F E Thermodynamics Review

Properties

- p = Pressure (kpa = kN/m^2)
- T = Temperature (°C)
- v = Specific volume = V/m (m^3/kg)
- ρ = Density = $1/v$ (kg/m^3)
- u = Internal energy (kJ/kg)
- h = Enthalpy = $u + p\,v$ (kJ/kg)
- s = Entropy (kJ/kg °K)

Phase Regions

Two Phase Region
   Under dome
   P & T are dependent
Superheated Vapor Region
   T > Tsat at given P
   Fluid is all vapor
Subcooled liquid Region
   T < Tsat at given P
   Fluid is all liquid
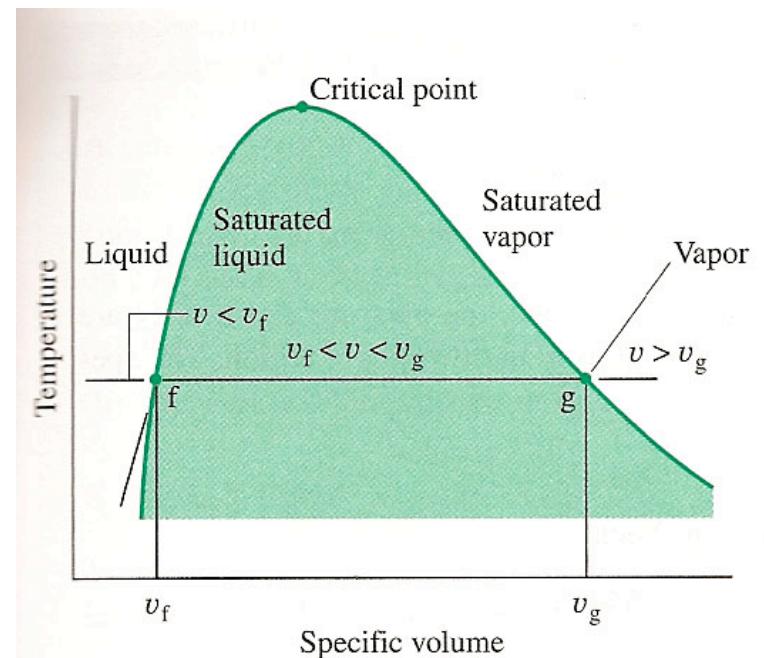
Phase Region Properties

- Two Phase Region

  $P = Psat, \ T = Tsat, \ \ $ Quality: $\ x \ = \ m_v \ /m_t$

  $0 \leq \ x \ \leq \ 1$

  $x = 0$, Sat. Liquid, $\ v_f, \ u_f, \ h_f, \ s_f$

  $x = 1$, Sat. Vapor, $\ v_g, \ u_g, \ h_g, \ s_g$

  $v = v_f \ + x \ (v_g - v_f) \ ; \ \ \ u = u_f \ + \ x \ u_{fg}$

  $h = h_f \ + x \ h_{fg} \ \ \ \ ; \ \ \ \ s = s_f \ + \ x \ s_{fg}$

Phase Region Properties (Cont.)

Superheated Vapor

$T > T_{sat}$ at given P , $P < P_{sat}$ at given T

Quality, x, is not defined

$v > v_g$, $u > u_g$, $h > h_g$, $s > s_g$

Subcooled Liquid

$T < T_{sat}$ at given P, $P > P_{sat}$ at given T

To a good approximation, properties given by

$v = v_f$ (at T), $u = u_f$ (at T), $h = h_f$ (at T)

Using the 2-phase, saturation tables

Example: At T = 145 ^{o}C,   Psat = 0.4154 Mpa

v_f = 0.001085 m^3/kg v_g = 0.4463 m^3/kg

u_f = 610.18 kJ/kg, u_g = 2554.9 kJ/kg

h_f = 610.63 kJ/kg, h_g = 2740.3 kJ/kg

s_f = 1.7907 kJ/kg ^{o}K, s_g = 6.8833 kJ/kg ^{o}K

For any point in between sat. liq. & sat. vapor

$v = v_f + x (v_g - v_f)$; $u = u_f + x u_{fg}$

$h = h_f + x h_{fg}$; $s = s_f + x s_{fg}$

Using superheated vapor tables

Example: At P = 0.2 Mpa, Tsat = 120.23 ^{o}C

First Line: at P = 0.2 Mpa, and T = Tsat

v_g = 0.8857 m^3/kg, u_g = 2529.5 kJ/kg

h_g = 2706.7 kJ/kg, s_g = 7.1272 kJ/kg ^{o}K

At T = 250 ^{o}C   and P = 0.2 Mpa

v = 1.1988 m^3/kg,   u = 2731 kJ/kg

h = 2971 kJ/kg,   s = 7.7086 kJ/kg ^{o}K

Properties for a subcooled liquid

For a subcooled liquid

$T <$ Tsat at P   or $P >$ Psat at T

For these conditions, use sat. liquid properties at the given temperature (T)

Example: At $T = 145$ ^{o}C and $P = 0.6$ Mpa

Tsat $= 158.85$ ^{o}C,   Fluid is a subcooled liquid

$v = v_f = .001085$ m^3/kg, $u = u_f = 610.18$ kJ/kg

$h = h_f = 610.63$ kJ/kg, $s = s_f = 1.7907$ kJ/kg ^{o}K

All at 145 ^{o}C,   Pressure is not used

Ideal Gases

General : $\quad PV = mRT \quad Pv = RT \quad P = \rho RT$

$$R = \bar{R} \,/\, M \quad \bar{R} = 8.314 \text{kJ} \,/\, \text{kgmole K}$$

$$u_2 - u_1 = c_v \left(T_2 - T_1 \right) \qquad h_2 - h_1 = c_p \left(T_2 - T_1 \right)$$

Isentropic Process : $p_1 v_1^k = p_2 v_2^k \quad \dfrac{T_2}{T_1} = \left(\dfrac{P_2}{P_1} \right)^{(k-1)/k} = \left(\dfrac{v_1}{v_2} \right)^{k-1}$

$$Q = 0$$

Air: R = .287 kJ/kg K, c_p=1 kJ/kg K, c_v = .718 kJ/kg K
      k = 1.4

Heat and Work

W - work: work done by a system is positive

Q - heat: heat transfer to a system is positive

For a closed system, piston cylinder problem

$$W = \int_1^2 p\, dV \quad \text{or per unit mass} \quad w = \int_1^2 p\, dv$$

$$P = \text{const.} \quad W_{1-2} = P\left(V_2 - V_1\right) \quad \text{or} \quad W_{1-2} = P\left(v_2 - v_1\right)$$

$$PV^n = \text{const.} \quad W_{1-2} = \frac{P_1 V_1 - P_2 V_2}{n - 1}$$

$$PV = \text{const.} \quad W_{1-2} = P_1 V_1 \, Ln\left(\frac{V_2}{V_1}\right) = P_1 V_1 \, Ln\left(\frac{P_1}{P_2}\right)$$

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Energy Equations

Closed Systems

$$Q_{1-2} - W_{1-2} = m\left(u_2 - u_1\right) + m\frac{\left(V_2^2 - V_1^2\right)}{2} + m\, g\left(z_2 - z_1\right)$$

Simplifications :   Piston cylinder, $W_{1-2} = \int_1^2 p\, dV$

Adiabatic : $Q_{1-2} = 0$,   Reversible: $Q_{1\text{-}2} = m\int_1^2 T\, ds$

Ideal gas : $u_2 - u_1 = c_v\left(T_2 - T_1\right)$

Energy Equations

Open System, Steady State

$$\dot{Q} - \dot{W} = \dot{m}\left(h_2 - h_1\right) + \dot{m}\frac{\left(V_2^2 - V_1^2\right)}{2} + \dot{m}\,g\left(z_2 - z_1\right)$$

Simplifications :   Liquid pump, ideal $W = -v\left(p_2 - p_1\right)$

Adiabatic : $Q = 0$,   Reversible: $Q = m\displaystyle\int_1^2 T\,ds$

Ideal gas : $h_2 - h_1 = c_p\left(T_2 - T_1\right)$

mass flow : $\dot{m} = A\,V\,/\,v = \rho\,A\,V$

Second Law - Cycles

Heat Engine: A cycle the produces work output, W_{net}, by having energy input, Q_H, from an energy source.

$$Q_H - Q_L = W_{net} \qquad \text{Efficiency}: \ \eta_{th} = \frac{W_{net}}{Q_H} = \frac{Q_H - Q_L}{Q_H}$$

Second Law, Cycles (cont.)

Heat Pump: A device that transfers heat from a low temperature to a high temperature with work input from a compressor.

$$\text{Heating}: \quad COP_H = \frac{Q_H}{W_{net}} = \frac{Q_H}{Q_H - Q_L}$$

$$\text{Cooling}: \quad COP_c = \frac{Q_L}{W_{net}} = \frac{Q_L}{Q_H - Q_L}$$

Component Efficiencies-Turbines

Turbine

$$\eta_T = \frac{W_{T,a}}{W_{T,s}} = \frac{h_1 - h_2}{h_1 - h_{2,s}}$$

where: $s_1 = s_{2,s}$

Ideal: $w_s = h_1 - h_{2,s}$

Actual:

$$w_a = \eta_T w_s = h_1 - h_2$$

Assume: $Q = 0$

$P_1 = 5$ MPa
$T_1 = 450°C$

STEAM TURBINE

$w_{out} = ?$

$P_2 = 1.4$ MPa

h

Inlet state

h_1 — 1 — Actual process

w_a w_s

Exit pressure

P_1

P_2

h_{2a} — 2a

h_{2s} — 2s

Isentropic process

$s_{2s} = s_1$

s
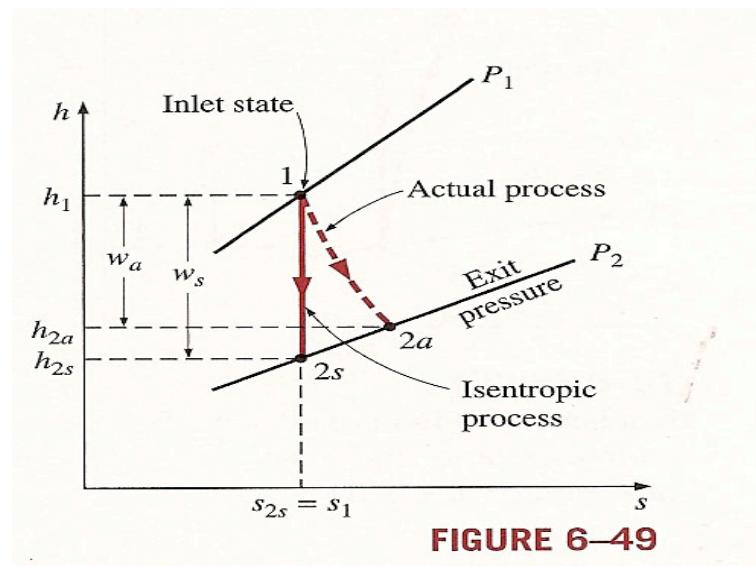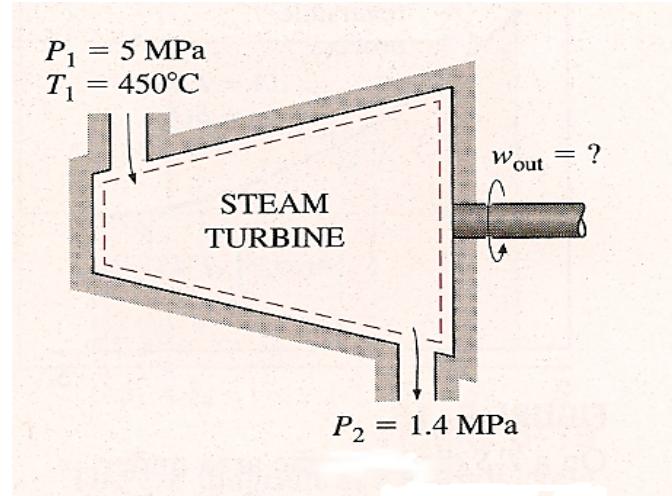
FIGURE 6–49

Compressors and Pumps

Compressors and Pumps

$$\eta_p = \frac{W_{p,s}}{W_{p,a}} = \frac{h_{2,s} - h_1}{h_2 - h_1}$$

where: $s_1 = s_{2,s}$

Ideal: $w_s = - (h_{2,s} - h_1)$

Actual:

$w_a = w_s/\eta_p = - (h_2 - h_1)$

Assume: $Q = 0$

$T_2 = 780$ R
$P_2 = ?$

He
COMPRESSOR

$P_1 = 14$ psia
$T_1 = 510$ R
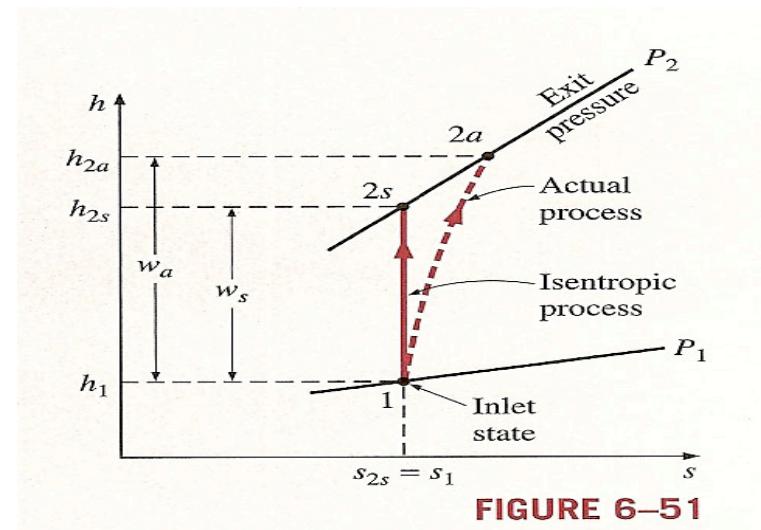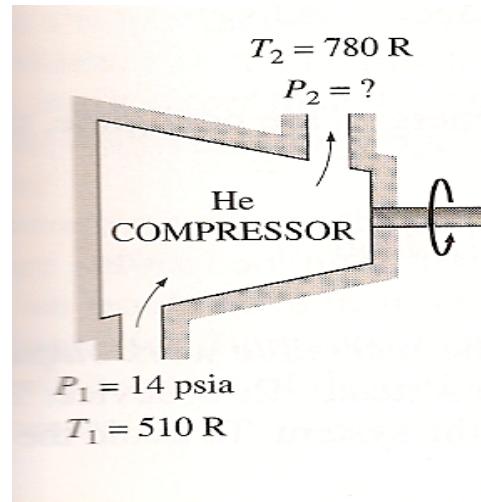
FIGURE 6–51

Carnot Cycle

Carnot cycle : $\dfrac{Q_H}{Q_L} = \dfrac{T_H}{T_L}$

Heat engine : $\eta_{th} = 1 - \dfrac{T_L}{T_H}$

Heat pump : $COP_H = \dfrac{T_H}{T_H - T_L}$

$COP_C = \dfrac{T_L}{T_H - T_L}$
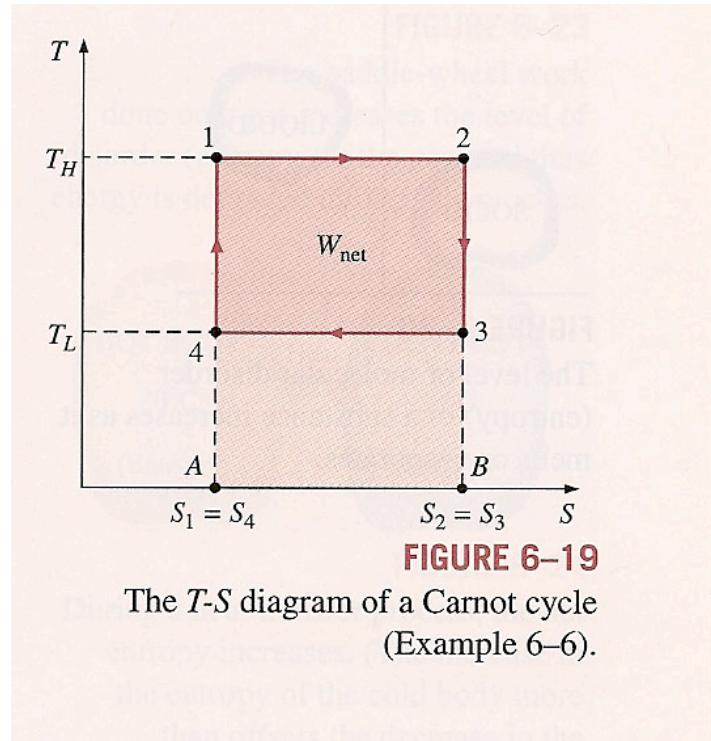
FIGURE 6-19

The T-S diagram of a Carnot cycle (Example 6-6).

Combustion

Must balance the combustion equation

Oxidizer: Air   a [O_2 + 3.76 N_2]

Example: Methane - CH_4

With Theoretical Air:

$CH_4 + a_{th}\ O_2 + 3.76\ a_{th}\ N_2 = b\ CO_2 + d\ H_2O + e\ N_2$

Carbon: $b = 1$, H_2: $d = 2$, O_2: $a_{th} = 1 + 1 = 2$

N_2: $e = 3.76\ a_{th} = 7.52$

Yields:

$CH_4 + 2\ O_2 + 7.52\ N_2 - CO_2 + 2\ H_2O + 7.52\ N_2$
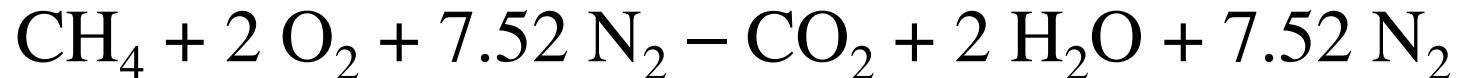
Combustion Cont.

Repeat for 150 % theoretical air

$= 50 \%$ excess air

$CH_4 + a\ O_2 + 3.76\ a\ N_2 = b\ CO_2 + d\ H_2O +$
  $e\ N_2 + f\ O_2$
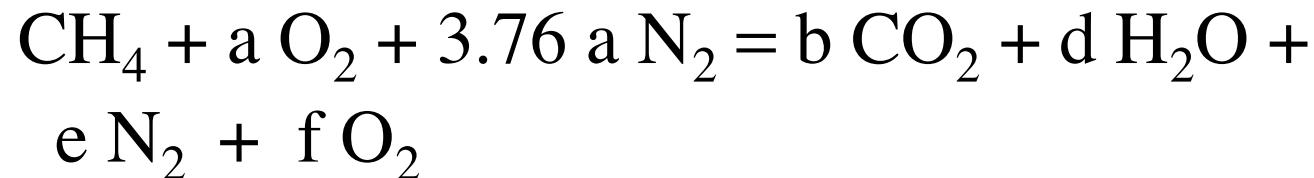
$a = 1.5\ a_{th} = 1.5{*}2 = 3, \quad e = 3.76\ a = 11.28,$

$b = 1,\ d = 2,\ f = 3 - 1 - 1 = 1,\ e = 11.28$

$CH_4 + 3\ O_2 + 11.28\ N_2 - CO_2 + 2\ H_2O +$
   $11.28\ N_2 + O_2$
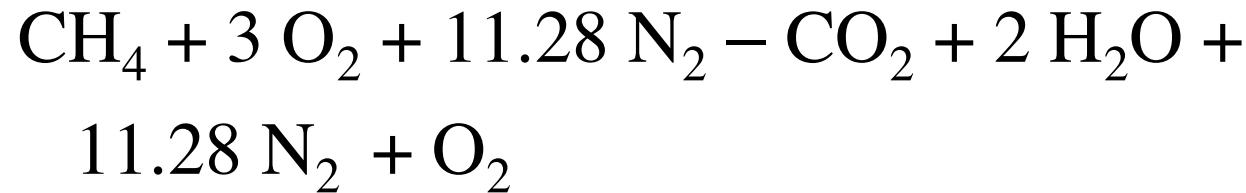
Combustion Cont.

No. moles of air - n_a = 3 + 11.28 = 14.28

No. mole of fuel - n_f = 1

A/F)$_{mole}$ = n_a /n_f , A/F)$_{mass}$ = $n_a M_a/n_f M_f$

A/F)$_{mole}$ = 14.28:1

A/F)$_{mass}$ = 14.28*28.97/(1*16.04)

A/F)$_{mass}$ = 25.8 kg air/kg fuel