Section 2

Energy Fundamentals

1

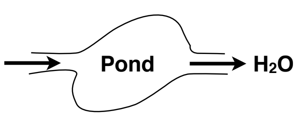
Energy Fundamentals

- Open and Closed Systems
- First Law of Thermodynamics
- Second Law of Thermodynamics
  - → Examples of heat engines and efficiency
- Heat Transfer
  - → Conduction, Convection, Radiation
- Radiation and Blackbodies
  - → Electromagnetic Radiation
  - → Wien's Law, Stefan-Boltzmann Law

2

Energy Fundamentals

- To analyze energy flows,
  - → Define type of system
  - → Use 1st and 2nd Laws of Thermodynamics



Open System: energy or matter flow across boundaries

Closed System: only energy flows across boundaries

3

First Law of Thermodynamics

- **"Energy cannot be created or destroyed"**
- **Energy balance equation:**
  Energy in =
  Energy out + Change in internal energy

→ Change in internal energy ΔU commonly due to change in temperature:

$$\Delta U = mc\Delta T$$

m = mass
c = specific heat
ΔT = temperature change

4

Units of specific heat c (definitions):

$$\frac{\text{Energy}}{\text{Unit mass} \times \text{Temperature}}$$

1 BTU is the energy required to raise the temperature of 1 lb of water by 1°F.

1 calorie is the energy required to raise the temperature of 1 gram of water by 1°C.

1 kilojoule (preferred)

For water, $c = 1 \frac{\text{cal}}{\text{g} \cdot {}^\circ\text{C}} = 4.184 \frac{\text{kJ}}{\text{kg} \cdot \text{K}}$

5

TABLE 1.3 Specific Heat Capacity c of Selected Substances

	(kJ/kg °C)	(kcal/kg °C, Btu/lb °F)
Water (15 °C)	4.18	1.00
Air (20 °C)	1.01	0.24
Aluminum	0.92	0.22
Copper	0.39	0.09
Dry soil	0.84	0.20
Ice	2.09	0.50
Steam (100 °C)[a]	2.01	0.48
Water vapor (20 °C)[a]	1.88	0.45

[a]Constant pressure values.

6

When a substance changes phase by freezing or boiling,

$$\Delta U = mH_L$$

H_L **= latent heat**

m **is the mass of substance**

Internal energy changes due to phase changes:

Changing from solid → liquid:
Latent Heat of Fusion

Changing from liquid → gas:
Latent Heat of Vaporization

H_L **(fusion of 0°C water) = 333 kJ/kg**
H_L **(vaporization of 100°C H_2O) = 2257 kJ/kg**

7

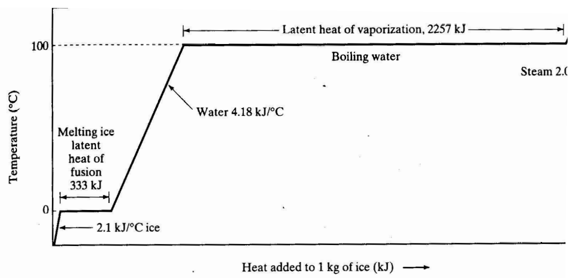


FIGURE 1.9 Heat needed to convert 1 kg of ice to steam. To change the temperature of 1 kg of ice, 2.1 kJ/ °C needed. To completely melt that ice requires another 333 kJ (latent heat of fusion). Raising the temperature c liquid water requires 4.184 kJ/ °C, and converting it to steam requires another 2257 kJ (latent heat of vaporiz: To raise the temperature of 1 kg of steam (at atmospheric pressure) requires another 2.0 kJ/ °C.

8

Example: Global Precipitation

Over entire globe (area of globe 5.1×10^{14} m^2), precipitation averages 1 m/yr.
What energy is required to evaporate all of the precipitation if the temperature of the water is 15 °C?

Specific heat (15°C)	4.184 kJ/kg
Heat of Vaporization (100°C)	2257 kJ/kg
Heat of Vaporization (15°C)	2465 kJ/kg
Heat of Fusion	333 kJ/kg

9

Use First Law of Thermodynamics:

Energy = Energy + Change in
In Out Internal Energy

In this case, assume "energy out" = 0 (no losses, and all energy put into the system is used for evaporation)

⇒ Energy In = Change in Internal Energy
= mH_L

10

m = (1m/yr)(5.1 × 10^{14} m^2)(1000 kg/m^3)
= 5.1 × 10^{17} kg/yr

Energy = (5.1 × 10^{17} kg/yr)(2465 kJ/kg)
= 1.3 × 10^{21} kJ/yr

IMPORTANT: use the latent heat for water at 15°C, not 100°C

This is ~4000 times larger than world energy consumption!

(Global fossil fuel consumption is about 3.5 × 10^{17} kJ/yr)

11

Example: An Open System

Many practical situation exist where both mass and energy flow across boundaries: heat exchangers, cooling water, flowing rivers

Rate of change in stored energy (due to flow)

$$= \dot{m}c\Delta T$$

where $\dot{m}$ is the mass flow rate across boundaries of the system of interest

12

A coal-fired powerplant converts one-third of the coal's energy into electricity, with an electrical output rate of 1000 MW (1 MW = 10^6 J/s)

The other 2/3 goes back into the environment:
- **15% to the atmosphere, up the stack**
- **85% into a nearby river**

The river flows at 100 m^3/s and is 20°C upstream of the plant

If the stream of water that is put back into the river is to be at no more than 30°C, how much water needs to be drawn from the river?

13

Amount of waste heat going into the river:

$$2000 \text{ MW} \times 85\% = 1700 \text{ MW}$$
$$= 1700 \times 10^6 \frac{\text{J}}{\text{s}} = 1.700 \times 10^9 \frac{\text{J}}{\text{s}}$$

Rate of change in stored energy due to flow

$$= \dot{m} c \Delta T$$

$$\dot{m}(\text{kg/s}) = \frac{\text{waste heat}}{c \Delta T}$$

$$= \frac{1.700 \times 10^9 \frac{\text{J}}{\text{s}}}{4184 \frac{\text{J}}{\text{kg K}} \times 10 \text{ K}} = 4.063 \times 10^4 \frac{\text{kg}}{\text{s}}$$

14

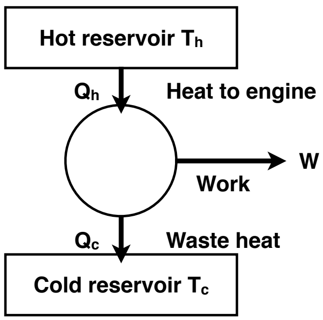
Second Law of Thermodynamics

- **"The entropy of a system tends to increase."**
- **Entropy is a measure of disorganization in a system**
  - **→ Thermal energy not available for conversion into mechanical work**
  - **→ Conversion of heat to work results in some waste heat—a heat engine cannot be 100% efficient**

15

- **A coal-fired powerplant is a type of heat engine**
  - ➔ **Burn coal for heat**
  - ➔ **Boil water to make steam**
  - ➔ **Steam turns turbine—some of heat in steam converted to electricity**
  - ➔ **Exiting steam is at a lower temperature—waste heat**
    - — **Co-generation?**

Heat Engine



$$\text{Efficiency} \equiv \frac{\text{work}}{\text{heat input}} = \frac{W}{Q_h} = \eta$$

- **Theoretically, the most efficient heat engine is the Carnot Engine:**

For Carnot, $\eta = 1 - \frac{T_c}{T_h}$

T_c, T_h = absolute temperature, in K or R

c = cold, h = hot, η = efficiency

- **As T_h increases η increases; as T_c decreases, η increases**

➡ **The larger the difference in temperature, the more efficient the process**

Typical Powerplant

Energy output = 1000 MW
Pressurized steam boiler = 600°C = 873 K
Cooled to ambient temperature = 20°C = 293 K

$$\eta_{max} = 1 - \frac{293}{873} = 0.66 = 66\%$$

Real-world efficiencies in U.S. powerplants average 33% (range ~ 25 to 40% depending on age of plant)

19

Some conversions

Kilowatt-hour (KWH or kW-hr)

1 W = 1 J/s ⇒ 1 J = 1 W · s

1 Watt-hour = 1 W · 3600 s = 3600 J

1 kW-hr = 1000 · 1 W · 3600 s = 3.6×10^6 J = 3.6 MJ

20

Example (Prob. 1.31)

A 15W compact fluorescent lamp (CFL) provides the same light as a 60W incandescent lamp. Electricity costs the end user 10¢ per kW-hr.

a. If an incandescent lamp costs 60¢ and the CFL costs $2, what is the "payback" period?

b. Over the 9000-hr lifetime, what would be saved in carbon emissions? (280 g carbon emitted per kW-hr)

c. At a (proposed) carbon tax of $50/tonne, what is the equivalent dollars saved as carbon emissions? (1 tonne = 1000 kg)

21

Energy saved with the CFL:

(60W – 15W)(9000 hr) = 405 kW-hr

At 10¢ per kW-hr, this is $40 over the lifetime of the lamp.

Payback period: As an example, use 6 hr/day usage.

Then $$\frac{(60\text{W} - 15\text{W})\left(6\,\frac{\text{hr}}{\text{day}}\right)\left(\$0.10\,\frac{1}{\text{kW-hr}}\right)}{1000\,\frac{\text{W-hr}}{\text{kW-hr}}}$$

= $0.027 saved per day

$2/$0.027 per day = 74 days or about 2.5 months

Emissions savings:

(280 g carbon/kW-hr)(405 kW-hr) = 113400 g C

⇒ 0.113 T × $50/T = $5.65

Example

Could the temperature difference between the top and bottom of a lake be used as a cheap, renewable source of a megawatt of electricity?

Say the temperatures are 25°C and 15°C, maintained by sunlight (~ 500 W/m²) and the lake has an area of 10^4 m².

Are the first and second laws of thermodynamics obeyed? [first: energy is conserved; second: entropy of systems increase and there is a limit on the efficiency of any process]

Evaluate maximum efficiency, then calculate energy output

$$\eta = 1 - \frac{T_c}{T_h}$$

$$\eta_{\max} = 1 - \frac{288}{298} = 0.034$$

What is the maximum possible energy output from this system, given the solar energy input?

$$\left(500\,\frac{\text{W}}{\text{m}^2}\right)\left(10^4\ \text{m}^2\right)(0.034) = 170000\ \text{W} = 0.17\ \text{MW}$$

Example

A very efficient gasoline engine runs at 30% efficiency. If the engine expels gas into the atmosphere, which has a temperature of 300 K, what is the temperature of the cylinder immediately after combustion?

If 837 J of energy are absorbed from the hot reservoir during each cycle, how much energy is available for work?

$$\eta = 1 - \frac{T_c}{T_h}$$

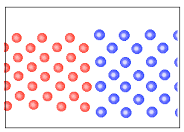
$$\eta = \frac{W}{Q_h}$$

25

Heat Transfer

- **Heat transfer always occurs between hot and cold objects**

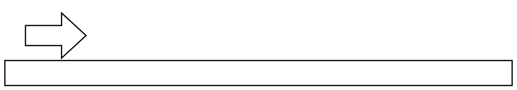
→ **Conduction: heat transfer occurs when there is direct physical contact; kinetic energy is transferred when atoms or molecules collide**



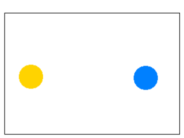
26

→ **Convection: heat transfer is mediated by the flow of a fluid**

– **Free convection occurs without human intervention; forced convection requires mechanical pumping of the fluid**



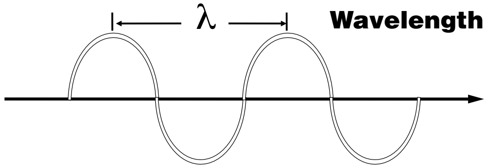
→ **Radiation: heat transfer mediated by the propagation of electromagnetic radiation (such as light)**



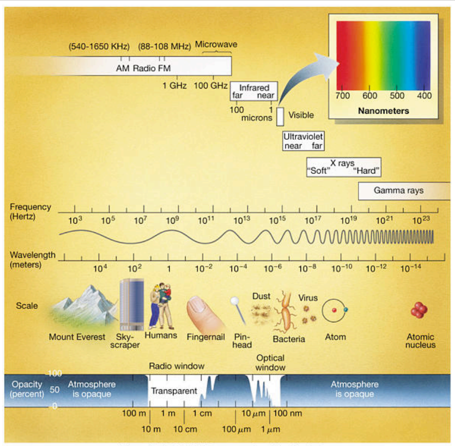
27

Radiation

- All objects radiate energy continuously in the form of electromagnetic waves, if their temperature is greater than 0 K
- Type of radiation depends on wavelength



28



29

Blackbody Radiation

- Blackbodies absorb and emit at all wavelengths
- Amount of radiation emitted depends on temperature

Stefan-Boltzmann Law $$E = \sigma A T^4$$

E = total blackbody emission rate (W)
σ = Stefan-Boltzmann constant = 5.67×10^{-8} W/m^{2}K^4
T = temperature (K)
A = surface area of blackbody (m^2)

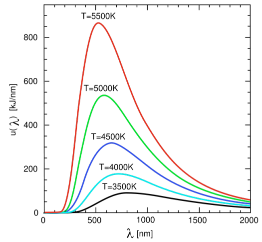
30

A more familiar form uses the energy flux *F*, where *F* = *E*/*A* W/m²

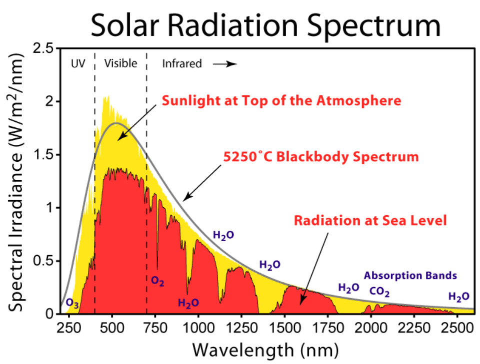
$$F = \sigma T^4$$

Wien's Law

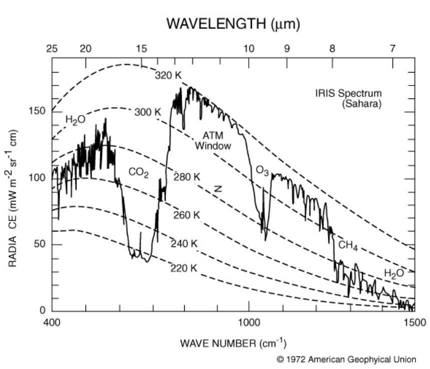
$$\lambda_{max}(\mu m) = \frac{2898\ \mu m \cdot K}{T\ (K)}$$



31



32



33

Example: Human Body as an Energy Converter

How high can you climb on the energy from a liter of milk?

One liter of milk contains about 2.4×10^6 J.

$$\left(2.4 \times 10^6 \text{ J}\right) \times \left(\frac{1 \text{ kJ}}{1000 \text{ J}}\right) \times \left(\frac{1 \text{ cal}}{4.184 \text{ kJ}}\right) = 574 \text{ cal}$$

Work needed to move your body = *mgh*

where *m* = your mass, *g* = acceleration due to gravity, *h* = change in height

Work available from milk

= (metabolic efficiency)*Q* = ε*Q*

where *Q* is the internal energy of the milk

Example input values: *m* = 50 kg (110 lb), efficiency ~ 100%

$$\varepsilon Q = mgh$$

$$(1.0)\left(2.4 \times 10^6 \text{ J}\right) = (50 \text{ kg})\left(9.8 \text{ m/s}^2\right)h$$

$$h = 4900 \text{ m}$$

Considering that Mt. Whitney has an elevation gain of about 3000 m, does this sound reasonable?