Unit Seven – Introduction to the Second Law

Mechanical Engineering 370

Thermodynamics

Larry Caretto

October 19, 2010

California State University Northridge

Outline

- Quiz six and midterm results and solution (Note revised schedule)
- Introduction to the Second Law of Thermodynamics
- Physical background for second law
- Mathematical statement of second law
- Use of entropy as determination of maximum efficiency
- Deriving other common forms of the second law

California State University Northridge 2

Unit Seven Goals

- As a result of studying this unit you should be able to
  - recognize that there is a thermodynamic property, called entropy, s, defined as follows: $ds = (du + Pdv) / T$
  - understand the inequality that $dS \geq dQ/T$
  - understand that $dS \geq 0$ for isolated systems
  - recognize that entropy is a property
  - Understand that the = part of the $\geq$ sign applies in a reversible process

California State University Northridge 3

More Unit Seven Goals

  - understand the definitions of engine and refrigeration cycles
  - apply the definitions of work and heat flow for these cycles
  - compute the efficiency of an engine cycle
  - compute the coefficient of performance (COP) for a refrigeration cycle
  - perform Carnot cycle computations
- Read second law notes from web site

California State University Northridge 4

Why the Second Law?

- Encapsulates the phenomenon that certain process in nature flow one way
  - Water flows downhill
  - Heat flows from high to low temperatures
- We know that we can reverse these processes with an external effect
  - pump water uphill
  - use a refrigerator to transfer heat from low to high temperature

California State University Northridge 5

Second Law Application

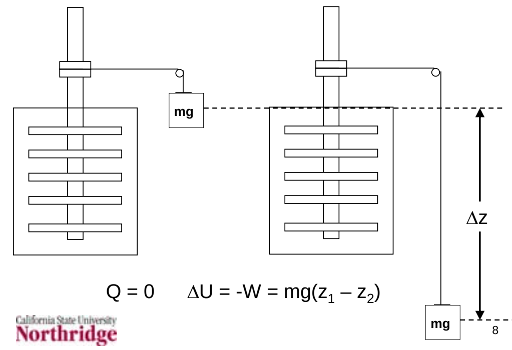
- Based on entropy, a thermodynamic property
- Used to define ideal (reversible) processes
- Shows that maximum efficiency of conversion of heat to work occurs in a reversible process
- Gives quantitative calculations for this maximum efficiency

California State University Northridge 6

Approach to Second Law

- Developed around 1850 by considering of engine and refrigeration cycles
- Text considers similar derivation
- Important idea is in result using entropy
- Class notes will start at this point
  - Provide focus on ultimate calculations
  - Show equivalence to text derivation

Joule’s Experiment



Q = 0 $\Delta U = -W = mg(z_1 – z_2)$

Joule’s Experiment Explained

- The falling weight, mg, turns the paddle wheels increasing the system energy
- For an insulated system Q = ΔU + W = 0 so that $\Delta U = -W = mg(z_{initial} – z_{final})$
- For falling weight, $z_{initial} – z_{final} > 0$, so ΔU > 0, corresponding to water heating.
- What about process where weight rises and water cools?

Another Example

- Two identical blocks
  - Same mass and heat capacity
  - Block A at 300 K, block B at 500 K
  - Blocks placed in contact each reaching a final temperature of 400 K
  - No heat or work external to blocks
  - $\Delta U = \Delta U_A + \Delta U_B = 0$ or $\Delta U_A = -\Delta U_B$
- Can $T_{A,Final}$ = 200 K and $T_{B,Final}$ = 600 K?
  - This also gives $\Delta U = \Delta U_A + \Delta U_B = 0$ or $\Delta U_A = -\Delta U_B$

General Idea

- Some processes in nature are observed to only proceed in one direction
- First law does not prohibit these processes going in the opposite direction
- Is there any general rule that shows the one-directional nature of processes
- Yes, it is the second law

The Second Law

- There exists an extensive thermo-dynamic property called the entropy, S, defined as follows:

$$dS = (dU + PdV)/T$$

- For any process $dS \geq dQ/T$
- For an isolated system $dS \geq 0$
- T must be absolute temperature
- Inequality is required to show directional effects

Entropy as a Property

- Have total entropy, S, and specific entropy, s = S/m
- Dimensions of entropy are energy divided by temperature
- For S, typical units are kJ/K or Btu/R
  - Units for s: kJ/kg·K or Btu/lb_m·R
  - s in tables is similar to v
  - One-phase regions give s(T,P)
  - In mixed region, $s = s_f + x\, s_{fg}$
  - Ideal gas equations for entropy as well

California State University Northridge 13

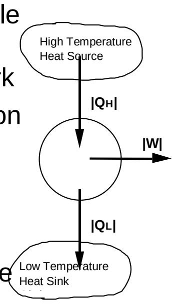
Cyclic Processes

- In a cycle, the initial and final states of the system are the same
- Since the initial and final states are the same, the properties of the initial and final states are the same
- Thus, for a cycle, $\Delta u = \Delta s = 0$
- Since heat and work depend on path, these may be nonzero, but $Q = \Delta U + W$ means that Q = W for a cycle

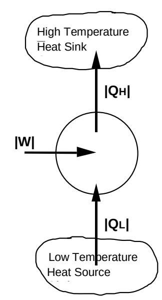
California State University Northridge 14

Cycles with $|Q_H| = |Q_L| + |W|$

- Engine cycle converts heat to work
- Refrigeration cycle transfers heat from low to high temperature



Engine Cycle



Refrigeration Cycle

California State University Northridge 15

Engine Cycle Heat and Work

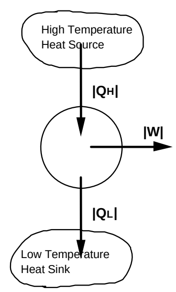
- Relation between cycle terms and usual sign conventions
- Engine cycle

$|Q_H| = -Q_{HTHS} = Q_{H,Cycle}$

$|Q_L| = Q_{LTHS} = -Q_{L,Cycle}$

$Q_{cycle} = |Q_H| - |Q_L|$

$Q_{cycle} = W > 0$



Engine Cycle Schematic

California State University Northridge 16

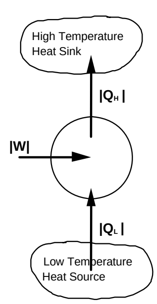
Refrigeration Cycle Heat/ Work

- Relation between cycle terms and usual sign conventions
- Refrigeration cycle

$|Q_H| = Q_{HTHS} = -Q_{H,Cycle}$

$|Q_L| = -Q_{LTHS} = Q_{L,Cycle}$

$Q_{cycle} = |Q_L| - |Q_H| = W < 0$



Refrigeration Cycle Schematic

California State University Northridge 17

Cycle Parameters

- Engine cycle efficiency $\eta = \frac{|W|}{|Q_H|}$
- Refrigeration cycle COP (coefficient of performance) $COP = \beta = \frac{|Q_L|}{|W|}$
- General definitions, valid for any cycle
- Engine efficiency always less than one
- COP can be greater than one

California State University Northridge 18

Reversible Process

- In a reversible process where $dS_{isolated\ system} = 0$ it is possible to return a system to its initial state with no changes in the surroundings
- This is an idealization; we cannot do better than a reversible process
- External reversibility is when $dS = 0$ is true for an isolated system
- Internal reversibility is when $dS = dQ/T$ for one subsystem in an isolated system
  – May still have $dS_{isolated\ system} > 0$

California State University Northridge 19

Temperature Reservoir

- A body that transfers heat with no change in its temperature
- Two-phase fluid is best example
- Reservoir usually envisioned as very large body such that $\Delta T = Q/(mc_v) \approx 0$
- Basic idea is that instead of $dS = dQ/T$ we can write $\Delta S = \int dQ/T = Q/T$
- Temperature reservoir is internally reversible

California State University Northridge 20

Carnot Cycle Introduction

- This cycle has theoretical significance but is not a practical cycle
- In traditional approaches to the second law, results for Carnot cycles are used to derive entropy
- Here we will show that Carnot cycle results can be obtained from principle that $dS_{isolated\ system} \geq 0$

California State University Northridge 21

Carnot Cycle Results

- Carnot cycle uses one high temperature reservoir at T_H and one low temperature reservoir at T_L
- We have results for Carnot engine cycle efficiency and Carnot refrigeration cycle coefficient of performance
- Efficiency $\eta = |W| / |Q_H| \leq 1 - T_L / T_H = \eta_C$
- COP $= |Q_L| / |W| \leq T_L / (T_H - T_L) = \beta_{Carnot}$

California State University Northridge 22

Carnot Cycle

- Cycle with only two temperature reservoirs, HTR at T_H and LTR at T_L
- $\Delta S_{isol\ syst} = \Delta S_{HTR} + \Delta S_{cycle} + \Delta S_{LTR} \geq 0$
- $\Delta S_{isol\ syst} = Q_{HTR}/T_H + 0 + Q_{LTR}/T_L \geq 0$
- For the engine cycle $Q_{HTR} = -|Q_H|$ and $Q_{LTR} = |Q_L|$, so $-|Q_H|/T_H + |Q_L|/T_L \geq 0$
- Refrigeration cycle $Q_{HTR} = |Q_H|$ and $Q_{LTR} = -|Q_L|$, so $|Q_H|/T_H - |Q_L|/T_L \geq 0$

California State University Northridge 23

Carnot Cycle Continued

- For both cycles, $|Q_H| = |Q_L| + |W|$
- For the engine cycle
  – $-|Q_H|/T_H + |Q_L|/T_L \geq 0$ so that $-|Q_H|/T_H + (|Q_H| - |W|)/T_L \geq 0$
  – Rearrange to get $|Q_H|(1/T_L - 1/T_H) \geq |W|/T_L$
  – $\eta = |W| / |Q_H| \leq 1 - T_L / T_H = \eta_{Carnot}$
- It is impossible to construct an engine cycle without heat rejection

California State University Northridge 24

Carnot Cycle Concluded

- For both cycles, $|Q_H| = |Q_L| + |W|$
- For the refrigeration cycle
  - $|Q_H|/T_H - |Q_L|/T_L \geq 0$ so that $(|Q_L| + |W|)/T_H - |Q_L|/T_L \geq 0$ or $(|Q_L| + |W|)/T_H \geq Q_L|/T_L$
  - Divide by |W| and rearrange to get
  - $\beta = |Q_L| / |W| \leq T_L / (T_H – T_L) = \beta_{Carnot}$
- It is impossible to transfer heat from low to high temperature without work input

This Week's Homework

- Generally deal with definitions of efficiency, $\eta = |W| / |Q_H|$, or coefficient of performance, $\beta = |Q_L| / |W|$
- Also require use of $|Q_H| = |Q_L| + |W|$
- For Carnot Cycles, $\eta = 1 – T_L / T_H$
- A heat pump cools outside air while heating inside air; $\beta_{heat\ pump} = |Q_H| / |W|$

Class Exercise

- Find the entropy and enthalpy of water at a pressure of 1000 psia and 1000ºF
- What is the enthalpy at a state with the same entropy you just found and a pressure of 80 psia?
- What is the enthalpy at a state with the same entropy you found above and a pressure of 5 psia?

Class Exercise Solution

- At 1000 psia and 1000ºF, h = 1506.2 Btu/lb_m s = 1.6535 Btu/lb_m·R (Table A-6E, p946)
- At 80 psia, s = 1.6535 Btu/lb_m·R is between s = 1.6271 Btu/lb_m·R at 320ºF and s = 1.6545 Btu/lb_m·R at 360ºF

Interpolate h and s

$$h = \frac{1187.9\,kJ}{kg} + \frac{\frac{1209.9\,kJ}{kg} - \frac{1187.9\,kJ}{kg}}{\frac{1.6545\,kJ}{kg} - \frac{1.6271\,kJ}{kg}} \bullet \left(\frac{1.6535\,kJ}{kg} - \frac{1.6271\,kJ}{kg}\right) = \frac{1209.1\,kJ}{kg}$$

Class Exercise Solution II

- At 5 psia, s = 1.6535 Btu/lb_m·R is between s_f = 0.23488 Btu/lb_m·R and s_g = 1.8438 Btu/lb_m·R (Table A-5E, p 942)
- Compute $h = h_f + xh_{fg}$ and $x = (s – s_f)/s_{fg}$
  - Combine these equations to eliminate x

$$h = h_f + \frac{s - s_f}{s_{fg}} h_{fg} = \frac{130.18\,kJ}{kg} + \frac{\frac{1.6535\,kJ}{kg \cdot K} - \frac{0.23488\,kJ}{kg \cdot K}}{\frac{1.60894\,kJ}{kg \cdot K}} \frac{1000.5\,kJ}{kg} = \frac{1012.3\,kJ}{kg}$$

Meaning of Class Exercise

- Entropy is a property
- We can find the entropy if we know two independent properties that can specify the state
- We can use entropy and one other property to identify the state
- Mixed region calculations for entropy are the same as those for volume, internal energy and enthalpy