Unit Three – Heat, Internal Energy and the First Law

Mechanical Engineering 370

Thermodynamics

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Outline

- Quiz solution
- Unit three – heat, internal energy and the first law of thermodynamics
  - Heat, Q, is energy in transit due only to a temperature gradient
  - Internal energy, U, is a property found from tables or relations for ideal gases
  - $Q = \Delta U + W$ or $Q_{in} - Q_{out} = \Delta U + W_{out} - W_{in}$
  - Specific internal energy: $\Delta U = m\Delta u$

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Unit Three Goals

- As a result of studying this unit you should be able to
  - find properties more easily than you were able to do after units one and two
  - describe the path for a process and determine the work with more confidence
  - understand that heat is energy in transit due only to a temperature difference

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Unit Three Goals Continued

- understand the meaning of the internal energy as a property giving the amount of energy stored in a body.
- use the first law as $Q = \Delta U + W = m\Delta u + W$ to solve problems in closed (fixed mass) systems
- use the sign convention for heat and work
  - Heat added to a system is positive; heat removed from a system is negative: $Q = Q_{in} - Q_{out}$
  - Work done by a system is positive; work done on a system is negative: $W = W_{out} - W_{in}$

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Unit Three Goals Continued

- we do not have to worry about the sign convention when we use $W = \int PdV$; we automatically get the correct sign
- use the first law as $q = \Delta u + w$ where $q = Q/m$ and $w = W/m$, in problem solving
- find the internal energy in tables from any definition of the state in one-phase or mixed regions

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Unit Three Goals Concluded

- find the internal energy from the enthalpy as $u = h - Pv$ (with correct units) – this is needed for quiz tables
- use the enthalpy in place of the internal energy when enthalpy is given in a table but internal energy is not
- work problems, possible involving trial-and-error solutions, using the first law, property relations and a path equation

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First Law as Energy Balance

- Change in Energy = energy added as heat – energy lost by doing work
- Heat and work are processes
- We can store energy as kinetic energy, potential energy or thermodynamic internal energy, $U = mu$
  - u is a property (depends on state)
- Most processes have negligible KE and PE changes; consider only ΔU here

Northridge 7

First-law Problems

- Start with closed (fixed mass) systems
- Here $\Delta U = m\Delta u$, and we find u from tables or ideal gas relationships
- In tables, u acts like volume
  - Find u(T,P) in gas (superheat) region (or compressed liquid tables for water)
  - $u = u_f + x(u_g - u_f)$ in mixed region
  - Compressed liquid: $u(T,P) \approx u_f(\boldsymbol{T})$
  - Can find u given v and (T or P) by same rules used to find state previously

Northridge 8

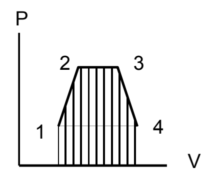
Solving First-law Problems

- Data usually given: partial information about state points along a path
- Usually want to find heat transfer
- Have to do same calculations done previously to find work: $W = \int_{path} PdV$
  - May have other types of work such as electrical work or applied torque
- Use property data to get u at initial and final states of overall process
- $Q = m(u_{final} - u_{initial}) + W$

Northridge 9

First Law for a Complex Path

- Here we have an initial point (1) and a final point (4)
- Work = area under path = $(P_1 + P_2)\bullet(V_2 - V_1)/2 + P_{2\text{-}3}(V_3 - V_2) + (P_3 + P_4)(V_4 - V_3)/2$



- $Q = (U_{final} - U_{initial}) + W = m(u_4 - u_1) + W$
- Do not need intermediate u values
- Use property data for u (and possibly v)

Northridge 10

Enthalpy

- Defined property $H \equiv U + PV$
- $h = H/m = U/m + P(V/m) = u + Pv = u + P/\rho$
- Constant pressure path has solution that $Q = m(u_2 - u_1) + P_{1\text{-}2}\, m(v_2 - v_1) = m[(u_2 + P_2v_2) - (u_1 + P_1v_1)] = m(h_2 - h_1)$
- For constant pressure process $Q = \Delta H$
- H used in open systems and quiz tables require calculation of $u = h - Pv$

Northridge 11

Is Electricity Heat or Work?

- We know that "resistance heating" is I^2R
- If the system boundary is defined such that electricity crosses boundary then we do I^2R work on system
  - For $Q = 0$, $\Delta U = -W = -(-I^2R) = I^2R$
- If resistor is outside system boundary then I^2R heat is added to system
  - For $W = 0$, $\Delta U = Q = I^2R$
- Either approach gives $\Delta U = I^2R$

Northridge 12

Example Calculation

- Refrigerant 134a, initially at 100°F and 20 psia fills a container with an initial volume of 20 ft³. It is cooled in two steps: (1) at constant volume to 40°F and (2) at constant pressure to 0°F.
- What is the heat transfer?

Northridge 13

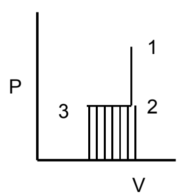
Example Calculation II

- **Given data:**
  - **Initial state:** p_1 = 20 psia, T_1 = 100°F, V_1 = 20 ft³
  - **Path:** Constant volume to intermediate state then constant pressure to final state
  - **Intermediate state:** $v_2 = v_1$ and T_2 = 40°F
  - **Final state:** $P_3 = P_2$ and T_3 = 0°F
- **Equations:**
  - **First law:** $Q = \Delta U + W = m(u_3 - u_1) + W$
  - **Work:** $W = \int_{path} P dV$
  - **Mass:** $m = V_1 / v_1$

Northridge 14

Finding the Work

- No work done during the first (constant-volume) part of the path (1 to 2)
- Total work comes from second (constant-pressure) part (2 to 3)
- $W = P_{2\text{-}3}(V_3 - V_2)$ where $P_{2\text{-}3} = P_2 = P_3$
- $V_3 = mv_3$ and $V_2 = mv_2$



- $Q = \Delta U + W = m(u_3 - u_1) + mP_{2\text{-}3}(v_3 - v_2)$

Northridge 15

Solving the Problem

- $Q = m(u_3 - u_1) + mP_{2\text{-}3}(v_3 - v_2)$
- $m = V_1 / v_1$
- We have to find u_1 and v_1, $P_2 = P_3 = P_{2\text{-}3}$, v_2, v_3 and u_3.
- State 1 has P_1 = 20 psia, T_1 = 100°F
- State 2 has $v_2 = v_1$ and T_2 = 40°F
- State 3 has $P_3 = P_2$ and T_3 = 0°F
- Find properties from R-134a tables

Northridge 16

States 1 and 2 and Mass

- We can find P_1 = 20 psia and T_1 = 100°F in superheat tables giving v_1 = 2.8726 ft³/lb$_m$ and u_1 = 112.66 Btu/lb$_m$

$$m = \frac{V_1}{v_1} = \frac{20\ ft^3}{\frac{2.8726\ ft^3}{lb_m}} = 6.962\ lb_m$$

Properties from Table A-13E, page 978

- State 2 has $v_2 = v_1$ and T_2 = 40°F
- This is between 15 and 20 psia

$$P_2 = 15\ psia + \frac{20\ psia - 15\ psia}{\frac{2.5306\ ft^3}{lb_m} - \frac{3.4074\ ft^3}{lb_m}}\left(\frac{2.8726\ ft^3}{lb_m} - \frac{3.4074\ ft^3}{lb_m}\right) = 18.086\ psi$$

Northridge 17

Interpolate for Final State

- Final state has $P_3 = P_2$ = 18.086 psia and T_3 = 0°F – interpolate between 15 and 20 psia to find u_3 and v_3

$$v_3 = \frac{3.1001\ ft^3}{lb_m} + \frac{18.086\ psia - 15\ psia}{20\ psia - 15\ psia}\left(\frac{2.2922\ ft^3}{lb_m} - \frac{3.1001\ ft^3}{lb_m}\right) = \frac{2.549\ ft^3}{lb_m}$$

$$u_3 = \frac{95.08\ Btu}{lb_m} + \frac{18.086\ psia - 15\ psia}{20\ psia - 15\ psia}\left(\frac{94.72\ Btu}{lb_m} - \frac{95.08\ Btu}{lb_m}\right) = \frac{94.86\ Btu}{lb_m}$$

- Common interpolation factor for u and v

Northridge 18

Compute Heat Transfer

- $Q = m(u_3 - u_1) + mP_{2\text{-}3}(v_3 - v_2)$
- Apply previous results to obtain

$$Q = (6.962\ lb_m)\left(\frac{94.86\ Btu}{lb_m} - \frac{112.66\ Btu}{lb_m}\right) +$$
$$(6.962\ lb_m)\frac{18.086\ lb_f}{in^2}\left(\frac{2.549\ ft^3}{lb_m} - \frac{2.8726\ ft^3}{lb_m}\right)\frac{in^2 \cdot Btu}{5.40395\ lb_f \cdot ft^3} = -145\ Btu$$

- Negative Q means heat is rejected from system

California State University Northridge 19

Another Example Calculation

- ***Given:*** 10 kg of H_2O at 200°C and 50% quality is expanded to 400°C at constant pressure
- ***Find:*** Heat Transfer
- **Given data:**
  - **Initial state:** T_1 = 200°C, x_1 = 0.5
  - **Path:** Constant pressure $P_1 = P_2 = P_{1\text{-}2}$
  - **Final state:** T_2 = 400°C
  - **Substance:** Water, use property tables
  - **Mass:** m = 10 kg

California State University Northridge 20

Another Example Calculation II

- **Equations:**
  - First Law: $Q = \Delta U + W = m(u_2 - u_1) + W$
  - $W = \int_{path} PdV$
  - $W = P_{1\text{-}2}(V_2 - V_1)$ for constant pressure, $P_{1\text{-}2} = P_1 = P_2$
- Combine first law and work equation to get $Q = m(u_2 - u_1) + P_{1\text{-}2}(V_2 - V_1)$
  - $V_2 = mv_2$ and $V_1 = mv_1$
- We have to find v_1, v_2, $P_1 = P_2 = P_{1\text{-}2}$, u_1, and u_2
- Use property tables for water

California State University Northridge 21

Find Initial State Properties

- Initial state is x_1 = 50% and T_1 = 200°C
- x_1 = 50% quality implies mixed region at T_1 = 200°C
- $P_1 = P_{sat}(T_1 = 200°C) =$ 1554.9 kPa
- $v_1 = (1 - x_1)\,v_f(T_1 = 200°C) + x_1\,v_g(T_1 = 200°C)$ = 0.06426 m³/kg
- $u_1 = (1 - x_1)\,u_f(T_1 = 200°C) + x_1\,u_g(T_1 = 200°C)$ = 1723.0 kJ/kg

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Saturation properties from Table A-4, page 916

22

Find Final State Properties

- Point 2 has T_2 = 400°C and $P_2 = P_1$ = 1554.9 kPa
- Interpolation in superheat table between 1.40 MPa and 1.60 MPa at T_2 = 400°C
  - At P = 1.40 MPa, u = 2953.1 and v = 0.21782 m³/kg
  - At P = 1.60 MPa, u = 2950.8 kJ/kg and v = 0.19007 m³/kg
- Interpolation (details next page) gives v_2 = 0.19646 m³/kg and u_2 = 2951.3 kJ/kg

California State University Northridge Properties from Table A-6, page 921 23

Interpolation Details

- Interpolation calculations for both u and v have common factor for pressure

$$u = 2953.1\,{}^{kJ}\!/_{kg} + \frac{1.5549\ MPa - 1.40\ MPa}{1.60\ MPa - 1.40\ MPa} \bullet \left(2950.8\,{}^{kJ}\!/_{kg} - 2953.1\,{}^{kJ}\!/_{kg}\right) = 2951.4\,{}^{kJ}\!/_{kg}$$

$$v = 0.21782\,{}^{m^3}\!/_{kg} + \frac{1.5549\ MPa - 1.40\ MPa}{1.60\ MPa - 1.40\ MPa} \bullet \left(0.19007\,{}^{m^3}\!/_{kg} - 0.21782\,{}^{m^3}\!/_{kg}\right) = 0.19646\,{}^{m^3}\!/_{kg}$$

California State University Northridge 24

First Law Gives Answer

- $Q = \Delta U + W = \Delta U + P_{1\text{-}2}(V_2 - V_1) = m(u_2 - u_1) + P_{1\text{-}2}\, m(v_2 - v_1)$

$$Q = (10\ kg)\left(2951.4\,{}^{kJ}\!/_{kg} - 1723.0\,{}^{kJ}\!/_{kg}\right)\frac{1\ MJ}{1000\ kJ} +$$
$$(10\ kg)(1.5549\ MPa)\left(0.19646\,{}^{m^3}\!/_{kg} - 0.06426\,{}^{m^3}\!/_{kg}\right)\frac{1\ MJ}{MPa\cdot m^3}$$

- Q = 14.33 MJ (added to system)

Northridge 25

Third Example Calculation

- ***Given:*** 110 kg of H_2O at 200°C and 50% quality is compressed along a linear path, P = a + bV to 400°C and 10 MPa
- ***Find:*** Heat Transfer
- **Given data:**
  - **Initial state:** T_1 = 200°C, x_1 = 0.5
  - **Path:** Straight line, P = a + bV
  - **Final state:** T_2 = 400°C, P_2 =10 MPa
  - **Substance:** Water, use property tables
  - **Mass:** 110 kg

Northridge 26

Third Example Calculation II

- **Equations:**
  - First Law: $Q = \Delta U + W = m(u_2 - u_1) + W$
  - $W = \int_{path} PdV$
  - $W = (P_1 + P_2)(V_2 - V_1)/2$ for straight line path (area of a trapezoid)
  - Combine first law and work equation to get $Q = m(u_2 - u_1) + (P_1 + P_2)(V_2 - V_1)/2$
  - $V_2 = mv_2$ and $V_1 = mv_1$
- We have to find v_1, v_2, P_1, u_1, and u_2
- Use property tables for water

Northridge 27

Find Initial State Properties

- Initial state: x_1 = 50% and T_1 = 200°C
- x_1 = 50% quality implies mixed region at T_1 = 200°C
- $P_1 = P_{sat}(T_1 = 200°C)$ = 1554.9 kPa
- $v_1 = (1 - x_1)\, v_f(T_1 = 200°C) + x_1\, v_g(T_1 = 200°C)$ = 0.06426 m³/kg
- $u_1 = (1 - x_1)\, u_f(T_1 = 200°C) + x_1\, u_g(T_1 = 200°C)$ = 1723.0 kJ/kg

Saturation properties from Table A-4, page 916

Northridge 28

Final State, Work and Heat

- At point 2, T_2 = 400°C and P_2 = 10 MPa
- In superheat table, v_2 = 0.026436 m³/kg and u_2 = 2833.1 kJ/kg (page 922)

$$W = \frac{P_1 + P_2}{2}(V_2 - V_1) = \frac{P_1 + P_2}{2} m(v_2 - v_1) = \frac{1.5549\ MPa + 10\ MPa}{2}(10\ kg)\bullet$$
$$\left(0.026436\,{}^{m^3}\!/_{kg} - 0.06426\,{}^{m^3}\!/_{kg}\right)\frac{1\ MJ}{1\ MPa\cdot m^3} = -0.4373\ MJ$$
$$Q = (10\ kg)\left(2833.1\,{}^{kJ}\!/_{kg} - 1723.0\,{}^{kJ}\!/_{kg}\right)\frac{1\ MJ}{1000\ kJ} - 0.4373\ MJ$$

- Q = 10.67 MJ (heat added)

Northridge 29

Solving First Law Problems

- Get moving boundary work as done previously: $W = \int_{path} PdV$
- May have other work terms
- Find internal energy from tables
- May find m = V/v from given data
- $Q = \Delta U + W = m(u_{final} - u_{initial}) + W$
- If m not known, $q = \Delta u + w$
- Observe that u depends more on temperature, T, than pressure, P

Northridge 30