FE Review Course

Thermodynamics

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Thermodynamics 10-1

Single-Component Systems

Definitions:

Intensive properties: independent of system mass
Extensive properties: proportional to system mass
Specific properties: extensive properties divided by mass

Example (FEIM):

Which of the following is an extensive property?
(A) temperature
(B) weight
(C) composition
(D) pressure

Weight is dependent on the amount of material, so it is extensive.
Therefore, (B) is correct.

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Thermodynamics 10-2a

Single-Component Systems—State Functions

- Pressure: $$P = \lim_{A \to 0} \frac{F}{A}$$

- Temperature: $$T_K = T_{°C} + 273.15°$$ 26.3

- Specific Volume: $$v = \frac{1}{\rho}$$ 26.5

- Internal Energy: $$U = MW \times u$$ 26.7

- Enthalpy: $$h = u + pv$$ 26.8

Example (FEIM):
Steam at pressure 48 kPa and 167K has a specific volume of 0.40 m³/kg and a specific enthalpy of 29 000 J/kg. Find the internal energy per kilogram of steam.

$$h = u + Pv$$

$$u = h - Pv = 29\,000\,\frac{J}{kg} - (48\,000\ Pa)\left(0.40\,\frac{m^3}{kg}\right) = 9800\ J/kg$$

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Thermodynamics 10-2b

Single-Component Systems—State Functions

- Entropy: $\Delta S = \dfrac{Q}{T_0}$ (constant temperature processes)

- Gibbs' Free Energy: $$G = H - TS = U + pV - TS$$ 26.16

- Helmholtz Free Energy: $$a = u - Ts = h - pv - Ts$$ 26.18

- Heat Capacity:

  - At constant pressure: $$c_p = \left(\frac{\partial h}{\partial T}\right)_p$$

  - At constant volume: $$c_v = \left(\frac{\partial u}{\partial T}\right)_v$$

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Thermodynamics 10-3

Two-Phase Systems

Quality (x) – the fraction by weight of the total mass that is vapor

$$x = \frac{m_{\text{vapor}}}{m_{\text{vapor}} + m_{\text{liquid}}}$$
$$= \frac{m_g}{m_g + m_f} \qquad 26.26$$

Thermodynamics 10-4a

Ideal Gases

Ideal Gas Law

$$pv = RT \qquad 26.38$$

$$pV = \frac{m\overline{R}T}{\text{MW}} = m\left(\frac{\overline{R}}{\text{MW}}\right)T \qquad 26.36$$

$$= mRT$$

where
$$R = \frac{\overline{R}}{\text{MW}} \qquad 26.37$$

$\overline{R}$ = universal gas constant = 8314 J/kmol·K

$$c_p - c_v = R \qquad 26.39$$

$$\Delta h = c_p \Delta T \qquad 26.40$$

$$\Delta u = c_v \Delta T \qquad 26.41$$

For constant heat capacities near room temperature:

$$\Delta s = c_p \ln \frac{T_2}{T_1} - R \ln \frac{p_2}{p_1} \qquad 26.42$$

$$\Delta s = c_v \ln \frac{T_2}{T_1} + R \ln \frac{v_2}{v_1} \qquad 26.43$$

For an isentropic (constant entropy) process:

$$\frac{p_2}{p_1} = \left(\frac{v_1}{v_2}\right)^k \qquad 26.44$$

where $k = \dfrac{c_p}{c_v}$ \qquad 26.47

$$\frac{T_2}{T_1} = \left(\frac{v_1}{v_2}\right)^{k-1} \qquad 26.45$$

$$\frac{T_2}{T_1} = \left(\frac{p_2}{p_1}\right)^{(k-1)/k} \qquad 26.46$$

Thermodynamics 10-4b
Ideal Gases

Example 1 (FEIM):
A 0.71 m³ tank contains 4.5 kg of an ideal gas. The gas has a
molecular weight of 44 g/mol and is at 21°C. What is the gas pressure?

$$R = \frac{\overline{R}}{MW} = \frac{8314\,\dfrac{J}{kmol\cdot K}}{44\,\dfrac{kg}{kmol}} = 189\ J/kg\cdot K$$

$$p = \frac{mRT}{V} = \frac{(4.5\ kg)\left(189\,\dfrac{J}{kmol\cdot K}\right)(294K)}{(0.71\ m^3)\left(1000\,\dfrac{Pa}{kPa}\right)} = 352.2\ kPa$$

Thermodynamics 10-4c
Ideal Gases

Example 2 (FEIM):
Find the change in specific internal energy of 10 kg of oxygen gas
when the temperature changes from 38°C to 50°C.

From the table in the NCEES Handbook: c_v = 0.658 kJ/kg·K

$$\Delta u = c_v \Delta T$$
$$\Delta T = (50°C + 273.16) - (38°C + 273.16) = 12K$$
$$\Delta u = \left(0.658\,\frac{kJ}{kg\cdot K}\right)(12K) = 7.896\ kJ/kg$$

Thermodynamics 10-4d
Ideal Gases

Example 3 (FEIM):
When the pressure on an ideal gas is doubled while the absolute temperature is also halved, the volume is

(A) quartered
(B) halved
(C) constant
(D) doubled

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

$$V_2 = V_1\left(\frac{p_1}{p_2}\right)\left(\frac{T_2}{T_1}\right) = V_1\left(\frac{1}{2}\right)\left(\frac{1}{2}\right)$$

Therefore, (A) is correct.

Thermodynamics 10-5a
Mixtures of Gases, Vapors, and Liquids

Ideal Gas Mixtures
Mole Fraction: moles of a substance divided by total moles

$$x_i = \frac{N_i}{N} \qquad 29.4$$

$$\sum x_i = 1 \qquad 29.6$$

Mass Fraction: mass of substance divided by total mass

$$w_i = \frac{m_i}{m} \qquad 29.1$$

$$\sum w_i = 1 \qquad 29.3$$

To convert from mole fraction to mass fraction: $w_i = \dfrac{x_i (MW)_i}{\sum x_i (MW)_i}$ 29.7

To convert from mass friction to mole friction: $x_i = \dfrac{\frac{w_i}{(MW)_i}}{\sum \frac{w_i}{(MW)_i}}$ 29.9

Thermodynamics   10-5b
Mixtures of Gases, Vapors, and Liquids

Partial Pressures:
Dalton's Law—The total pressure equals the sum of partial pressures.

$$p = \sum p_i \qquad 29.11 \qquad \text{where} \qquad p_i = \frac{m_i R_i T}{V} = x_i p \qquad 29.10$$

Partial Volume:

$$V = \sum V_i \qquad 29.13 \qquad \text{where} \qquad V_i = \frac{m_i R_i T}{p} \qquad 29.12$$

Thermodynamics   10-5c
Mixtures of Gases, Vapors, and Liquids

Example (FEIM):
0.064 kg of octane vapor (MW = 114) is mixed with 0.91 kg of air (MW = 29). The total pressure is 86.1 kPa. What is the partial pressure of air? Assume ideal gas.

Let y be the mass fraction, and let x be the mole fraction.

$$y_{air} + y_{octane} = 1$$
$$y_{air} = 1 - y_{octane}$$
$$y_{air} = \frac{0.91\ \text{kg}}{0.91\ \text{kg} + 0.064\ \text{kg}} = 0.934\ \text{kg}$$

$$x_i = \frac{\dfrac{y_i}{(MW)_i}}{\sum \dfrac{y_i}{(MW)_i}} = \frac{\dfrac{0.934\ \text{kg}}{29}}{\dfrac{0.934\ \text{kg}}{29} + \dfrac{0.064\ \text{kg}}{114}} = \frac{p_i}{\sum p_i} = \frac{p_{air}}{86.1\ \text{kPa}}$$

$$p_{air} = 84.6\ \text{kPa}$$

Thermodynamics 10-5d

Mixtures of Gases, Vapors, and Liquids

Other Properties:

$$u = \sum w_i u_i \qquad 29.15$$

$$h = \sum w_i h_i \qquad 29.16$$

$$s = \sum w_i s_i \qquad 29.17$$

Thermodynamics 10-6a

The 1st Law of Thermodynamics

Closed Systems: no mass crosses the boundary

$$Q = \Delta U + W \qquad 27.2$$

Reversible Work:

$$W_{\text{rev}} = \int p \, dV \qquad 27.3$$

Special Cases of Closed Systems:
- constant pressure
- constant volume
- constant temperature
- isentropic
- polytropic

The 1st Law of Thermodynamics

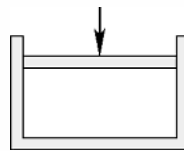Ideal Gas, Isobaric Process—Constant Pressure:

$$\frac{T}{v} = \text{constant} \qquad \qquad 27.4$$

$$W = p\Delta v \qquad \qquad 27.5$$

Example (FEIM):
An ideal gas is enclosed in a cylinder with a weighted piston as the top boundary. The gas is heated and expands from a volume of 0.04 m³ to 0.10 m³ and a constant pressure of 200 kPa. What is the work done by the system?

(A) 8 kJ
(B) 10 kJ
(C) 12 kJ
(D) 14 kJ

$W = p\Delta v = (200 \text{ kPa})(0.10 \text{ m}^3 - 0.04 \text{ m}^3) = 12 \text{ kJ}$

Therefore, (C) is correct.

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The 1st Law of Thermodynamics

Ideal Gas, Isometric Process—Constant Volume:

$$\frac{T}{p} = \text{constant} \qquad \qquad 27.6$$

$$W = 0 \qquad \qquad 27.7$$

Example (FEIM):
0.9 kg of hydrogen gas is cooled from 400°C to 350°C in an isometric process. How much heat is removed from the system?

From the Heat Capacity table in the NCEES Handbook,

$$c_v = 10.2 \frac{\text{kJ}}{\text{kg} \cdot \text{K}}$$

$$Q = mc_v(T_2 - T_1)$$

$$= (0.9 \text{ kg})\left(10.2 \frac{\text{kJ}}{\text{kg} \cdot \text{K}}\right)(350°\text{C} - 400°\text{C}) = -459 \text{ kJ}$$

(The minus sign signifies heat lost by the system)

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Thermodynamics 10-6d

The 1st Law of Thermodynamics

Ideal Gas, Isothermal Process—Constant Temperature:

$$pv = \text{constant} \qquad 27.8$$

$$W = RT \ln \frac{v_2}{v_1} = RT \ln \frac{p_1}{p_2} \qquad 27.9$$

Example 1 (FEIM):

4 kmol of air initially at 1 atm and 295K are compressed isothermally to 8 atm. How much heat is removed from the system during compression?

$$Q = W = nRT \ln \frac{P_1}{P_2}$$

$$= (4 \text{ kmol}) \left(8.314 \frac{\text{kJ}}{\text{kmol} \cdot \text{K}} \right) (295\text{K}) \ln \left(\frac{1 \text{ atm}}{8 \text{ atm}} \right) = -20000 \text{ kJ}$$

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Thermodynamics 10-6e

The 1st Law of Thermodynamics

Example 2 (FEIM):

A cylinder fitted with a frictionless piston contains an ideal gas at temperature T and pressure p. If the gas expands reversibly and isothermally until the pressure is $p/5$, the work done by the gas is equal to

(A) the heat absorbed by the gas
(B) the internal energy change of the gas
(C) the enthalpy change of the gas
(D) $5p$ times the volume change in the gas

Because the internal energy of an ideal gas depends only on the temperature, $\Delta u = Q - W$, so $Q = W$. Thus, the work done by the gas is equal to the heat absorbed by the gas.

Therefore, (A) is correct.

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Thermodynamics 10-6f

The 1st Law of Thermodynamics

Isentropic Process

In an **adiabatic** process: $Q = 0$

An **isentropic** process is a special case of an adiabatic process where the process is entirely reversible.

$$Q = 0$$

$$\Delta s = 0$$

$pv^k = \text{constant}$ *27.10* , where k is the ratio of specific heats

$$W = \frac{p_2 v_2 - p_1 v_1}{1 - k}$$

$$= \frac{R(T_2 - T_1)}{1 - k}$$

$$= \left(\frac{RT_1}{k-1}\right)\left(1 - \left(\frac{p_2}{p_1}\right)^{(k-1)/k}\right) \qquad \textit{27.11}$$

Example (FEIM):

In an isentropic compression of an ideal gas, p_1 = 100 kPa, p_2 = 200 kPa, V_1 = 10 m³, and k = 1.4. Find V_2.

$$p_1 V_1^k = p_2 V_2^k$$

$$V_2 = \left(\frac{p_1}{p_2}\right)^{1/k} (V_1) = \left(\frac{100\text{ kPa}}{200\text{ kPa}}\right)^{1/1.4} (10\text{ m}^3) = 6.095\text{ m}^3$$

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Thermodynamics 10-6g

The 1st Law of Thermodynamics

Polytropic Process

$pv^n = \text{constant}$ *27.12* , where n = polytropic exponent; n is dependent on the process and must be given in the problem statement.

$$W = \frac{p_2 v_2 - p_1 v_1}{1 - n} \qquad \textit{27.13}$$

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Thermodynamics 10-6h

The 1st Law of Thermodynamics

Open Systems: mass crosses the boundary

$$Q = \Delta U + \Delta PE + \Delta KE + W_{\text{rev}} + W_{\text{shaft}} \qquad 27.14$$

Reversible Work:

$$W_{\text{rev}} = -\int v\, dp$$

$$= -\int v\, dp + \Delta KE + \Delta PE \qquad 27.15$$

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Thermodynamics 10-6i

The 1st Law of Thermodynamics

Special Cases for Ideal Gases:

- Constant volume, isometric process: $\quad W = -v(p_2 - p_1) \qquad 27.16$

- Constant pressure, isobaric process: $\quad W = 0 \qquad 27.17$

- Constant temperature, isothermal process:

$$pv = \text{constant} \qquad 27.18$$

$$W = RT \ln \frac{v_2}{v_1} = RT \ln \frac{p_1}{p_2} \qquad 27.19$$

- Isentropic process:

$$W = \frac{k(p_2 v_2 - p_1 v_1)}{1 - k}$$

$$pv^k = \text{constant} \qquad 27.20$$

$$= \frac{kR(T_2 - T_1)}{1 - k}$$

$$= \left(\frac{k}{k-1}\right) RT_1 \left(1 - \left(\frac{p_2}{p_1}\right)^{(k-1)/k}\right) \qquad 27.21$$

- Polytropic process:

$$pv^n = \text{constant} \qquad 27.22$$

$$W = \frac{n(p_2 v_2 - p_1 v_1)}{1 - n} \qquad 27.23$$

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Thermodynamics 10-6j

The 1st Law of Thermodynamics

Solids and Incompressible Fluids

$Q = mc_p\Delta T$ [all processes]

Example (FEIM):
Two copper blocks are initially 50°C and 1 kg, and 100°C and 3 kg. The blocks are brought into contact and reach thermal equilibrium with no outside heat exchanged. What is the final temperature of the blocks?

$Q_1 = -Q_2 = m_1 c_p \Delta T_2 = -m_2 c_p \Delta T_2$

$m_1(T_f - T_1) = m_2(T_2 - T_f)$

$(1\text{ kg})(T_f - 50°C) = (3\text{ kg})(100°C - T_f)$

$4T_f = 350°C$

$T_f = 87.5°C$

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Thermodynamics 10-6k

The 1st Law of Thermodynamics

Steady-State Systems

$$\sum \dot{m}_i \left(h_i + \frac{v_i^2}{2} + gz_i \right)$$

$$- \sum \dot{m}_e \left(h_e + \frac{v_e^2}{2} + gz_e \right)$$

$$+ \dot{Q} - \dot{W} = 0 \qquad \text{[SI]} \quad 27.24(a)$$

Special Cases:
• Nozzles, diffusers

$$h_i + \frac{v_i^2}{2} - h_e + \frac{v_e^2}{2} \qquad \text{[SI]} \quad 27.25(a)$$

$$\eta = \frac{\Delta h_{\text{actual}}}{\Delta h_{\text{ideal}}}$$

$$= \frac{v_e^2 - v_i^2}{2(h_i - h_{es})} \qquad 27.26$$

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Thermodynamics 10-6l

The 1st Law of Thermodynamics

Special Cases (*cont.*):
- Turbines, pumps, compressors

$$W_{\text{per kilogram}} = h_i - h_e \qquad \text{[SI]} \quad 27.28(a)$$

$$\eta_{\text{turbine}} = \frac{h_i - h_e}{h_i - h_{es}} \qquad 27.29$$

$$\eta_{\text{pump}} = \frac{h_{es} - h_i}{h_e - h_i} \qquad 27.30$$

- Throttling valves and processes

$$h_i = h_e \qquad 27.31$$

- Boilers, condensers, evaporators, one-side heat exchangers

$$h_i + q = h_e \qquad 27.32$$

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Thermodynamics 10-6m

The 1st Law of Thermodynamics

Special Cases (*cont.*):
- Heat exchangers

$$\dot{m}_1(h_{1i} - h_{1e}) = -\dot{m}_2(h_{2i} - h_{2e}) \qquad 27.34$$

- Mixers, separators, open or closed feedwater heaters

$$\sum \dot{m}_i h_i = \sum \dot{m}_e h_e \qquad 27.35$$

$$\sum \dot{m}_i = \sum \dot{m}_e \qquad 27.36$$

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Thermodynamics 10-7a

Psychrometrics

Total Atmospheric Pressure:

$$p = p_a + p_v \qquad 29.20$$

Specific Humidity:

$$\omega = \frac{m_v}{m_a} \qquad 29.23$$

$$\omega = 0.622\left(\frac{p_v}{p_a}\right) = 0.622\left(\frac{p_v}{p - p_v}\right) \qquad 29.24$$

Relative Humidity:

$$\phi = \frac{p_v}{p_g} = \frac{m_v}{m_g} \qquad 29.25$$

Three Important Temperatures:
- dew-point temperature
- dry-bulb temperature
- wet-bulb temperature

Thermodynamics 10-7b

Psychrometrics

Psychrometric Chart
- Dry-bulb temperature = vertical lines
- Relative humidity = parabolic lines
- Wet-bulb temperature = dashed diagonals to the left
- Enthalpy = solid diagonals to the left
- Humidity ratio = horizontal lines to the right
- Dew point = intersection of horizontal lines with saturation line (left)
- Specific volume = steep diagonals

Thermodynamics 10-7c
Psychrometrics
Example (FEIM):

Air is 24°C dry bulb with 50% relative humidity. Find the wet-bulb temperature, humidity ratio, enthalpy, specific volume, and dew-point temperature.

Follow the vertical line up from 24°C until it meets the 50% curve. (The chart in the NCEES Handbook has a small circle around this point, so it is easy to find.)

The dotted diagonal line is the one for 17°C (follow the line to the left until it intersects the saturation temperature scale). The wet-bulb temperature is 17°C.

Follow the horizontal line to the right; the humidity ratio is about 9.25 g/kg.

Follow the solid diagonal to the left, using a straight edge; the enthalpy is about 47.5 kJ/kg.

The air is between the 0.85 and 0.86 specific volume lines and is closer to the 0.85 line, so the specific volume is about 0.854 m³/kg.

Follow the horizontal line to the left until it intersects the saturation temperature scale. The dew-point temperature is about 12.6°C.

Thermodynamics 10-8a
Mixtures of Gases, Vapors, and Liquids
Phase Relations
- Clapeyron equation for phase transition:

$$\left(\frac{dp}{dT}\right)_{sat} = \frac{h_{fg}}{Tv_{fg}} = \frac{s_{fg}}{v_{fg}} \qquad \textit{29.28, where}$$

h_{fg} = entropy change for phase transition

v_{fg} = volume change

s_{fg} = entropy change

$(dp/dT)_{sat}$ = slope of vapor-liquid saturation line

- Gibbs' phase rule:

$$P + F = C + 2 \qquad \textit{29.29, where}$$

P = number of phases in the system

F = degrees of freedom

C = number of components

Thermodynamics 10-8b

Mixtures of Gases, Vapors, and Liquids

Example (FEIM):

How many independent properties are required to completely fix the equilibrium state of a pure gaseous compound?

(A) 0
(B) 1
(C) 2
(D) 3

$P = 1$, $C = 1$
$F = C - P + 2$
$\quad = 1 - 1 + 2 = 2$

Therefore, (C) is correct.

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Thermodynamics 10-8c

Mixtures of Gases, Vapors, and Liquids

Vapor-Liquid Mixtures

- Henry's Law: partial pressure is related to the mole fraction

$$p_i = x_i h = y_i p \qquad \text{29.18}$$

- Raoult's Law: partial pressure due to the i th gas is related to its mole fraction

$$p_i = x_i p_i^* \qquad \text{29.19}$$

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Thermodynamics   10-9a

Power Cycles and Entropy

2nd Law of Thermodynamics:

- Kelvin-Plank statement
  - It is impossible to build a cyclical engine that will have a thermal efficiency of 100%.
- Clausius statement
  - It is impossible to devise a cycle that produces, as its only effect, the transfer of heat from a low-temperature to a high-temperature body.

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Thermodynamics   10-9b

Power Cycles and Entropy

Entropy

- Inequality of Clausius:

$$\oint \frac{\delta Q_{reversible}}{T} \leq 0 \qquad 28.12 \qquad s_2 - s_1 = \int ds = \int \frac{\delta Q_{reversible}}{T} \qquad 28.10$$

- For Constant Temperature: $\Delta s = s_2 - s_1 = \frac{Q}{T}$ 28.13
  $W = Q$

- Adiabatic Process: $\Delta s \geq 0$ 28.15
  $Q = 0$

- Insentropic Process: $\Delta s = s_2 - s_1 = 0$ 28.14
  $Q = 0$

- Increasing Entropy:
  $$\Delta s_{total} = \Delta s_{system} + \Delta s_{surroundings} \geq 0 \qquad \Delta s = \sum m_{out} s_{out} - \sum m_{in} s_{in} - \sum \frac{Q_{external}}{T_{external}} \geq 0$$

- Temperature-Entropy (T-s) Diagrams:

$$Q_{reversible} = \int_{s_1}^{s_2} T \, ds \qquad 28.24 \qquad W = \int_{V_1}^{V_2} p \, dV \qquad 28.23 \qquad Q = W$$

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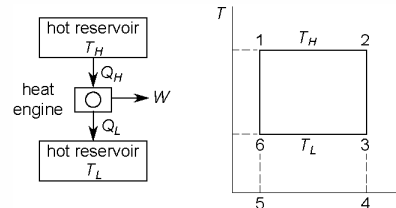
Thermodynamics   10-9c
Power Cycles and Entropy

Example (FEIM):

For the reversible heat engine shown, which area of the *T-s* diagram corresponds to the work done by the system?

(A) work = 0
(B) 1-2-4-5
(C) 6-3-4-5
(D) 1-2-3-6

$W = Q_H - Q_C$
$\quad = T_H \Delta s - T_C \Delta s$
$\quad = (1\text{-}2\text{-}4\text{-}5) - (3\text{-}4\text{-}5\text{-}6)$
$\quad = (1\text{-}2\text{-}3\text{-}6)$

Therefore, (D) is correct.

Thermodynamics   10-9d
Power Cycles and Entropy

Entropy for Solids and Incompressible Liquids

$$s_2 - s_1 = \int c\,\frac{dT}{T} = c \ln \frac{T_2}{T_1} \qquad 28.16$$

Example (FEIM):
Lead is cooled from 100.0°C to 50.0°C. What is the change in specific entropy?

T_2 = 50.0°C + 273.16 = 323.16K
T_1 = 100.0°C + 273.16 = 373.16K

$$s_2 - s_1 = c_{mean} \ln \frac{T_2}{T_1}$$

$$= 0.128 \frac{kJ}{kg \cdot K} \ln \frac{323.16K}{373.16K}$$

$$= -0.0184 \text{ kJ/kg} \cdot K$$

Thermodynamics 10-9e

Power Cycles and Entropy

Irreversibility

$$I = W_{\text{reversible}} - W_{\text{actual}} \qquad 28.21$$

Availability

- Closed System

$$\phi = u - u_o - T_o(s - s_o) + p_o(v - v_o) \qquad [\text{SI}] \quad 28.17(a)$$

$$W_{\text{reversible}} = \phi_1 - \phi_2 \qquad 28.18$$

- Open System

$$\Psi = h - h_o - T_o(s - s_o) + \frac{v^2}{2} + gz \qquad [\text{SI}] \quad 28.19(a)$$

$$W_{\text{reversible}} = \Psi_1 - \Psi_2 \qquad 28.20$$

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Thermodynamics 10-10a

Power Cycles and Entropy—Basic Cycles

Thermal Efficiency for an Engine

$$\eta_{\text{th}} = \frac{W_L - W_H}{Q_H} = \frac{W_{\text{net}}}{Q_H}$$

$$= \frac{Q_H - Q_L}{Q_H} = \frac{Q_{\text{net}}}{Q_H} \qquad 28.1$$

Coefficient of Performance (COP)

- Heat Pump:

$$(\text{COP})_{\text{heat pump}} = \frac{Q_H}{W}$$

$$= (\text{COP})_{\text{refrigerator}} + 1 \qquad 28.7$$

- Refrigerator:

$$(\text{COP})_{\text{refrigerator}} = \frac{Q_L}{W} \qquad 28.6$$
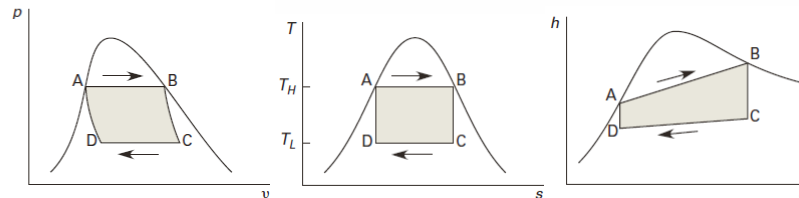
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Thermodynamics 10-10b

Power Cycles and Entropy—Basic Cycles

Carnot Cycle

Figure 28.2 *Carnot Cycle*

For a Carnot engine:

$$\eta_{th,Carnot} = \frac{T_H - T_L}{T_H} = 1 - \frac{T_L}{T_H} \qquad 28.2$$

COP for a Carnot heat pump:

$$(COP)_{Carnot} = \frac{T_H}{T_H - T_L} \quad \left[\begin{array}{c}\text{Carnot}\\\text{heat pump}\end{array}\right] \qquad 28.9$$

COP for a Carnot refrigerator:

$$(COP)_{Carnot} = \frac{T_L}{T_H - T_L} \quad \left[\begin{array}{c}\text{Carnot}\\\text{refrigerator}\end{array}\right] \qquad 28.8$$

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Thermodynamics 10-10c

Power Cycles and Entropy—Basic Cycles

Example (FEIM):
A Carnot engine operates between 500K and 625K.
What is the thermal efficiency?
(A) 20%
(B) 30%
(C) 40%
(D) 50%

$$\eta_{Carnot} = \left(1 - \frac{T_L}{T_H}\right)100\% = \left(1 - \frac{500K}{625K}\right)100\% = 20\%$$

Therefore, (A) is correct.

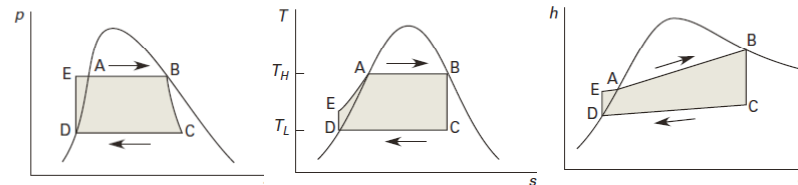FERC

Thermodynamics   10-10d

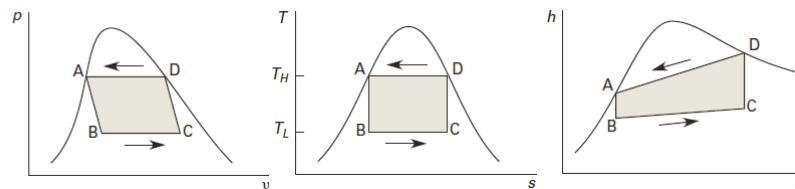## Power Cycles and Entropy—Basic Cycles

Rankine Cycle

Figure 28.4 Basic Rankine Cycle

$$\eta_{th} = \frac{W_L - W_H}{Q_H} = \frac{(h_B - h_C) - (h_E - h_D)}{h_B - h_E} \qquad 28.3$$

Carnot Refrigeration

Figure 28.7 Carnot Refrigeration Cycle

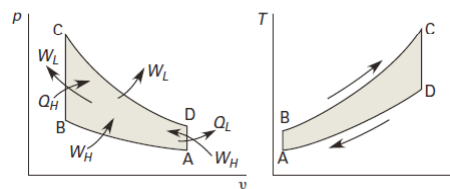# Thermodynamics   10-10e

Power Cycles and Entropy—Basic Cycles

Otto Cycle

Figure 28.6 Air-Standard Otto Cycle

$$\eta_{th} = 1 - r_v^{1-k} \qquad 28.4$$

$$r_v = \frac{V_A}{V_B} = \frac{V_D}{V_C} \qquad 28.5$$

Example 1 (FEIM):
In the process from C to D in the ideal Otto cycle, what is the
   entropy change?

C-D is isentropic, so the change in entropy is 0.

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Example 2 (FEIM):

What is the efficiency of an ideal Otto cycle device with a
compression ratio of 6:1? Air is used with k = 1.4.
(A) 0.167
(B) 0.191
(C) 0.488
(D) 0.512

$$\eta = 1 - \left(\frac{V_1}{V_2}\right)^{1-k} = 1 - \left(\frac{6}{1}\right)^{1-1.4} = 0.512$$

Therefore, (D) is correct.

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For examples 3–7, use the following data:

An ideal Otto cycle has the following properties: T_A = 290K, T_D = 1350K,
T_C = 3100K, p_A = 100 kPa, a compression ratio of 8, k = 1.4, and $Q_{B\text{-}C}$ =
1740 kJ/kg. The intake is mostly air with some gasoline mixed in.

Example 3 (FEIM):

The temperature at state B is most nearly
(A) 460K
(B) 670K
(C) 690K
(D) 1800K

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$A \rightarrow B$ and $C \rightarrow D$ are isentropic, so

$$p_A V_A^k = p_B V_B^k, \quad p_C V_C^k = p_D V_D^k$$

$B \rightarrow C$ and $D \rightarrow A$ are isometric, so

$$V_B = V_C; \quad V_A = V_D$$

$$\frac{p_B}{p_A} = \frac{V_A^k}{V_B^k} = \frac{p_C}{p_D} = \frac{V_D^k}{V_C^k}$$

$$\frac{p_B}{p_A} = \frac{T_A}{T_B} = \frac{p_C}{p_D} = \frac{T_D}{T_C}$$

$$\frac{T_D}{T_C} = \frac{T_A}{T_B}$$

$$T_B = \frac{T_A T_C}{T_D} = \frac{(290\text{K})(3100\text{K})}{1350\text{K}} = 666\text{K} \quad (670\text{K})$$

Therefore, (B) is correct.

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Power Cycles and Entropy—Basic Cycles

Example 4 (FEIM):

The pressure at state 2 is most nearly
(A) 240 kPa
(B) 680 kPa
(C) 1200 kPa
(D) 1870 kPa

$$T_A p_A^{\frac{1-k}{k}} = T_B p_B^{\frac{1-k}{k}}$$

$$p_B = p_A \left(\frac{T_A}{T_B}\right)^{\frac{k}{1-k}} = (100\text{ kPa})\left(\frac{290\text{K}}{670\text{K}}\right)^{\frac{1.4}{1-1.4}}$$

$$= 1874\text{ kPa}$$

or,

$$\frac{p_B}{p_A} = \left(\frac{V_A}{V_B}\right)^k = (8)^{1.4} = 18.38$$

Therefore, (D) is correct.

Example 5 (FEIM):

The specific volume at state 1 is most nearly
(A) 0.83 m³/kg
(B) 8.9 m³/kg
(C) 75 m³/kg
(D) 115 m³/kg

$$\upsilon = \frac{\overline{R}T}{(MW)p}$$

$$= \left(\frac{\left(8314\dfrac{\text{J}}{\text{kmol}\cdot\text{K}}\right)(290\text{K})}{\left(29\dfrac{\text{kg}}{\text{kmol}}\right)(100\text{ kPa})}\right)\left(\frac{1\text{ kPa}}{1000\text{ Pa}}\right)$$

$$= 0.83\text{ m}^3/\text{kg}$$

Therefore, (A) is correct.

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Example 6 (FEIM):
The thermal efficiency of the cycle is most nearly
(A) 0.30
(B) 0.38
(C) 0.4
(D) 0.57

$$\eta = 1 - \left(\frac{V_A}{V_B}\right)^{1-k}$$

$$= 1 - \left(\frac{8}{1}\right)^{1-1.4}$$

$$= 0.565 \quad (0.57)$$

Therefore, (D) is correct.

Example 7 (FEIM):
The heat rejected by the cycle is most nearly
(A) 755 kJ/kg
(B) 1010 kJ/kg
(C) 1060 kJ/kg
(D) 1300 kJ/kg

$$\text{Heat rejected} = (1-\eta)Q_{B-C}$$

$$= (1-0.565)\left(1740\,\frac{kJ}{kg}\right)$$

$$= 757 \quad (755 \text{ kJ/kg})$$

Therefore, (A) is correct.

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Steam Tables

Note: Tables are provided in the NCEES Handbook.

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Thermodynamics 10-11

Combustion

Combustion Process

- Stoichiometric Combustion
  $CH_4 + 2O_2 \rightarrow CO_2 + 2H_2O$
  For each mole of CH_4, there should be 2 moles of O_2.
  However, in air there are 3.76 moles of N_2 for each mole of O_2,
  so $CH_4 + 2O_2 + 2(3.76)N_2 \rightarrow CO_2 + 2H_2O + 7.53N_2$
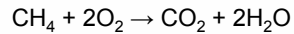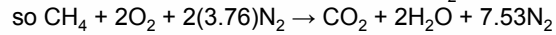
- Stoichiometric Air/Fuel Ratio: $\dfrac{A}{F} = \dfrac{m_{air}}{m_{fuel}}$ *30.1*

- Incomplete Combustion

$$\begin{array}{l}\text{percent}\\ \text{theoretical}\\ \text{air}\end{array} = \frac{\left(\frac{A}{F}\right)_{actual}}{\left(\frac{A}{F}\right)_{stoichiometric}} \times 100\% \qquad 30.2$$

$$\begin{array}{l}\text{percent}\\ \text{excess}\\ \text{air}\end{array} = \frac{\left(\frac{A}{F}\right)_{actual} - \left(\frac{A}{F}\right)_{stoichiometric}}{\left(\frac{A}{F}\right)_{stoichiometric}} \times 100\% \qquad 30.3$$

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