PHYS 157 Notes

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1 Temperature

1.1 Temperature and Thermal Equilibrium

- Key terms: temperature, thermometer, thermal equilibrium, insulator, conductor.
- The Zeroth Law of Thermodynamics: If C is initially in thermal equilibrium with both A and B, then A and B are also in thermal equilibrium with each other.
- Condition for Thermal Equilibrium: Two systems are in thermal equilibrium if and only if they have the same temperature.

1.2 Temperature Scales

1.2.1 Celsius and Fahrenheit Scales

- Celsius temperature scale: water's freezing point is 0 °C and water's boiling point is 100 °C.
- Fahrenheit temperature scale: water's freezing point is 32 °F and water's boiling point is 212 °F.

$$T_F = \frac{9}{5}T_C + 32^\circ$$
$$T_C = \frac{5}{9}(T_F - 32^\circ)$$

1.2.2 Kelvin Scale

- Has the same increments as the Celsius temperature scale, but 0 K is defined at absolute zero.

$$T_K = T_C + 273.15$$

- Can be defined using a gas thermometer and one reference temperature.

$$\frac{T_2}{T_1} = \frac{p_2}{p_1}$$

2 Thermal Expansion, Stress, and Strain

2.1 ΔL due to ΔT

$$\Delta L = \alpha L_0 \Delta T$$

$$L = L_0(1 + \alpha \Delta T)$$

2.2 ΔV due to ΔT

$$\Delta V = \beta V_0 \Delta T$$

$$V = V_0(1 + \beta \Delta T)$$

$$\beta = 3\alpha$$

2.3 Young's Modulus

$$\frac{\Delta F}{A} = Y \frac{\Delta L}{L_0} \implies Y = \frac{\Delta F/A}{\Delta L/L_0}$$

$$\Delta L = \frac{L_0 \Delta F}{YA}$$

2.4 ΔL due to ΔT and ΔF

$$\Delta L = \Delta L_T + \Delta L_F = \alpha L_0 \Delta T + \frac{L_0 \Delta F}{YA}$$

3 Heat and Temperature/Phase Change

3.1 Heat of Temperature Change

$$Q = mc\Delta T$$

3.2 Heat of Phase Change

$$Q = \pm mL$$

4 Heat Flow: Conduction and Convection

4.1 Heat Conduction

$$H = \frac{dQ}{dt} = kA\frac{T_H - T_C}{L}$$

4.2 Thermal Resistance

$$R = \frac{L}{k}$$

$$H = \frac{A(T_H - T_C)}{R}$$

In layers (series): $R_{total} = R_1 + R_2 + \cdots + R_n$

5 Radiation

5.1 Radiation

$$H = Ae\sigma T^4$$

$$\sigma = 5.67 \times 10^{-8}\,\mathrm{W/(m^2\,K^4)}$$

5.2 Net Radiation

$$H_{net} = Ae\sigma(T^4 - T_s^4)$$

5.3 Intensity at Distance R

$$I = \frac{H}{A} = \frac{H}{4\pi R^2}$$

$$\frac{I_2}{I_1} = \left(\frac{R_1}{R_2}\right)^2$$

5.4 Wien Displacement Law

$$\lambda_{max} = \frac{b}{T}$$

$$b = 2.90 \times 10^{-3}\,\mathrm{m\,K}$$

6 Thermodynamic Processes, Work, Heat, and Internal Energy

6.1 Ideal Gas Law

$$pV = nRT$$

6.2 Work Done by Gas

$$W = F\Delta x_{\|} = \int_{x_1}^{x_2} F(x)dx$$

$$W = p\Delta V = \int_{V_1}^{V_2} p(V)dV$$

6.3 First Law of Thermodynamics

$$\Delta U = Q - W$$

$$Q = \Delta U + W$$

- ΔU: change in internal energy of the gas
- Q: heat added to gas
- W: work done by the gas

For cyclic processes, $\Delta U = 0$, so $Q = W$.

6.4 Internal Energy

$$U = \frac{3}{2}nRT \text{ (monoatomic)}$$
$$U = \frac{5}{2}nRT \text{ (diatomic)}$$
$$\Delta U = nC_V\Delta T$$

For all ideal gases, where $C_V = \frac{3}{2}R$ for monoatomic gases and $C_V = \frac{5}{2}R$ for diatomic gases.

6.5 Thermodynamic Processes

6.5.1 Isochoric

Constant volume process.

$$W = 0$$
$$Q = \Delta U = nC_V\Delta T$$
$$Q = \left(\frac{C_V}{R}\right)V\Delta p$$

6.5.2 Isobaric

Constant pressure process. Can be indicated by "moveable piston."

$$W = p\Delta V$$
$$W = nR\Delta T$$
$$Q = \Delta U + W = nC_V\Delta T + nR\Delta T = nC_p\Delta T$$
$$Q = \left(\frac{C_p}{R}\right)p\Delta V$$

Where $C_p = C_V + R$.

6.5.3 Isothermal

Constant temperature process. Slow process where temperature is allowed to equilibrate with surroundings.

$$\Delta U = 0$$
$$Q = W = nRT\ln\left(\frac{V_2}{V_1}\right)$$
$$Q = W = p_1V_1\ln\left(\frac{V_2}{V_1}\right) = p_2V_2\ln\left(\frac{V_2}{V_1}\right)$$

6.5.4 Adiabatic

No heat transfer. Fast process where there is no time for significant heat flow.

$$Q = 0$$
$$\gamma = \frac{C_p}{C_V}$$
$$TV^{\gamma-1} = \text{ constant}$$
$$pV^{\gamma} = \text{ constant}$$

$$\begin{aligned} W = -\Delta U &= nC_V(T_1 - T_2) \\ &= \frac{C_V}{R}(p_1V_1 - p_2V_2) \\ &= \frac{1}{\gamma - 1}(p_1V_1 - p_2V_2) \end{aligned}$$

7 Cyclic Thermodynamic Processes, Heat Engines, and Refrigerators

7.1 Cyclic Processes

$$\Delta U = 0$$
$$Q = W$$

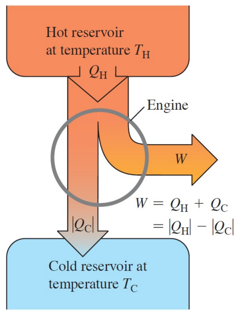
Sign convention:

- Q is positive when it enters the engine/refrigerator and negative when it exits.
- W is positive when there is work output and negative when there is work input.

7.2 Heat Engines

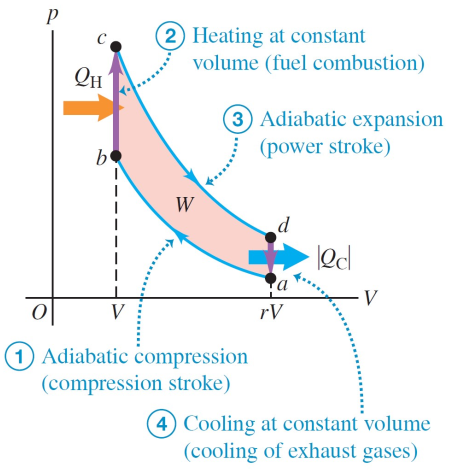
- $Q_H > 0$: heat absorbed during one cycle
- $Q_C < 0$: heat rejected during one cycle
- $W > 0$: work output during one cycle

$$Q = Q_H + Q_C = |Q_H| - |Q_C|$$
$$e = \frac{W}{Q_H} = 1 + \frac{Q_C}{Q_H} = 1 - \left|\frac{Q_C}{Q_H}\right|$$

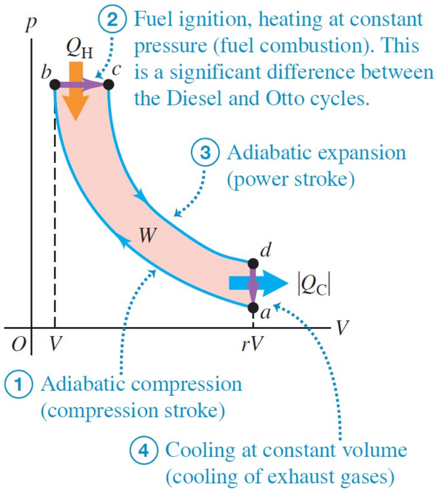


7.2.1 Otto Cycle

$$e = 1 - \frac{1}{r^{\lambda-1}} \approx 35\%$$



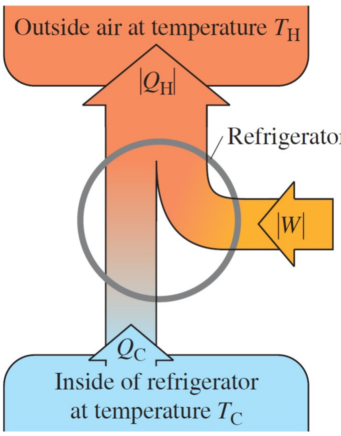
7.2.2 Diesel Cycle



7.3 Refrigerators

- $Q_H < 0$: heat discarded to the hot system (outside air)
- $Q_C > 0$: heat removed from cold system (refrigerator)
- $W < 0$: work input of refrigerator

$$Q = Q_H + Q_C = |Q_C| - |Q_H|$$
$$K = \frac{Q_C}{|W|} = \frac{|Q_C|}{|Q_H| - |Q_C|}$$



8 Entropy

- A state variable that measures the disorder of a system.

8.1 Microscopic Definition of Entropy

$$S = k \ln w$$

- k: Boltzmann constant
- w: number of microstates of a given macrostate

8.2 Macroscopic Definition of Entropy

$$dS = \frac{dQ}{T}$$

$$\Delta S = \int_1^2 \frac{dQ}{T}$$

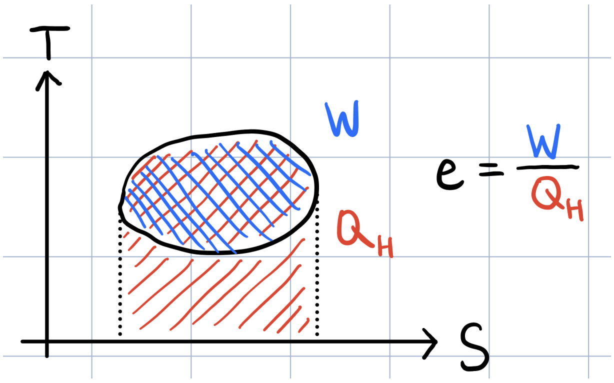
$$\Delta S = \frac{Q}{T} \text{ (reversible isothermal process)}$$

8.3 Second Law of Thermodynamics

The total entropy of a closed system never decreases.

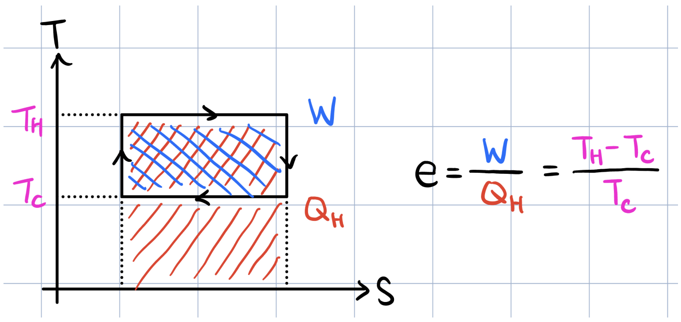
8.4 T-S Diagrams

- Q_H: area under curve
- W: area enclosed



8.5 Carnot Cycle

- Isothermal and adiabatic processes.
- Maximum efficiency of engine operating between temperatures of T_H and T_C.



9 Periodic Motion

9.1 Describing Oscillations

- A: amplitude $= |x|_{max}$.
- T: period = time to complete one cycle.

- f: frequency = number of cycles per unit time.
- ω: angular frequency.

$$\omega = 2\pi f = \frac{2\pi}{T}$$

9.2 Simple Harmonic Motion

$$F_x = -kx \text{ (Restoring Force)}$$
$$a_x = \frac{d^2x}{dt^2} = -\frac{k}{m}x$$
$$\omega = \sqrt{\frac{k}{m}}$$

9.3 Displacement, Velocity, and Acceleration

$$x = A\cos(\omega t + \phi)$$
$$v = -\omega A\sin(\omega t + \phi)$$
$$a = -\omega^2 A\cos(\omega t + \phi)$$

Plug in x_0 to find ϕ.

9.4 Energy in Simple Harmonic Motion

$$E = \frac{1}{2}mv^2 + \frac{1}{2}kx^2 = \frac{1}{2}kA^2 = \text{ constant}$$

9.5 Damped Oscillations

$$F_x = -kx - bv_x \text{ (restoring and damping/drag force)}$$
$$t_0 = \frac{2m}{b}, t_0 = -\frac{T}{\ln(r)} \text{ (where } r = \text{reduction fraction per period)}$$
$$x = Ae^{-t/t_0}\cos(\omega' t + \phi)$$
$$\omega' = \sqrt{\frac{k}{m} - \frac{b^2}{4m^2}}$$

- Critical damping: $b = 2\sqrt{km}$
- Overdamping: $b > 2\sqrt{km}$ (returns to equilibrium slower than critical damping)

9.6 Effective Spring Constant

$$k = -\frac{dF_{net}}{dx}(x_{eq})$$

10 Waves

- Transverse wave: displacement is perpendicular to direction of travel
- Longitudinal wave: displacement is in the same direction as direction of travel
- v: wave speed. Speed of disturbance propagation

10.1 Periodic Waves

$$v = \lambda f$$