# Mass and Energy Transfer-2

*Changha Lee*

School of Chemical and Biological Engineering
Seoul National University

# Energy Fundamentals

✓ **To analyze energy flows:**

- Define system
- 1st and 2nd laws of thermodynamics

- **Open System:**
  - Both energy and material flow across boundaries
  - e.g. lake: $H_2O$ & sun energy flow

- **Closed System:**
  - Only energy flows across boundaries
  - e.g. closed bottle: only heat flow

# 1st Law of Thermodynamics

✓ **Energy cannot be created or destroyed.**

- Energy balance equation:

  **Energy In = Energy Out + Change in Internal Energy**

- Commonly, change in Internal Energy is due to temperature changes (although it can also involve phase changes such as freezing or evaporation)

- Change in internal energy due to change in body T

  $= m\ c\ \Delta T$

  where, $m$ = mass of body

  $c$ = specific heat

  The energy required to raise T of unit mass by 1 degree

  $\Delta T$ = temperature change in the object or system under consideration

# 1st Law of Thermodynamics

- When substance changes state…
  - e.g. freezing or boiling
- Change in internal energy = $mH_L$
  - $H_L$ = latent heat
- Internal energy changes due to phase changes:
  - solid → liquid – latent heat of fusion
  - liquid → gas – latent heat of vaporization

**Total Change in Internal Energy = $m\,c\,\Delta T + m\,H_L$**

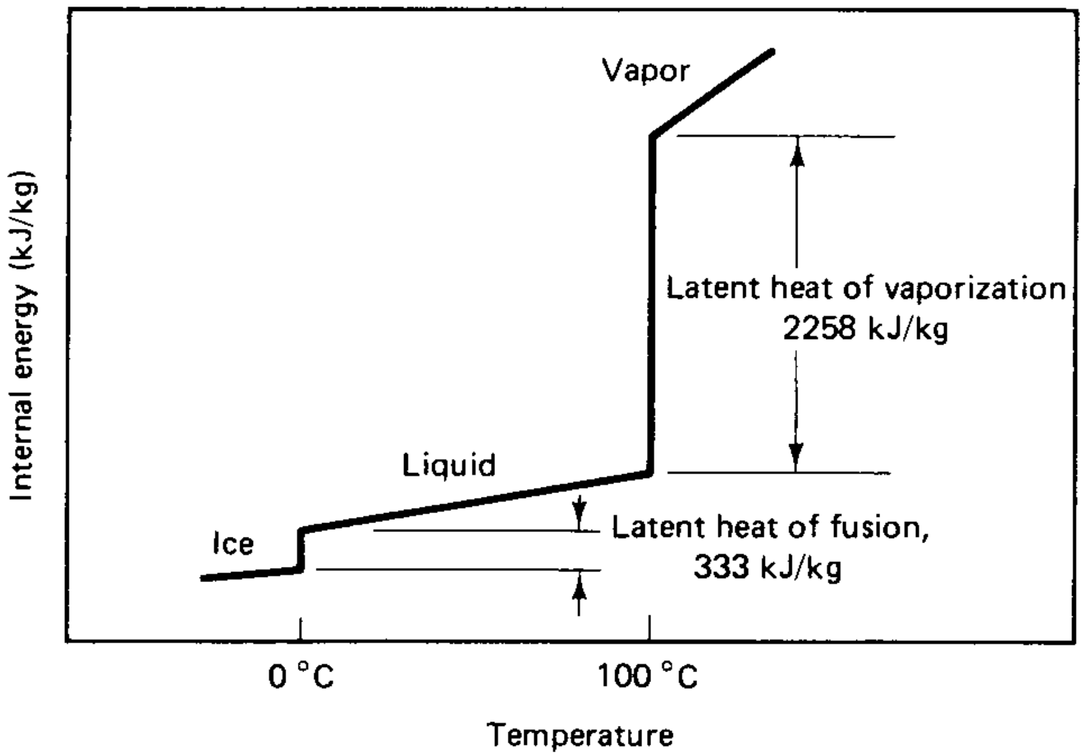
TABLE 4

**Important Physical Properties of Water**

| Property | SI Units | USCS Units |
|---|---|---|
| Specific heat (15°C) | 4.184 kJ/kg°C | 1.00 Btu/lb°F |
| Heat of vaporization (100°C) | 2,257 kJ/kg | 972 Btu/lb |
| Heat of vaporization (15°C) | 2,465 kJ/kg | 1,060 Btu/lb |
| Heat of fusion | 333 kJ/kg | 144 Btu/lb |
| Density (at 4°C) | 1,000 kg/m$^3$ | 62.4 lb/ft$^3$ (8.34 lb/gal) |

# 1st Law of Thermodynamics

- $H_L$ (fusion, 0℃ water) = 333 kJ/kg
- $H_L$ (vaporization, 100℃ water) = 2,258 kJ/kg
- slope = c = 4.184 kJ/kg℃



# Example – Global Precipitation

- Over entire globe (area = $5.1 \times 10^{14}$ $m^2$), precipitation averages 1 m/yr. What energy is required to evaporate all precipitation if water at 17℃?

(Put this amount in the context of the world's energy consumption
= $4.7 \times 10^{17}$ kJ/yr)

# Example (solution)

- Use 1st Law of Thermodynamics:
  - Energy In = Energy Out + Change in Internal Energy
  - In this case, no energy out (assume no losses)
  - Thus, all energy input used for evaporation

- Energy In = Change in Internal Energy

$$= mc\Delta T + mH_L$$

$$= (5.1 \times 10^{14}\ m^2)(1\ m/yr)(1000\ kg/m^3)$$

$$(4.184\ kJ/kg^oC)(100 - 17\ ^oC)$$

$$+ (5.1 \times 10^{14}\ m^2)(1\ m/yr)(1000\ kg/m^3)(2258\ kJ/kg)$$

**Energy In = 1.33 x $10^{21}$ kJ/yr**

- **This is 2,800 times larger than world energy consumption!**

# Open systems

- In open systems, mass flows across boundaries

$$\textbf{mass flow} = m' = dm/dt = \rho \times Q$$

$$(M/L^3)\ (L^3/T)$$

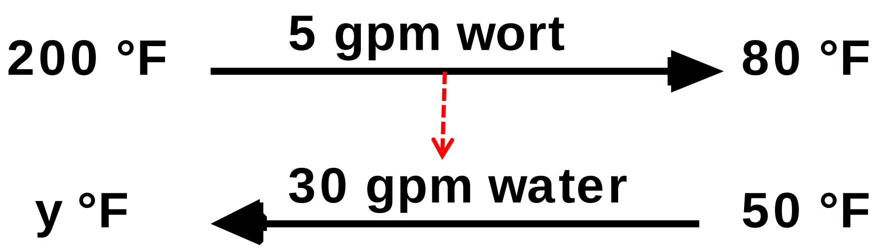
- Change in internal energy due to flow:

$$m' \, c \, \Delta T = \rho \, Q \, c \, \Delta T$$

$m'$ = mass flow rate across boundaries

# Example

- A brewery wants to cool a stream of wort that flows at 5 gpm (gal/min), from a temperature of 200°F to 80°F. The heat capacity of the wort is 1.2 times that of water, and the specific gravity is 1.1. the cooling system (water) has a flow rate of 30 gpm and is initially at 50°F. What is the final temperature of the cooling water?




Ideally, all heat from wort goes to $H_2O$

# Example (solution)

- Energy balance: rate of change of internal energy equal for wort and $H_2O$

$$(m'c\Delta T)_{wort} = (m'c\Delta T)_{water}$$

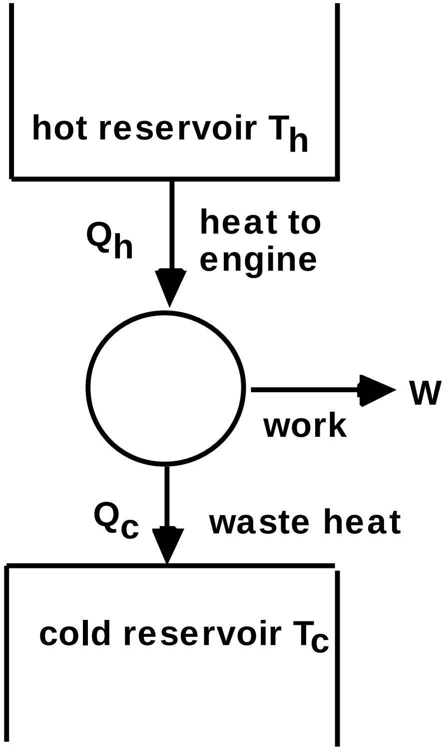
# 2nd Law of Thermodynamics

√ **The entropy of a system tends to increase**

- **Entropy**: measure of disorganization in the universe
  - Reflection system's thermal energy not available for conversion into mechanical work

- Macroscopic consequences:
  - When converting heat to work, waste heat
  - Heat engine cannot be 100% efficient

# 2nd Law of Thermodynamics




heat engine

takes heat from hot reservoir

converts some to work

rejects remainder of heat

- Define efficiency = $\dfrac{work}{heat\ input} = \dfrac{W}{Q_h}$ (dimensionless)

# 2nd Law of Thermodynamics

- Theoretically, most efficient engine is **"Carnot engine"**

- **Carnot engine (ideal) efficiency:** $\eta = 1 - \frac{T_c}{T_h}$

  - $T_c$, $T_h$ : absolute temperature
  - $T_h$ increases, η increases
  - $T_c$ decreases, η increases

# Typical Power Plant

- Pressurized steam boiler : 600℃
- Cooled to ambient temperatures : 20℃

- Converting to absolute temperature:

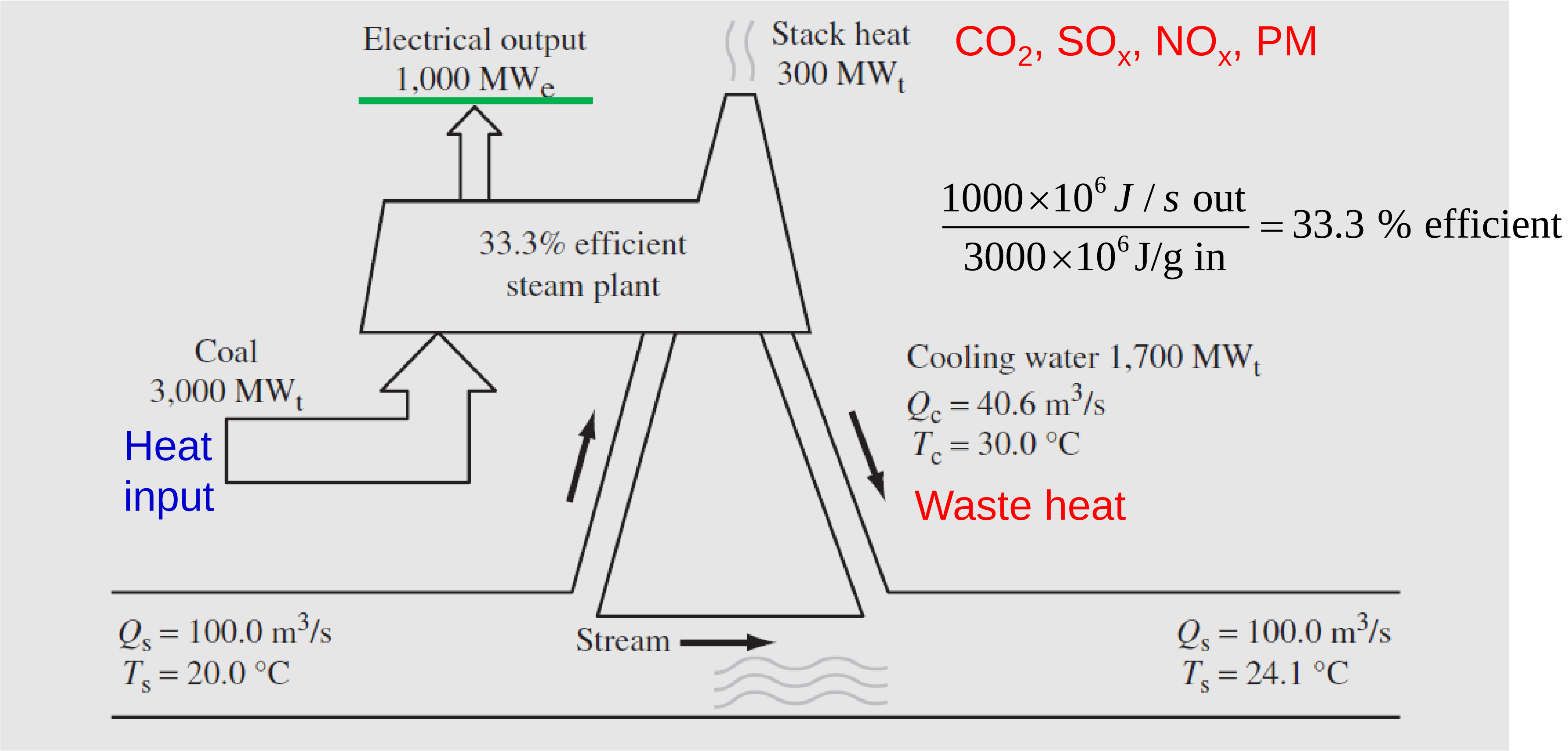
  600℃ + 273 = 873K

  20℃ + 273 = 293K

- $\eta_{max}$ = 1 – 293/873 = 66%

- average US thermal plant: 33% efficient
- nuclear plant: 33%
- new fossil-fuel plants: 40%

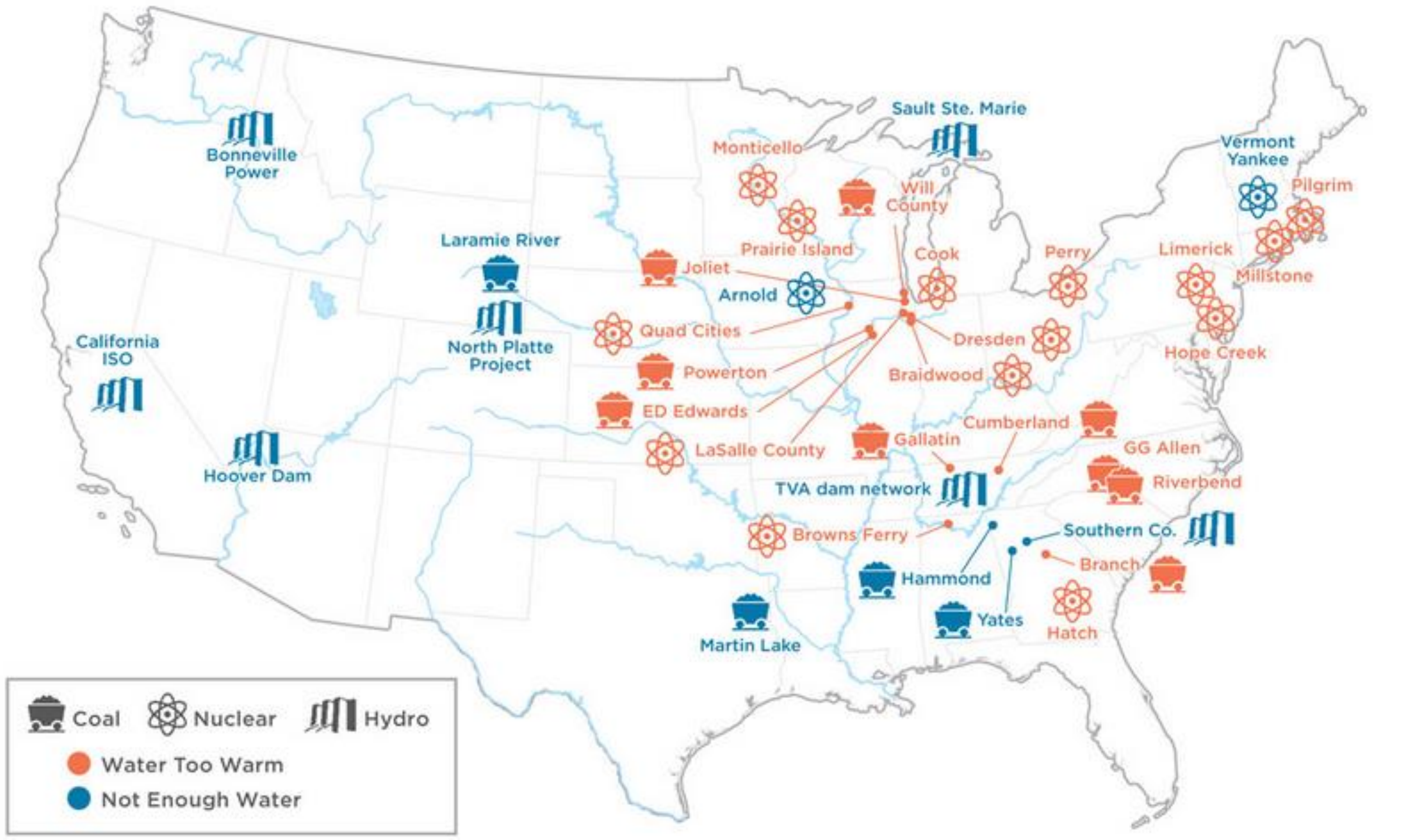
# Coal-Fired Power Plants




- Energy content of coal or other fuel
- Used to produce heat to boil water
- Resulting steam to 'move' turbines → electricity

# The Impact

Power Plants That Have Shut Down or Reduced Output Because of Water Problems, 2006–2013




*Rogers et al., 2013*

# Example

- A 3 MW coal-fired plant is 40% efficient.
  This coal has 2% S, heat content of $2.5 \times 10^4$ J/g.

  If 80 % of S is converted to $SO_2$, what is the rate of $SO_2$ emission?

# Example (solution)

- Determine heat input into plant:

- Determine rate of coal burned:

- Determine rate of $SO_2$ emission:

# Example

- A 15 W fluorescent bulb provides same light as a 60 W incandescent bulb. Over the 9,000 hr lifetime, what would be saved in carbon, $SO_2$, and particulate emissions by using a fluorescent bulb, using the following power plant:

$SO_2$ emission = 2.8 g $SO_2$/kWh (acid rain)

C emission = 280 g C/kWh (global warming)

Particulate emission = 0.14 g PM/kWh (health)

# Example (solution)

- Power saved by using fluorescent bulb

- Emissions Saving: