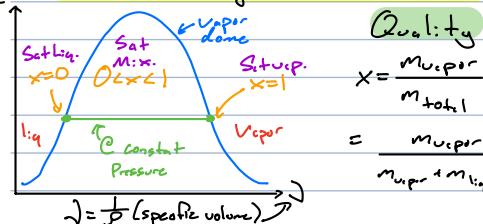


## Modes of Energy Storage @ Microscale

- Structure @ Microscale defines macrostate of energy
- |   |                                    |                     |
|---|------------------------------------|---------------------|
| <b>Scalable Modes</b>                   | (i) Translational Motion (KE)      | (ii) Phase Changes  |
| <b>Related to activity &amp; motion</b> | (iii) Vibrational Motion           | (iv) Chemical Bonds |
| <b>Related to density &amp; shape</b>   | (v) Rotational Motion              | (vi) Nuclear Bonds  |
| <b>to temp.</b>                         | Latent modes<br>Structural changes |                     |
|   | (vii) Electron Translation         |                     |

Energy can cross boundary as: (i) Heat (ii) Work (iii) Mass  
Mass Flow Rate:  $\dot{m} = \rho V_{avg} A_c$

## Phase Change Fluids (Tables)

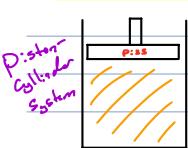


## Phase Regions

- |                                   |   |
|-----------------------------------|---|
| (i) Compressed Liquid             | (ii) Saturated mixture ( $0 < x < 1$ )                |
| → @ given P: $T_c < T_s$          | → $T = T_{sat}$ & $P = P_{sat}$                       |
| → @ given T: $P > P_{sat}$        | (iii) Saturated Vapor ( $x = 1$ )                     |
| (iv) Saturated Liquid ( $x = 0$ ) | → $T = T_{sat}$ & $P = P_{sat}$                       |
| → $T = T_{sat}$ & $P = P_{sat}$   | (v) Superheated Vapor → $T > T_{sat}$ & $P < P_{sat}$ |

No quality in compressed liquid or ST regions

## Closed Systems



$$1^{\text{st}} \text{ Law: } (Q_{in} - Q_{out}) + (W_{in} - W_{out}) = U_2 - U_1 \quad \text{or} \quad \Delta U = Q + W$$

Can be an adiabatic system

Qin: Heat Transfer into system

Qout: Heat Transfer out of system

Win: Work done on the system

Wout: Work done by the system

## Boundary Work (General)

$$W_{piston} = \int_1^2 P dV = P \Delta V = P_m \Delta V = W_{out}$$

→ True for isobaric situations

$$W_{piston} = W_{out} \rightarrow W_{out} > 0 \text{ if volume } \uparrow$$

## Polytropic Processes

$$PV^n = \text{Constant} \Rightarrow P_1 V_1^n = P_2 V_2^n \quad \text{and} \quad W_{piston} = \frac{P_2 V_2 - P_1 V_1}{1-n}$$

## Ideal Gas EoS

Law:  $PV = nRT$  Universal Gas Constant

EoS:  $PV = mRT$  Particular Gas Constant

$$P = RT$$

$$R = \frac{P}{MW}$$

## Specific Volume

$$\bar{V} = \frac{1}{\rho} = \frac{V}{m} \Rightarrow m = \frac{V}{\bar{V}}$$

$$\dot{m} = \frac{V}{\bar{V}} \quad \& \quad V = m\bar{V}$$

## Finding $\Delta U$

Treat air as ideal in this course

## 1) Ideal Gases

• Internal energy only a function of temperature

• Use specific heat value

$C_V$ : Specific Heat @ constant Vol.

$$C_V = \frac{du}{dt} = C_V \text{ (Typically constant)}$$

$\Delta u = C_V \Delta T$

$C_P$ : Specific Heat @ constant Press.

↳ See 'Open Systems'

## 2) Treat Liquids / Solids

$$C_V = C_P = C$$

$$\sum \Delta u = u_2 - u_1 = \int_{T_1}^{T_2} C_V dT = C_V (T_2 - T_1)$$

$$\sum \Delta u = \Delta T \quad \& \quad \Delta u = m \Delta T$$

↳ See 'Open Systems'

## 3) Phase Change Fluids

(i) For a saturated mixture

$$U = x U_g + (1-x) U_f$$

↳ Let  $\Phi$  be properties, so generally:

Boltzmann Family rule:  $\Phi = \Phi_f + x(\Phi_g - \Phi_f)$

↳ table properties

↳  $\Phi = x \Phi_g + (1-x) \Phi_f$

(ii) For compressed liquids

•  $U \propto \bar{V}$  much stronger function

of temp than Pressure

↳ Shortcuts: Evaluate compressed liquid (CLL)

properties based on saturated liquid value. e.g.  $u_{CLL} = u_f(T)$

↳ Note that  $u_{CLL} \neq u_f(T)$

## Steady Flow Devices

### 1) Nozzles / Diffusers

↳ Nozzle:  $V_1 < V_2$ ,  $P_1 > P_2$

Diffuser:  $V_2 < V_1$ ,  $P_2 < P_1$

$V \uparrow \text{as } A \downarrow, P \downarrow \text{as } A \uparrow, P \downarrow$

Exchanges enthalpy for KE

$$\dot{Q} = \dot{m} [h_2 - h_1] + \frac{1}{2} (V_2^2 - V_1^2)$$

Assume:  $\Delta PE \approx 0$ , adiabatic,  $W \approx 0$  (Pisue system)

$$\dot{Q} = \dot{m} [h_2 - h_1]$$

↳ Assume:  $\Delta PE \approx 0$ ,  $\dot{Q} \text{ small}$ ,  $\Delta KE \approx 0$

$$\dot{Q}_{net} \approx 0, \dot{W}_{net} \approx 0$$

↳ Assume:  $\Delta PE \approx 0$ , adiabatic,  $W \approx 0$  (Pisue system)

$$\dot{Q} = \dot{m} [h_2 - h_1]$$

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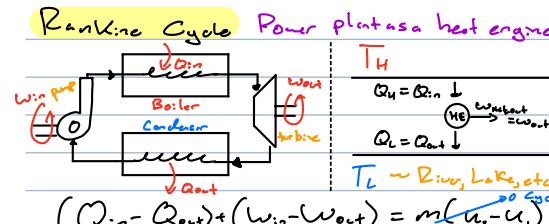
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$$\dot{Q}_{net} \approx 0, \dot{W}_{net} \approx 0$$



**Carnot Principles** Carnot cycles are ideal cycles under conditions

- (i) Efficiencies of an irreversible (real) cycle is always less than a reversible cycle
- (ii) Efficiency of all reversible engines acting between  $T_H$  and  $T_L$  is the same

$$\Rightarrow \left( \frac{Q_H}{Q_L} \right)_{rev} = \left( \frac{T_H}{T_L} \right)_{ideal} \rightarrow \eta_{th,Carnot} = 1 - \frac{T_L}{T_H} \text{ must be from } \eta_{th} = 1 - \frac{Q_L}{Q_H}$$

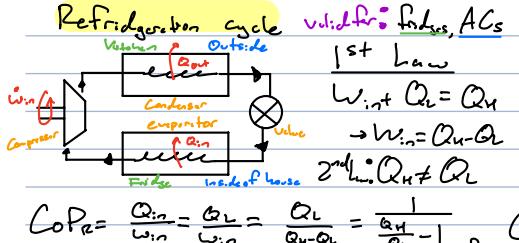
### Carnot Heat Engine

- (i) Isothermal expansion at  $T_H$  (iii) Isothermal compression at  $T_L$
- (ii) Adiabatic expansion:  $T_H \rightarrow T_L$  (iv) Adiabatic compression

$$COP_{Carnot} = \frac{1}{\frac{T_H}{T_L} - 1}$$

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

### Refrigeration cycle

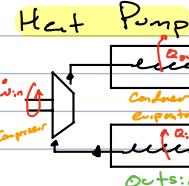


$$T_H \quad Q_H \uparrow Q_H = Q_{out}$$

$$W_{in} \rightarrow (R)$$

$$Q_L \uparrow Q_L = Q_{in}$$

$$T_L$$



### Two Types

- (i) Air Source  $\rightarrow T_L$ : stream
- (ii) Ground Source  $\rightarrow T_L$ : the ground

$$T_H \quad Q_H \uparrow Q_H = Q_{out}$$

$$W_{in} \rightarrow (HP)$$

$$Q_L \uparrow Q_L = Q_{in}$$

$$T_L$$

$$COP_{HP} = \frac{Q_{out}}{W_{in}} = \frac{Q_H}{W_{in}} = \frac{Q_H}{Q_H - Q_L} = \frac{1}{1 - \frac{Q_L}{Q_H}}, COP_{HP} = [1, 2] \text{ usually}$$

### Entropy

- (i) Entropy change as a measure of energy quality/degradation
- (ii) Entropy as a measure of molecular system disorder & measures heat is added

For an Internally Reversible Process

$$dS = \left( \frac{dQ}{T} \right)_{\text{ideal}}$$

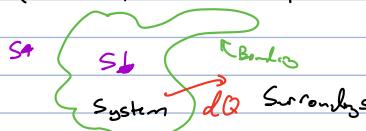
### Total Entropy Change

$$\Delta S_{\text{total}} = \Delta S_{\text{system}} + \Delta S_{\text{surv}}$$

(i)  $\Delta S_{\text{total}} > 0 \Rightarrow$  real (irreversible)

(ii)  $\Delta S_{\text{total}} = 0 \Rightarrow$  ideal (reversible)

(iii)  $\Delta S_{\text{total}} < 0 \Rightarrow$  impossible!



For a Real Process  $\stackrel{\text{Infinite}}{\Rightarrow} \Delta S = \int_1^2 \frac{dQ}{T} \text{ Ned Q and T relationship}$

$$\Delta S_{\text{real}} = \int_1^2 \left( \frac{dQ}{T} \right)_{\text{real}} + S_{\text{generated through irreversibilities}}$$

$$\Delta S_{\text{sys}} = \int_1^2 \left( \frac{dQ}{T} \right)_{\text{sys,real}} + \int_1^2 \left( \frac{dQ}{T} \right)_{\text{surv,real}} + S_{\text{generated}}$$

### Calculating Entropy Change

(i) Isothermal Process valid for surroundings

$$\Delta S_{\text{surv}} = \int_1^2 \frac{dQ}{T} = \int_1^2 \frac{dU}{T} = \frac{Q_2}{T_2} \leftarrow \text{Transfer from 1 to 2}$$

(ii) More Generally

$$\begin{aligned} dQ - dW = dU \\ \text{(Assume 1 atm, Pout)} \quad \text{(Work done)} \quad \text{Change in internal energy} \\ \Delta S = \frac{dQ}{T} \quad \text{Surroundings} \end{aligned} \quad \begin{aligned} dQ = dU + PdV \\ \text{Work done by surroundings} \end{aligned} \quad \begin{aligned} \Delta U = \int dU = \int dQ - \int PdV \\ \Delta U = \int dQ - \int PdV = \int (dQ - PdV) = \int dU \end{aligned} \quad \begin{aligned} \Delta U = \int dU = \int dQ - \int PdV \\ \Delta U = \int dQ - \int PdV = \int (dQ - PdV) = \int dU \end{aligned} \quad \begin{aligned} \Delta U = \int dU = \int dQ - \int PdV \\ \Delta U = \int dQ - \int PdV = \int (dQ - PdV) = \int dU \end{aligned}$$

In the Rankine Cycles, Boiler and Compressor are both isobaric (operate @ constant Pressure)

### Evaluating $\Delta S$

#### 1) Ideal Gases

$$\Delta S_{\text{sys}} = C_V \ln \left( \frac{T_2}{T_1} \right) + R \ln \left( \frac{V_2}{V_1} \right)$$

$$\Delta S_{\text{sys}} = C_P \ln \left( \frac{T_2}{T_1} \right) - R \ln \left( \frac{P_2}{P_1} \right)$$

1) **Sentropic Processes**  $\Delta S_{\text{sys}} = 0 \rightarrow S_2 = S_1$

#### 2) Ideal Gases

$$\frac{T_2}{T_1} = \left( \frac{V_1}{V_2} \right)^{k-1} \quad R = C_p - C_v$$

$$\frac{T_2}{T_1} = \left( \frac{P_2}{P_1} \right)^{\frac{k-1}{k}} \quad k = \frac{C_p}{C_v}$$

All 3 valid  
only for an  
ideal gas in an  
isentropic process

$$\frac{P_2}{P_1} = \left( \frac{V_1}{V_2} \right)^k$$

#### 2) Liquids/Solids

Incompressible:  $dV \approx 0$

$$C_p = C_v = C \quad dP \approx 0$$

$$\Delta S_{\text{sys}} = C \ln \left( \frac{T_2}{T_1} \right)$$

$$\Delta S_{\text{sys}} = C \ln \left( \frac{T_2}{T_1} \right) = 0$$

$T_2 = T_1$  false  
true  
Solids & incompressible liquids  
require sentropic process to be isothermal

#### 3) Phase Change Fluids

$$\Delta S_{\text{sys}} = S_2 - S_1$$

Use tables for  $S_2, S_1$   
Interpolate w/ quality

#### 3) Phase Change Fluids

$$S_2 = S_1$$

Use tables and interpolate

Beware of false assumptions in questions!

### 1) Sentropic Efficiency

(i) Turbines sentropic turbines produce most power

$$\eta_t = \frac{\text{actual}}{\text{isentropic}} = \frac{h_{2A} - h_{2s}}{h_{2i} - h_{2s}}$$

DIFF Enthalpies

$h_{2s} = \text{sentropic}$

$h_{2i} = \text{actual}$

$h_{2A} = \text{actual}$

$h_{2s} = \text{sentropic}$

$h_{2i} = \text{actual}$

$h_{2A} = \text{actual}$

Watch for  $h_{2A}$  vs.  $h_{2s}$  &  $Q_s$

$$\Delta S_{\text{sys}} = C \ln \left( \frac{T_2}{T_1} \right) = 0$$

$$T_2 = T_1$$

Solids & incompressible liquids  
require sentropic process to be isothermal

$h_{2s} = \text{sentropic}$

$h_{2i} = \text{actual}$

$h_{2A} = \text{actual}$