Adiabatic Processes and Heat Engines

CHEM 361A: Introduction to Physical Chemistry

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Lecture 5

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Learning Objective: Quantify processes where no heat is transferred between the system and the surroundings in order to discuss heat engines.

References:

- Atkins and de Paula Focus 3A.3
- Chang §4.5, §5.3

Adiabatic Behaviour

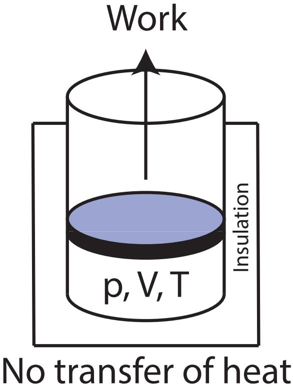
An **adiabatic** process occurs when the system is isolated thermally. No heat can transfer in or out of the system ($q = 0$).

Adiabatic expansions results in changes to p, V, and T. Revisiting the First Law of Thermodynamics:

$$\Delta U = q + w$$

Since q = 0

$$\Delta U = w$$



Adiabatic Behaviour: Work

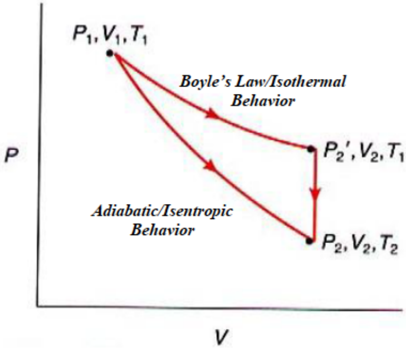
An **adiabatic** process occurs when the system is isolated thermally. No heat can transfer in or out of the system ($q = 0$).

Work is still defined as:

$$dw = -p_{ex}dV$$

Integrating this can be problematic since T must vary. We can use this to our advantage since:

$$dw = dU = nC_{V,m}dT$$



Reversible/Irreversible will differ in the change in temperature, however, once you know T_i and T_f, then you can calculate the work done.

Predicting p and V in Adiabiatic Expansions

To predict how pressure and volume change in adiabatic expansions, first set $dw = dU$. Assuming a reversible process:

$$-\frac{nRT}{V}dV = nC_{V,m}dT$$

Rearrange and integrate both sides:

$$\int_{T_i}^{T_f} C_{V,m}\frac{dT}{T} = -R\int_{V_i}^{V_f}\frac{dV}{V}$$

Since $C_{p,m} - C_{V,m} = R$ and setting $\gamma = C_{p,m}/C_{V,m}$ gives

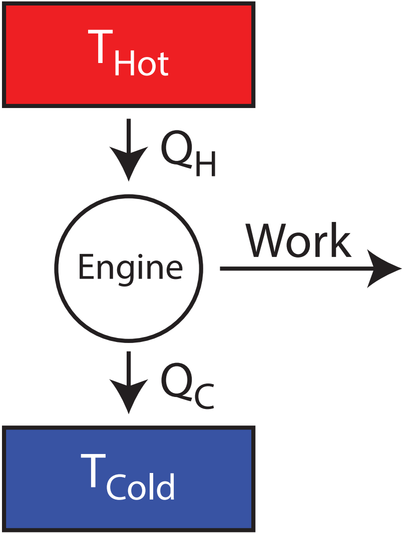
$$P_1 V_1^{\gamma} = P_2 V_2^{\gamma}$$

Adiabatic Expansion Problem

0.850 moles of a monatomic ideal gas is initially at a pressure of 15.0 atm and 300 K. It is allowed to expand until its final pressure is 1.00 atm. Calculate the work done if the expansion is carried out adiabatically and reversibly.

Heat Engines

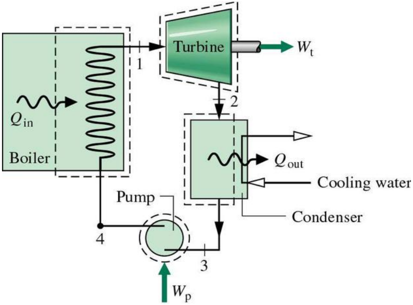
A **heat engine** is a device where heat is exchanged for work.



Examples of Heat Engines: Doing Work

All steam based power plants (coal, natural gas, nuclear) follow this type of principle:

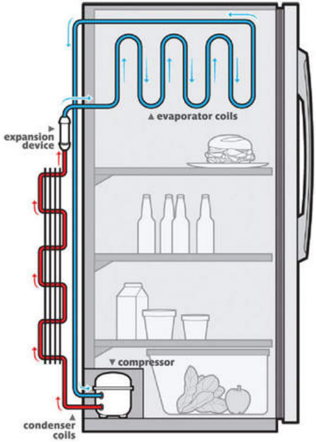
1. Water is heated to form steam
2. The steam expands into a turbine which spins it (produces electricity)
3. The steam is condensed in a heat exchanger and pumped back in to be turned into steam



Examples of Heat Engines: Cooling Objects

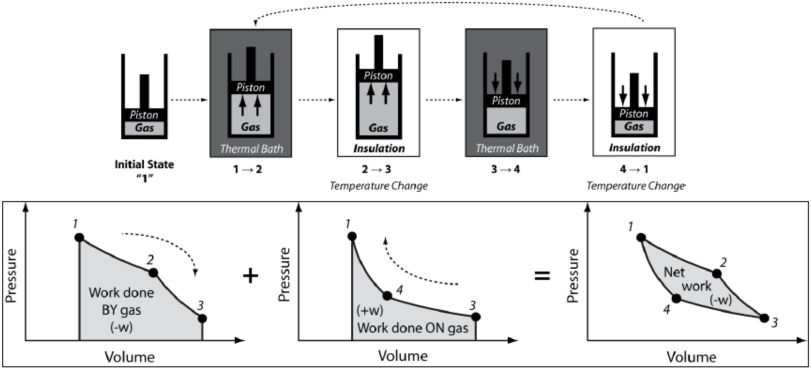
Refrigerators and air conditioners use work to pull heat from the cold region to a warmer one:

1. Coolant is cooled and condensed outside the refrigerator requiring work
2. It is then allowed to rapidly expand inside the refrigerator. As it expands, it absorbs heat.



The Carnot Cycle

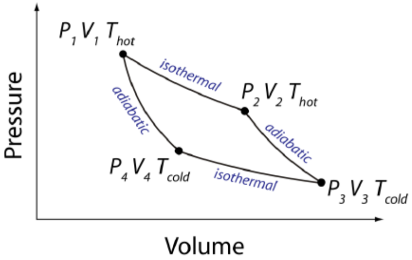
The Carnot Cycle is a theoretical thermodynamic cycle that represents the maximum efficiency possible from any classical heat engine.



The area bound by the four processes is the maximum amount of work possible. Note that every process is reversible.

Work and Heat of the Carnot Cycle

Find the work and heat for each step and determine the total work and heat for the complete cycle.



Heat Engine Efficiency

The efficiency of any heat engine is based on the usable energy extracted relative to the energy inputted. For a heat engine performing work:

$$\text{efficiency} = \frac{|w|}{q_H}$$

Substituting in the work performed

$$-nR(T_{Hot} - T_{Cold}) \ln \frac{V_2}{V_1}$$

and the heat inputted

$$q_H = nRT_{Hot} \ln \frac{V_2}{V_1}$$

and rearranging gives

$$\text{efficiency} = 1 - \frac{T_{Cold}}{T_{Hot}}$$

Heat Engine Efficiency Example

At a power plant, superheated steam at 560°C is used to drive a turbine for electricity generation. The steam is discharged to a cooling tower at 38°C. Calculate the efficiency of this process.

Summary

- An adiabatic process means $q = 0$ so $\Delta U = w$
- The work done during an adiabatic process is

$$w = \int_{T_1}^{T_2} nC_{V,m}\, dT$$

- a Heat Engine converts heat to work
- The Carnot Cycle provides an upper thermodynamic limit on the efficiency of a classical heat engine