right)_v \quad \text{and} \quad C_P = \left(\frac{\partial h}{\partial T}\right)_P$$

- C_V & C_P are thermodynamic properties



2.4.2 C_p, C_v for ideal gases

James Prescott Joule (1843) – Ideal gas: internal energy is a function of temperature only.

- Two tanks are submerged in a water bath, connected by a pipe with a valve.
- Water & tanks are in thermal equilibrium.
- Valve is opened & pressure is equalized.
- Water temperature does not change
  - No heat was transferred to / from the air.
- No work done. U is therefore independent of change in P and v.
- Internal energy for IDEAL GAS is function of temperature only: $u = u(T)$

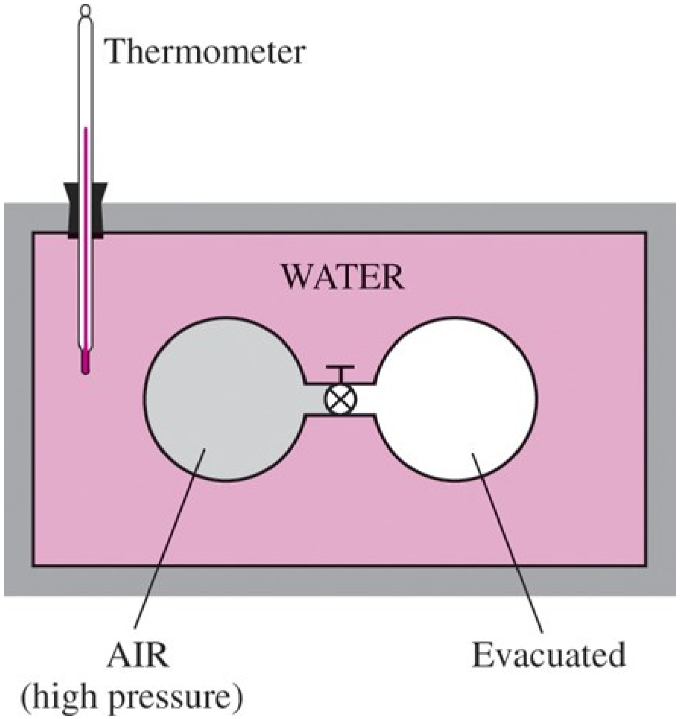


TABLE 3.1
Internal Energy for Superheated Vapor Steam

	P, kPa			
T, °C	10	100	500	1000
200	2661.3	2658.1	2642.9	2621.9
700	3479.6	3479.2	3477.5	3475.4
1200	4467.9	4467.7	4466.8	4465.6

2.4.2 C_p, C_v for ideal gases

- $u = u(T)$ for an ideal gas
- Recall, $h = u + Pv$ and $Pv = RT$
  - $h = u + RT = h(T)$ for an ideal gas.
  - All variables are function of temperature only

- Ideal gas: specific heats (C_v and C_p) will be a function of temperature only.

$$C_V = \left(\frac{\partial u}{\partial T}\right)_v \longrightarrow C_V = \left(\frac{du}{dT}\right)_{ideal\ gas} \longrightarrow du = C_V\,dT$$

$$C_P = \left(\frac{\partial h}{\partial T}\right)_P \longrightarrow C_P = \left(\frac{dh}{dT}\right)_{ideal\ gas} \longrightarrow dh = C_P\,dT$$

$$m(u_2 - u_1) = mC_V(T_2 - T_1) \qquad \& \qquad m(h_2 - h_1) = mC_P(T_2 - T_1)$$

2.4.2 C_p, C_v for ideal gases

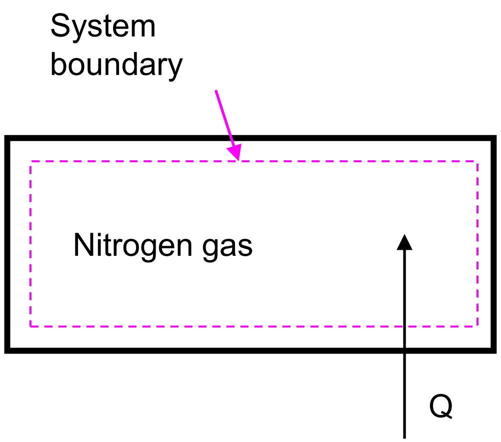
Example 2-4

A ridig tank contains nitrogen at 27°C. Heat is transferred to the system and the gas temperature rises to 127°C. Assume that nitrogen is an ideal gas with C_v = 0.743 kJ/(kgK).

Find:

(a) the <u>heat transfer per unit mass</u>

(b) the ratio of the final pressure to the initial pressure.



<u>Solution</u>:

2.4.2 C_p, C_v for ideal gases

Relation between C_P and C_V for Ideal Gases

- Recall definitions
  - $h = u + Pv$
  - $Pv = RT$
  - $dh = C_P dT$ & $du = C_V dT$

$$\boxed{\begin{aligned} h &= u + Pv \\ dh &= du + d(RT) \\ C_P dT &= C_V dT + RdT \\ C_P &= C_V + R \end{aligned}}$$

- The specific heat ratio *k* is defined as

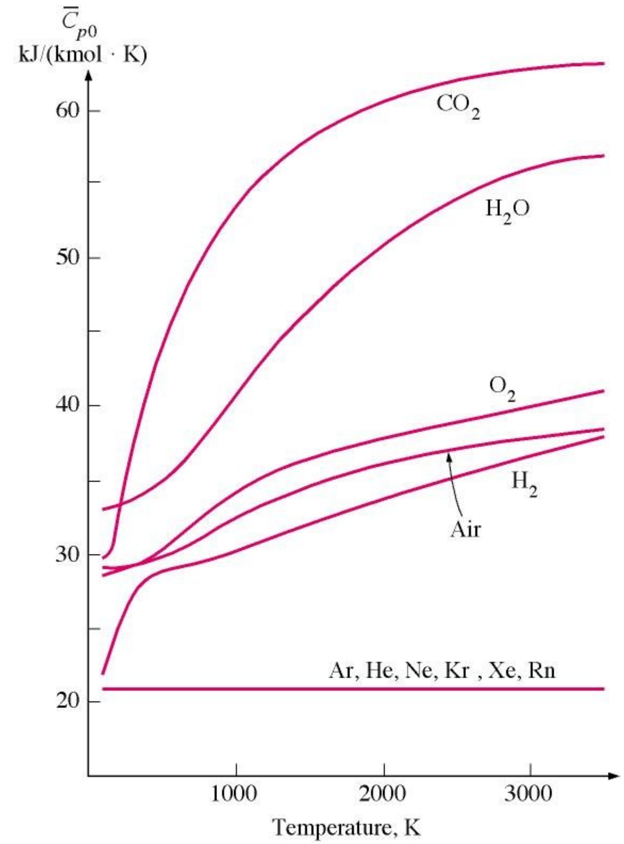
$$k = \frac{C_P}{C_V}$$

- Relationships between C_P and C_V for ideal gases:

$$C_P = \frac{kR}{k-1} \quad \text{and} \quad C_V = \frac{R}{k-1}$$

2.4.3 Values for C_p and C_v

- Where we do find these values?
- Are C_P and C_V constant?
- Specific heats are dependent on temperature



<u>Options (using C_P as example):</u>

(1) Constant value: Table A-5
- least accurate, but okay for low temperatures

(2) Use average value over T_2 and T_1
- $C_{P\,AVG} = (C_{P\,@T2} + C_{P\,@T1}) / 2$
- More accurate than (1)

(3) Table A.6 – Calculate C_P using empirical formula
- $C_P = C_0 + C_1\theta + C_2\theta^2 + C_3\theta^3$
- Coefficients given in table A.6
- More accurate than (1) & (2), but more work

(4) Ideal Gas Tables (A7, air), (A.8: N_2, O_2, CO_2)
- u & h values directly
- More accurate, but have to look up values

Ideal Gas Properties of Various Substances, Entrop
Mass Basis

Carbon Dioxide (CO_2)
$R = 0.1889$ kJ/kg-K
$M = 44.010$ kg/kmol

T (K)	u (kJ/kg)	h (kJ/kg)	s_T^0 (kJ/kg-K)
200	97.49	135.28	4.5439

2.4.3 Values for C_p and C_v

Specific heat variation with temperature

- Which method do we choose? In this course: (1) & (4) will be the most common methods used.

Options (using C_P as example):

(1) Constant value: Table A-5
- least accurate, but okay for low temperatures

(2) Use average value over T_2 and T_1
- i.e. $C_{P\,AVG} = (C_{P\,@T2} + C_{P\,@T1}) / 2$
- More accurate than (1)

(3) Table A.6 – Calculate C_P using empirical formula
- $C_P = C_0 + C_1\theta + C_2\theta^2 + C_3\theta^3$
- Coefficients given in table A.6
- More accurate than (1) & (2), but more work

(4) Ideal Gas Tables (A7, air), (A.8: N_2, O_2, CO_2)
- u & h values directly
- More accurate, but have to look up values

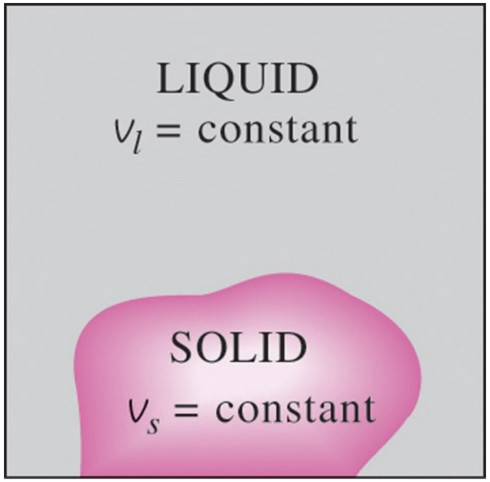
- **Problem statement will specify which method for you to use**

2.4.4 Specific heat for solids & liquids

Solids & Liquids

- Incompressible substances (i.e. constant specific volume)
  - Specific heats are identical.

$$C_P = C_V = C \qquad \left(\frac{kJ}{kg \cdot K}\right)$$



- Assuming constant specific heats

$$du = C_V dT = CdT$$

$$\Delta u = C\Delta T = C(T_2 - T_1)$$

- Recall, definition of enthalpy: $h = u + Pv$
- The differential of enthalpy: $dh = du + Pdv + vdP$
- For incompressible substances, dv = 0

$$dh = du + Pd\cancel{v}^0 + vdP$$

$$\boxed{dh = du + vdP}$$

2.4.4 Specific heat for solids & liquids

- If $\Delta u = C\Delta T$, find an expression for Δh:

$$\boxed{\Delta h = \Delta u + v\Delta P = C\Delta T + v\Delta P}$$

- Table A.3 & A.4: specific heats of selected liquids and solids

<u>SOLIDS</u>

- The term $v\Delta P$ is insignificant (v is very small)

$$\Delta h_{solid} = \Delta u_{solid} + \cancel{v}^{0}\Delta P$$

$$\boxed{\Delta h_{solid} = \Delta u_{solid} \cong C\Delta T}$$

<u>LIQUIDS</u>

Two special cases are encountered:

1) <u>Constant-pressure processes ($\Delta P = 0$)</u>:
   - $\Delta h_{liquid} = \Delta u_{liquid} \cong C\Delta T$

2) <u>Constant-temperature processes ($\Delta T = 0$)</u>
   - $\Delta h_{liquid} = \Delta u_{liquid} + v\Delta P \cong C\Delta T + v\Delta P$
   - $\Delta h_{liquid} = v\Delta P$

2.4.5 Example

Example 2-5:

A piston-cylinder device contains helium gas initially at 150 kPa, 20°C, and 0.5m³. The helium is now compressed in a polytropic process (PV^n = Constant) to 400 kPa and 140°C. Assume constant specific heats with

- R_{He} = 2.08 kJ/kgK; C_V = 3.12 kJ/kg K; n = 1.536.

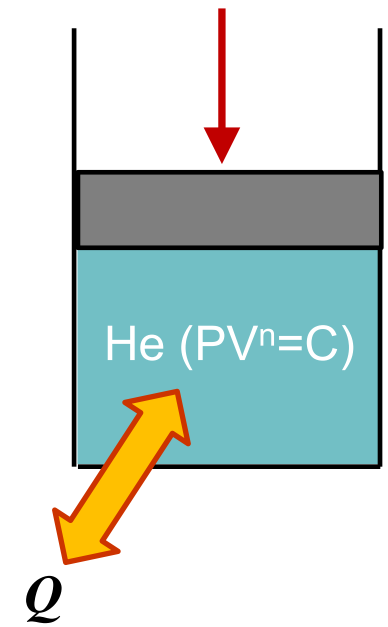
Using constant specific heats, determine the:

(a) Boundary work

(b) Heat transfer

Solution:

1) Sketch the system and show energy crossing the boundaries
2) Determine the proper relation (ideal gas or tables?)
3) Determine the states of the system
4) Determine the process and sketch the process diagram
5) Determine relevant equations
6) Solve



[ans: (a) W_{21} = 57.1 kJ into system (i.e. W_b = -57.1 kJ), (b) Q_{21} = -11.1 kJ]