

## Single-Component Systems

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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.

## Single-Component Systems—State Functions

- Pressure:  $P = \lim_{A \rightarrow 0} \frac{F}{A}$
- Temperature:  $T_K = T_{\circ C} + 273.15$  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 m<sup>3</sup>/kg and a specific enthalpy of 29 000 J/kg. Find the internal energy per kilogram of steam.

$$h = u + Pv$$

$$u = h - Pv = 29000 \frac{\text{J}}{\text{kg}} - (48000 \text{ Pa}) \left( 0.40 \frac{\text{m}^3}{\text{kg}} \right) = 9800 \text{ J/kg}$$

## Single-Component Systems—State Functions

- Entropy:  $\Delta S = \frac{Q}{T_0}$  (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:  $c_v = \left( \frac{\partial u}{\partial T} \right)_v$

## Two-Phase Systems

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

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

# Thermodynamics

10-4a

## Ideal Gases

### Ideal Gas Law

$$pv = RT \quad 26.38$$

$$pV = \frac{m\bar{R}T}{MW} = m \left( \frac{\bar{R}}{MW} \right) T = mRT \quad 26.36$$

$$\text{where } R = \frac{\bar{R}}{MW} \quad 26.37$$

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

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

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

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

For constant heat capacities near room temperature:

$$\Delta s = c_p \ln \left( \frac{T_2}{T_1} \right) - R \ln \left( \frac{p_2}{p_1} \right) \quad 26.42$$

$$\Delta s = c_v \ln \left( \frac{T_2}{T_1} \right) + R \ln \left( \frac{v_2}{v_1} \right) \quad 26.43$$

For an isentropic (constant entropy) process:

$$p_1 v_1^k = p_2 v_2^k \quad 26.44$$

$$\text{where } k = \frac{c_p}{c_v} \quad 26.47$$

$$T_1 v_1^{k-1} = T_2 v_2^{k-1} \quad 26.45$$

$$T_1 p_1^{(1-k)/k} = T_2 p_2^{(1-k)/k} \quad 26.46$$

## Ideal Gases

Example 1 (FEIM):

A 0.71 m<sup>3</sup> 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?

$$R = \frac{\bar{R}}{MW} = \frac{8314 \frac{\text{J}}{\text{kmol} \cdot \text{K}}}{44 \frac{\text{kg}}{\text{kmol}}} = 189 \text{ J/kg} \cdot \text{K}$$

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

## 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:  $c_v = 0.658 \text{ kJ/kg} \cdot \text{K}$

$$\Delta u = c_v \Delta T$$

$$\Delta T = (50^\circ\text{C} + 273.16) - (38^\circ\text{C} + 273.16) = 12\text{K}$$

$$\Delta u = \left( 0.658 \frac{\text{kJ}}{\text{kg} \cdot \text{K}} \right) (12\text{K}) = 7.896 \text{ kJ/kg}$$

## 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.

## Mixtures of Gases, Vapors, and Liquids

### Ideal Gas Mixtures

Mole Fraction: moles of a substance divided by total moles

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

$$\sum x_i = 1 \quad 29.6$$

Mass Fraction: mass of substance divided by total mass

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

$$\sum w_i = 1 \quad 29.3$$

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

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

## Mixtures of Gases, Vapors, and Liquids

Partial Pressures:

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

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

Partial Volume:

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

## 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.

$$y_{\text{air}} + y_{\text{octane}} = 1$$

$$y_{\text{air}} = 1 - y_{\text{octane}}$$

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

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

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

## Mixtures of Gases, Vapors, and Liquids

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Other Properties:

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

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

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

## The 1<sup>st</sup> Law of Thermodynamics

Closed Systems: no mass crosses the boundary

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

Reversible Work:  $W_{\text{rev}} = \int p dV \quad 27.3$

Special Cases of Closed Systems:

- constant pressure
- constant volume
- constant temperature
- isentropic
- polytropic

# Thermodynamics

10-6b

## The 1<sup>st</sup> Law of Thermodynamics

Ideal Gas, Isobaric Process—Constant Pressure:

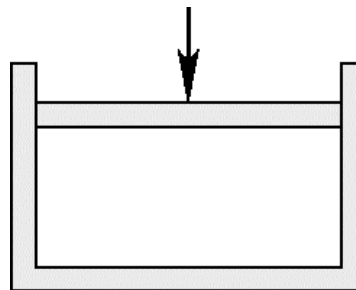
$$W = p\Delta v \quad 27.5$$

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

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  $0.04 \text{ m}^3$  to  $0.10 \text{ m}^3$  and a constant pressure of  $200 \text{ kPa}$ . 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.

## The 1<sup>st</sup> Law of Thermodynamics

Ideal Gas, Isometric Process—Constant Volume:

$$W = 0 \quad 27.7$$

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

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,

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

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

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

(The minus sign signifies heat lost by the system)

# Thermodynamics

10-6d1

## The 1<sup>st</sup> Law of Thermodynamics

Ideal Gas, Isothermal Process—Constant Temperature:

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

$$W = RT \ln \left( \frac{v_2}{v_1} \right) = RT \ln \left( \frac{p_1}{p_2} \right) \quad 27.9$$

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?

$$\begin{aligned} Q = W &= nRT \ln \frac{P_1}{P_2} \\ &= (4 \text{ kmol}) \left( 8.314 \frac{\text{kJ}}{\text{kmol} \cdot \text{K}} \right) (295\text{K}) \ln \left( \frac{1 \text{ atm}}{8 \text{ atm}} \right) = -20000 \text{ kJ} \end{aligned}$$

## The 1<sup>st</sup> 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.

## The 1<sup>st</sup> 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

$$W = \frac{p_2v_2 - p_1v_1}{1 - k} = \frac{R(T_2 - T_1)}{1 - k} = \left( \frac{RT_1}{k - 1} \right) \left( 1 - \left( \frac{p_2}{p_1} \right)^{\frac{k-1}{k}} \right) \quad 27.11$$

Example (FEIM):

In an isentropic compression of an ideal gas,  $p_1 = 100$  kPa,  $p_2 = 200$  kPa,  $V_1 = 10$  m<sup>3</sup>, and  $k = 1.4$ . Find  $V_2$ .

$$p_1V_1^k = p_2V_2^k$$

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

## The 1<sup>st</sup> 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.

$$W = \frac{p_2v_2 - p_1v_1}{1 - n} \quad 27.13$$

## The 1<sup>st</sup> Law of Thermodynamics

Open Systems: mass crosses the boundary

$$Q = \Delta U + \Delta E_p + \Delta E_k + W_{\text{rev}} + W_{\text{shaft}} \quad 27.14$$

Reversible Work:  $W_{\text{rev}} = - \int v dp \quad 27.15$

# Thermodynamics

10-6g2

## The 1<sup>st</sup> Law of Thermodynamics

Special Cases for Ideal Gases:

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

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

- Constant temperature, isothermal process:

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

$$W = RT \ln \left( \frac{v_2}{v_1} \right) = RT \ln \left( \frac{p_1}{p_2} \right) \quad 27.19$$

- Isentropic process:

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

$$W = \frac{k(p_2v_2 - p_1v_1)}{1 - k} = \frac{kR(T_2 - T_1)}{1 - k} = \left( \frac{k}{k - 1} \right) RT_1 \left( 1 - \left( \frac{p_2}{p_1} \right)^{\frac{k-1}{k}} \right) \quad 27.21$$

- Polytropic process:

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

$$W = \frac{n(p_2v_2 - p_1v_1)}{1 - n} \quad 27.23$$

## The 1<sup>st</sup> Law of Thermodynamics

Solids and Incompressible Fluids

$$Q = mc_p \Delta T \text{ [all processes]}$$

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?

$$Q_1 = -Q_2 = m_1 c_p \Delta T_1 = -m_2 c_p \Delta T_2$$

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

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

$$4T_f = 350^\circ\text{C}$$

$$T_f = 87.5^\circ\text{C}$$

## The 1<sup>st</sup> Law of Thermodynamics

### Steady-State Systems

$$\begin{aligned} & \sum \dot{m}_i \left( h_i + \frac{v_i^2}{2} + gz_i \right) \\ & - \sum \dot{m}_e \left( h_e + \frac{v_e^2}{2} + gz_e \right) \\ & + \dot{Q} - \dot{W} = 0 \quad [\text{SI}] \quad 27.24a \end{aligned}$$

### Special Cases:

- Nozzles, diffusers

$$h_i + \frac{v_i^2}{2} = h_e + \frac{v_e^2}{2} \quad [\text{SI}] \quad 27.25a$$

$$\begin{aligned} \eta &= \frac{\Delta h_{\text{actual}}}{\Delta h_{\text{ideal}}} \\ &= \frac{v_e^2 - v_i^2}{2(h_i - h_{es})} \quad 27.26 \end{aligned}$$

## The 1<sup>st</sup> Law of Thermodynamics

Special Cases (*cont.*):

- Turbines, pumps, compressors

$$\dot{W} = \dot{m}(h_i - h_e) \quad [\text{SI}] \quad 27.28a$$

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

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

- Throttling valves and processes

$$h_i = h_e \quad 27.31$$

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

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

## The 1<sup>st</sup> Law of Thermodynamics

Special Cases (*cont.*):

- Heat exchangers

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

- Mixers, separators, open or closed feedwater heaters

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

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

## Psychrometrics

Total Atmospheric Pressure:

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

Specific Humidity:

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

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

Relative Humidity:

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

Three Important Temperatures:

- dew-point temperature
- dry-bulb temperature
- wet-bulb temperature

## 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

## 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 m<sup>3</sup>/kg.

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

## Mixtures of Gases, Vapors, and Liquids

### Phase Relations

- Clapeyron equation for phase transition:

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

$h_{fg}$  = enthalpy change for phase transition

$v_{fg}$  = volume change

$s_{fg}$  = entropy change

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

- Gibbs' phase rule:

$$P + F = C + 2 \quad 29.29, \text{ where}$$

$P$  = number of phases in the system

$F$  = degrees of freedom

$C$  = number of components

## 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

$$P = 1, C = 1$$

$$F = C - P + 2$$

$$= 1 - 1 + 2 = 2$$

Therefore, (C) is correct.

## Mixtures of Gases, Vapors, and Liquids

### Vapor-Liquid Mixtures

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

$$p_i = x_i h = y_i P \quad 29.18$$

- Raoult's Law: partial pressure due to the  $i^{\text{th}}$  gas is related to its mole fraction

$$p_i = x_i p_i^* \quad 29.19$$

## Power Cycles and Entropy

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### 2<sup>nd</sup> Law of Thermodynamics:

- Kelvin-Planck 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.

## Power Cycles and Entropy

### Entropy

- Inequality of Clausius:

$$\oint \frac{dQ}{T} \leq 0 \quad 28.12 \quad S_2 - S_1 = \int dS = \int \frac{dQ_{\text{reversible}}}{T} \quad 28.10$$

- For Constant Temperature:  $\Delta S = S_2 - S_1 = \frac{Q}{T_0}$  28.13  
 $W = Q$

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

- Isentropic Process:  $\Delta S = S_2 - S_1 = 0$  28.14  
 $Q = 0$

- Increasing Entropy:

$$\Delta s_{\text{total}} = \Delta s_{\text{system}} + \Delta s_{\text{surroundings}} \geq 0 \quad \Delta \dot{S}_{\text{total}} = \sum \dot{m}_{\text{out}} s_{\text{out}} - \sum \dot{m}_{\text{in}} s_{\text{in}} - \sum \frac{\dot{Q}_{\text{external}}}{T_{\text{external}}} \geq 0$$

- Temperature-Entropy ( $T$ - $s$ ) Diagrams:

$$Q = \int_{s_1}^{s_2} T ds \quad 28.24 \quad W = \int_{V_1}^{V_2} p dV \quad 28.23 \quad Q = W$$

# Thermodynamics

10-9b

## Power Cycles and Entropy

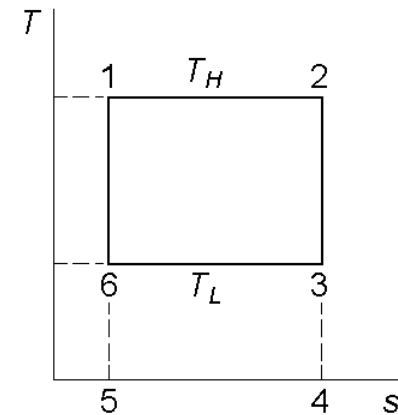
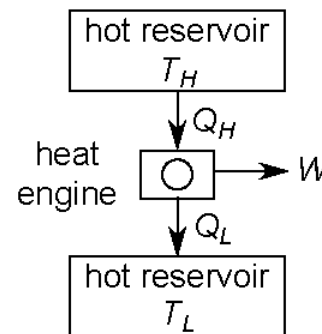
Example (FEIM):

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

$$\begin{aligned} W &= Q_H - Q_C \\ &= T_H \Delta s - T_C \Delta s \\ &= (1-2-4-5) - (3-4-5-6) \\ &= (1-2-3-6) \end{aligned}$$

Therefore, (D) is correct.



## Power Cycles and Entropy

Entropy for Solids and Incompressible Liquids

$$s_2 - s_1 = c \ln \left( \frac{T_2}{T_1} \right) \quad 28.16$$

Example (FEIM):

Lead is cooled from 100.0°C to 50.0°C. What is the change in specific entropy?

$$T_2 = 50.0^\circ\text{C} + 273.16 = 323.16\text{K}$$

$$T_1 = 100.0^\circ\text{C} + 273.16 = 373.16\text{K}$$

$$\begin{aligned} s_2 - s_1 &= c_{\text{mean}} \ln \frac{T_2}{T_1} \\ &= 0.128 \frac{\text{kJ}}{\text{kg} \cdot \text{K}} \ln \frac{323.16\text{K}}{373.16\text{K}} \\ &= -0.0184 \text{kJ/kg} \cdot \text{K} \end{aligned}$$

## Power Cycles and Entropy

### Irreversibility

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

### Availability

- Closed System

$$\phi = u - u_0 - T_0(s - s_0) + p_0(v - v_0) \quad [\text{SI}] \quad 28.17a$$

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

- Open System

$$\Psi = h - h_0 - T_0(s - s_0) + \frac{v^2}{2} + gz \quad [\text{SI}] \quad 28.19a$$

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

## Power Cycles and Entropy—Basic Cycles

Thermal Efficiency for an Engine

$$\begin{aligned}\eta_{\text{th}} &= \frac{W_{\text{out}} - W_{\text{in}}}{Q_{\text{in}}} = \frac{W_{\text{net}}}{Q_{\text{in}}} \\ &= \frac{Q_{\text{in}} - Q_{\text{out}}}{Q_{\text{in}}} = \frac{Q_{\text{net}}}{Q_{\text{in}}}\end{aligned}\quad 28.1$$

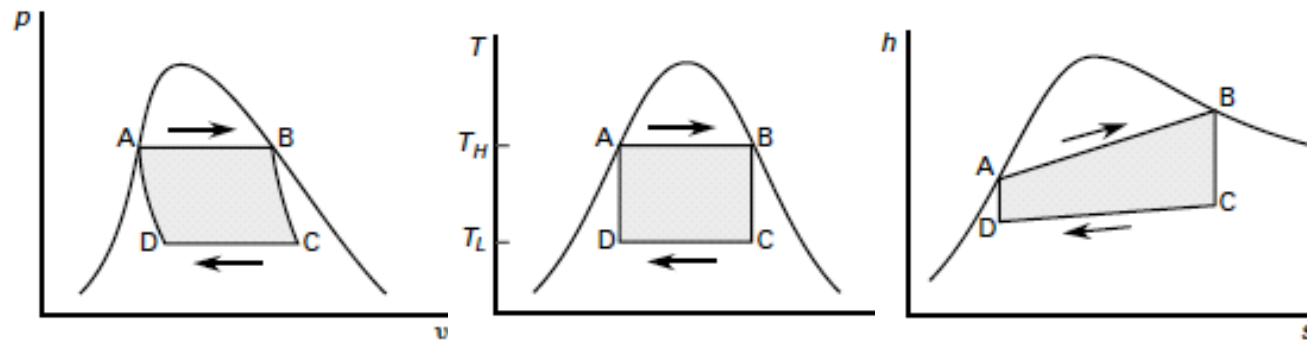
Coefficient of Performance (COP)

- Heat Pump:  $(\text{COP})_{\text{heat pump}} = \frac{Q_H}{W} = (\text{COP})_{\text{refrigerator}} + 1 \quad 28.7$
- Refrigerator:  $(\text{COP})_{\text{refrigerator}} = \frac{Q_L}{W} \quad 28.6$

## Power Cycles and Entropy—Basic Cycles

### Carnot Cycle

Figure 28.2 Carnot Cycle



For a Carnot engine:  $\eta_{th,Carnot} = \frac{T_H - T_L}{T_H} = 1 - \frac{T_L}{T_H}$  28.2

COP for a Carnot heat pump:  $(COP)_{Carnot} = \frac{T_H}{T_H - T_L}$  [Carnot heat pump] 28.9

COP for a Carnot refrigerator:  $(COP)_{Carnot} = \frac{T_L}{T_H - T_L}$  [Carnot refrigerator] 28.8

## 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%

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

Therefore, (A) is correct.

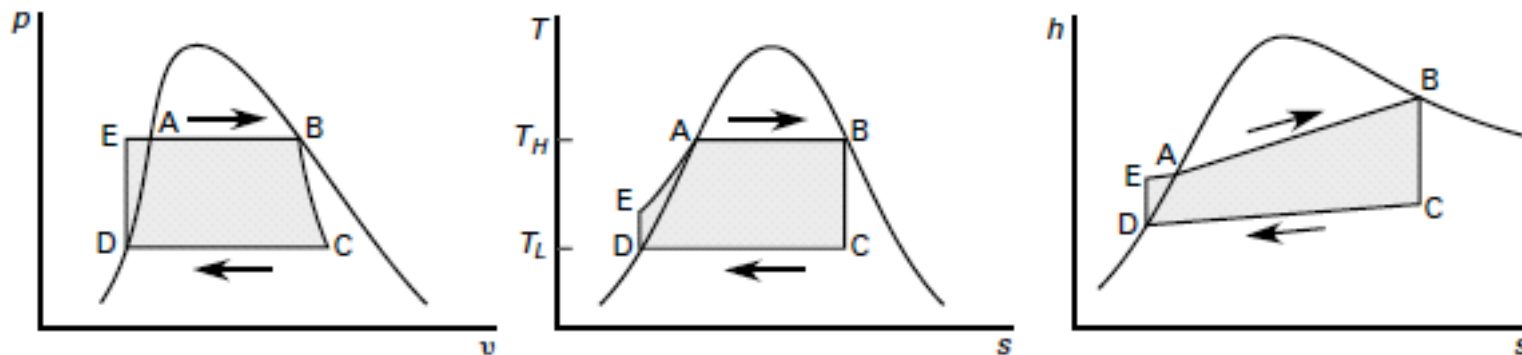
# Thermodynamics

10-10c

## Power Cycles and Entropy—Basic Cycles

### Rankine Cycle

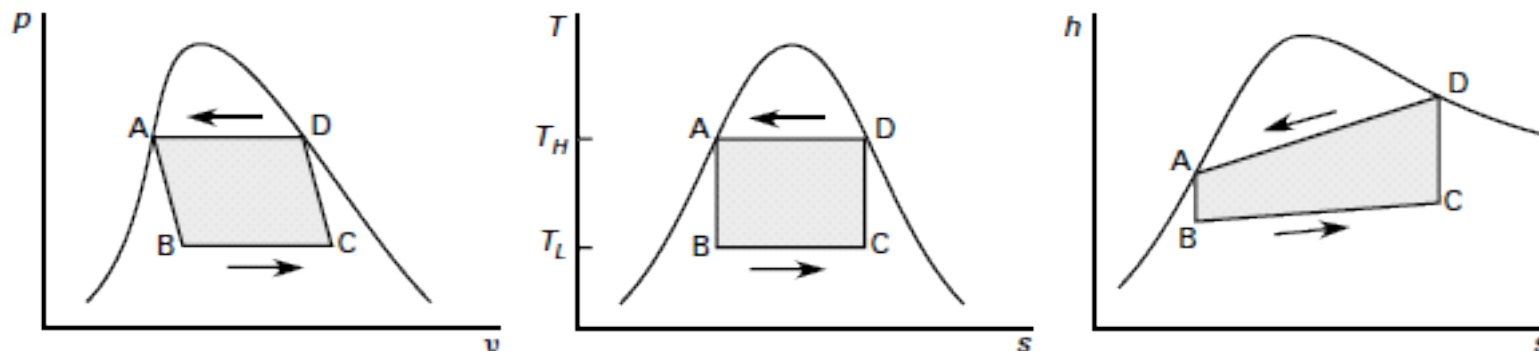
Figure 28.4 Basic Rankine Cycle



$$\eta_{th} = \frac{W_{out} - W_{in}}{Q_{in}} = \frac{(h_B - h_C) - (h_E - h_D)}{h_B - h_E} \quad 28.3$$

### Carnot Refrigeration

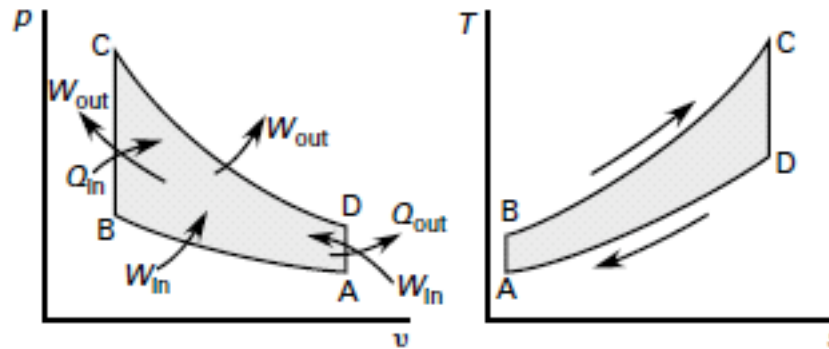
Figure 28.7 Carnot Refrigeration Cycle



## Power Cycles and Entropy—Basic Cycles

### Otto Cycle

Figure 28.6 Air-Standard Otto Cycle



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

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

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.

## Power Cycles and Entropy—Basic Cycles

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.

## Power Cycles and Entropy—Basic Cycles

For examples 3–7, use the following data:

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

## Power Cycles and Entropy—Basic Cycles

A → B and C → 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 → C and D → 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.

# Thermodynamics

10-10g

## 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

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

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

$$= 1874 \text{ kPa}$$

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 m<sup>3</sup>/kg
- (B) 8.9 m<sup>3</sup>/kg
- (C) 75 m<sup>3</sup>/kg
- (D) 115 m<sup>3</sup>/kg

$$v = \frac{\bar{R}T}{(MW)p}$$

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

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

Therefore, (A) is correct.

## Power Cycles and Entropy—Basic Cycles

Example 6 (FEIM):

The thermal efficiency of the cycle is most nearly

- (A) 0.30
- (B) 0.38
- (C) 0.4
- (D) 0.57

$$\begin{aligned}\eta &= 1 - \left(\frac{V_A}{V_B}\right)^{1-k} \\ &= 1 - \left(\frac{8}{1}\right)^{1-1.4} \\ &= 0.565 \quad (0.57)\end{aligned}$$

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

$$\begin{aligned}\text{Heat rejected} &= (1 - \eta)Q_{B-C} \\ &= (1 - 0.565) \left(1740 \frac{\text{kJ}}{\text{kg}}\right) \\ &= 757 \quad (755 \text{ kJ/kg})\end{aligned}$$

Therefore, (A) is correct.

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## Power Cycles and Entropy—Basic Cycles

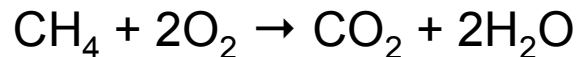
Steam Tables

Note: Tables are provided in the NCEES Handbook.

## Combustion

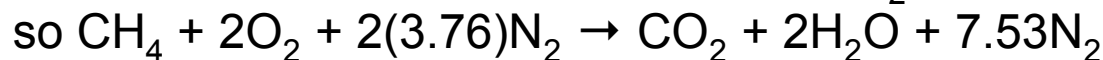
### Combustion Process

- Stoichiometric Combustion



For each mole of  $\text{CH}_4$ , there should be 2 moles of  $\text{O}_2$ .

However, in air there are 3.76 moles of  $\text{N}_2$  for each mole of  $\text{O}_2$ ,



- Stoichiometric Air/Fuel Ratio:  $\frac{A}{F} = \frac{m_{\text{air}}}{m_{\text{fuel}}}$  30.1

- Incomplete Combustion

$$\text{percent theoretical air} = \frac{\left(\frac{A}{F}\right)_{\text{actual}}}{\left(\frac{A}{F}\right)_{\text{stoichiometric}}} \times 100\% \quad 30.2$$

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