PHY101: Introduction to Physics I

Monsoon Semester 2024

Lecture 34

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Previous Lecture

Frist law of thermodynamics
PV diagrams
Thermodynamic processes

This Lecture

Second law of thermodynamics

Heat engine

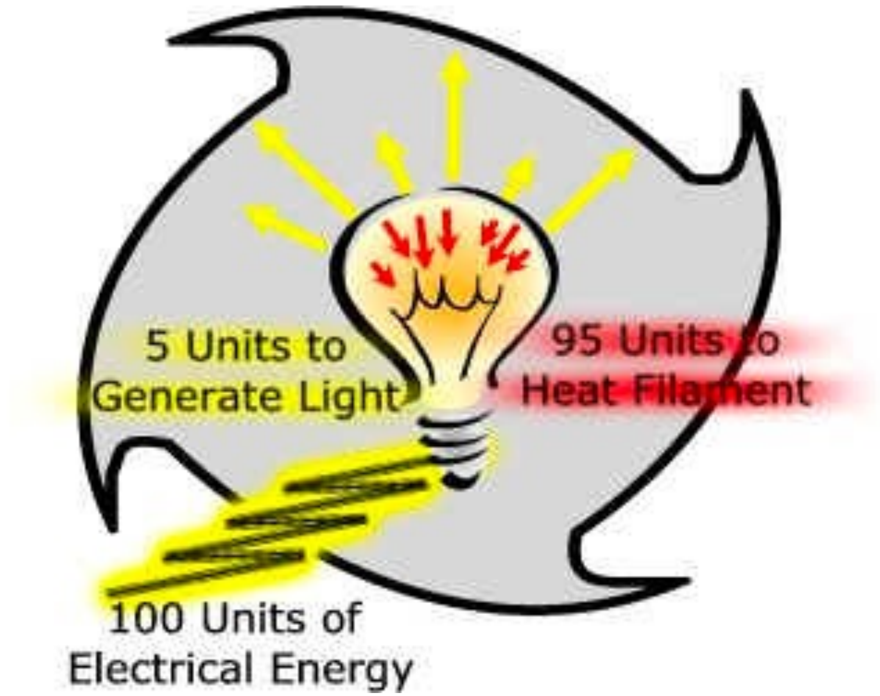
Second Law of Thermodynamics

- Second law of thermodynamics can be expressed in several ways. For instance,
  - It is not possible to completely change heat into work with no other change taking place.
  - Heat flows naturally from a hot object to a cold object. Heat will not flow spontaneously from a cold object to a hot object.

Entropy: If a process occurs in a closed system, the entropy increases for irreversible process and remains constant for reversible process, but it never decreases.

Efficiency of energy Conversion

All energy conversions eventually result in dissipated low-temperature heat



No energy has been *lost*, but its utility, its ability to perform useful work, is gone.
The light and heat become so dispersed and less useful.

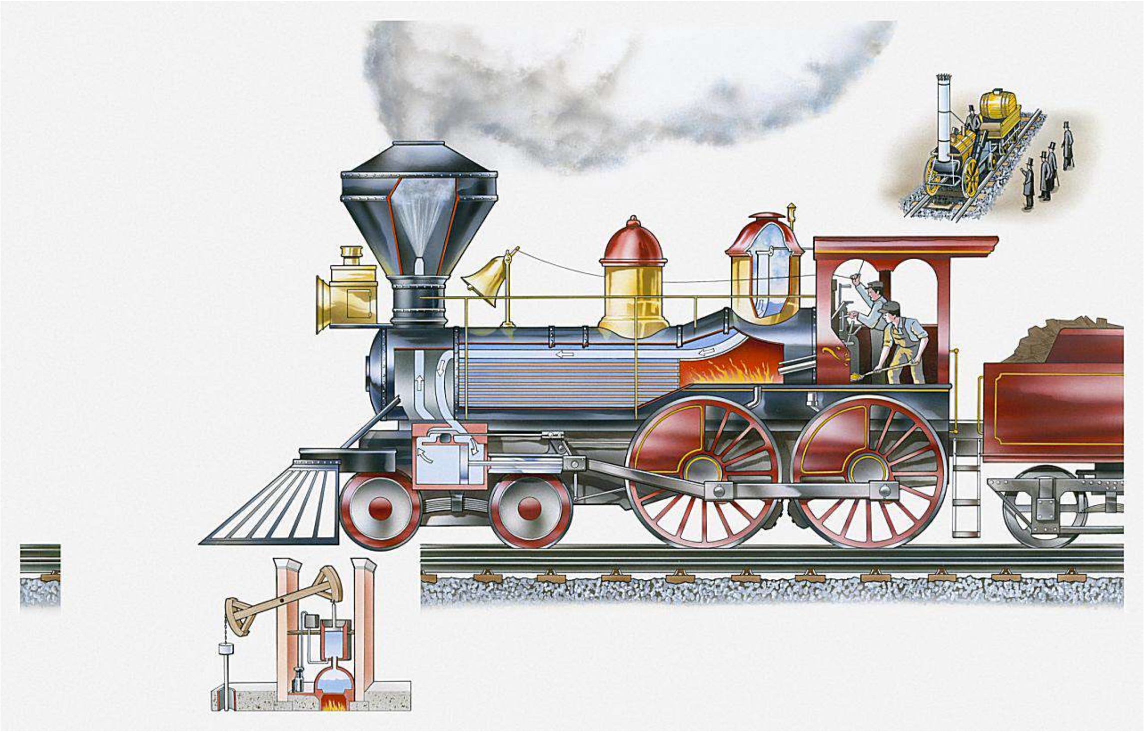
Efficiency (%) = (Useful Energy Output/ Energy Input) *100 **< 100%**

Second Law of Thermodynamics

"No energy conversion device is 100 percent efficient"

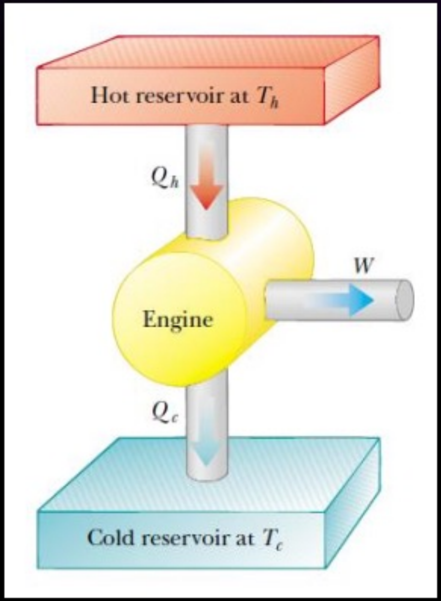
Engine!

An engine is a machine that converts energy into mechanical energy, which creates motion. Engines can use a variety of energy sources, including heat, chemical, potential, electric, and nuclear energy



Heat Engine

- Internal energy change, $\Delta U = 0$ (Cyclic)
- Heat supplied to the engine= $Q_h - Q_c$
- Work done by the engine= W
- Applying first law (Clausius sign convention)



$$\Delta U = Q - W$$
$$\Rightarrow 0 = (Q_h - Q_c) - W$$
$$\Rightarrow Q_c = Q_h - W$$

Image Source: http://www.cs.stedwards.edu/~wright/text/thermo.html

Thermal Efficiency of the Heat Engine

- The thermal efficiency of a heat engine is defined as the ratio of the net work done by the engine during one cycle to the energy absorbed at the higher temperature during the cycle.

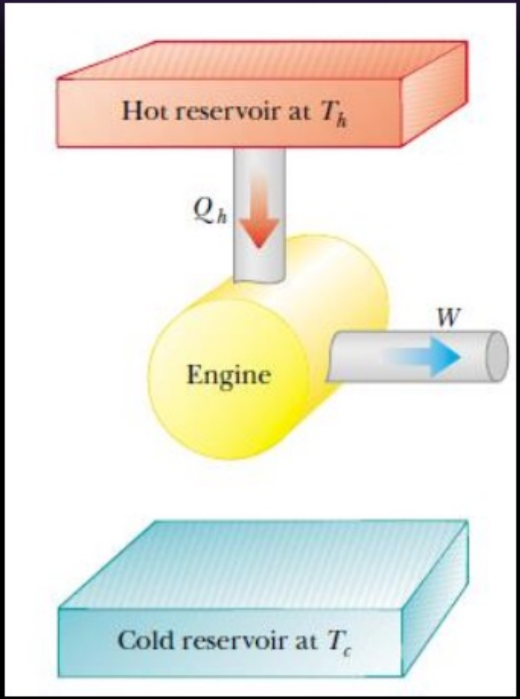
$$\eta = \frac{W}{|Q_h|} = \frac{|Q_h| - |Q_c|}{|Q_h|} = 1 - \frac{|Q_c|}{|Q_h|}$$

- Clearly η can be 1 (i.e., 100%) only if $Q_c = 0$, i.e., no energy is transferred to the cold reservoir. This will mean that all the heat is converted to work.
- Second law of thermodynamics forbids this. Efficiency of real engines are well below 100%.

  [$Q_h \rightarrow \infty$ is not attainable.]

Kelvin-Planck statement of Second Law

The Kelvin-Planck statement of the second law of thermodynamics states that no heat engine can produce a net amount of work while exchanging heat with a single reservoir only. In other words, the maximum possible efficiency is always less than 100 percent.



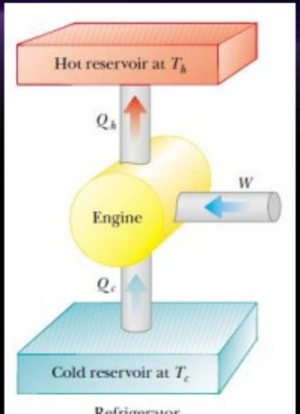
The impossible engine

Image Source: http://www.cs.stedwards.edu/~wright/text/thermo.html

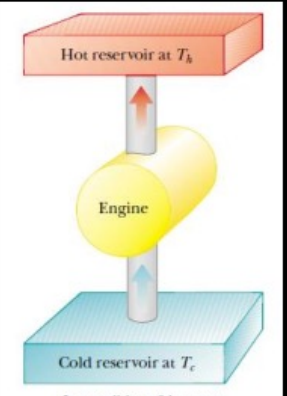
Heat Pumps and Refrigerators

- Heat pumps and refrigerators can be viewed as heat engines running in reverse. In these, the engine absorbs energy Q_c from a cold reservoir and expels energy Q_h to a hot reservoir. Clearly the work has to be done on the engine.
- First law tells that the energy given to the hot reservoir must equal the sum of the work done and the energy absorbed from the cold reservoir.
- One would desire to accomplish this task with minimum amount of work.
- The ideal condition would be when no work is required to be done—Perfect refrigerator.

  Second law again forbids this!



Refrigerator



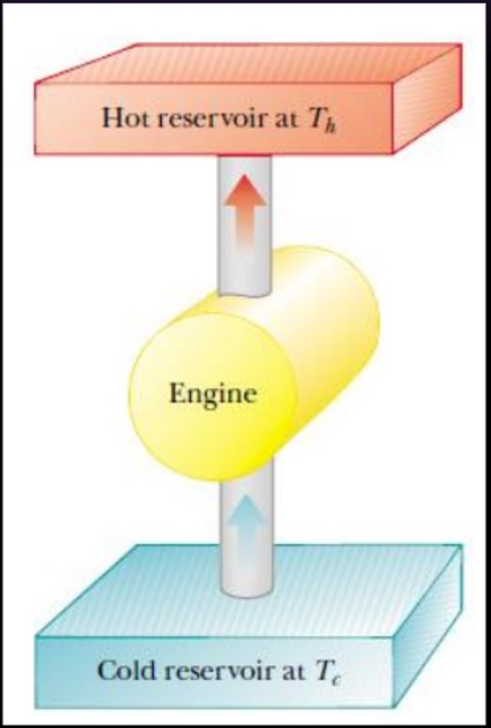
Impossible refrigerator

Clausius statement of Second Law

It is impossible to construct a cyclical machine whose sole effect is the continuous transfer of energy from one object at a **Cold** temperature without the input of energy by work.

This simply means that energy does not flow from a cold object to a hot object spontaneously.

For example, we can't make our refrigerators to function without the compressor working, which in turn get its power from the electricity.



The impossible refrigerator

Image Source: http://www.cs.stedwards.edu/~wright/text/thermo.html

The Carnot Engine

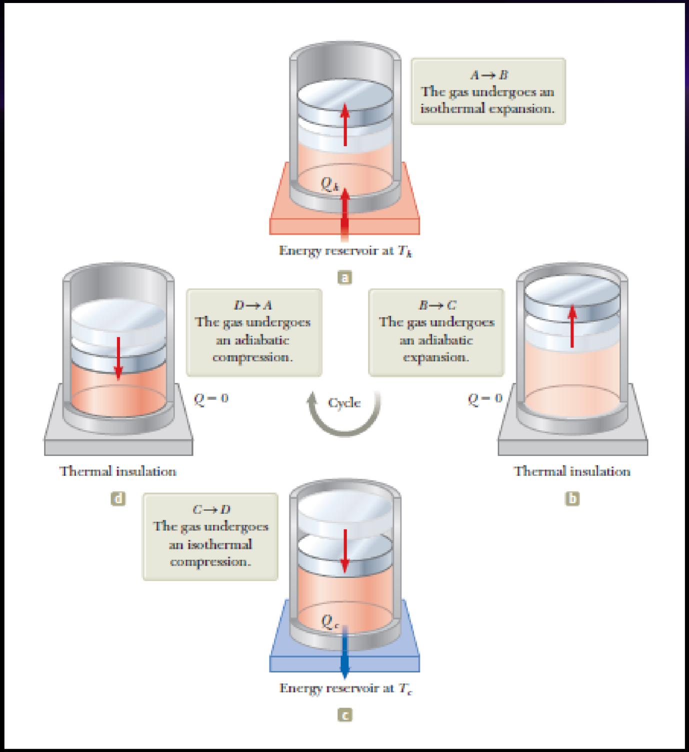
- Sadi Carnot, in 1824, described a theoretical engine, now called a Carnot engine, that is of great importance from both practical and theoretical viewpoints. He showed that a heat engine operating in an ideal, reversible cycle—called a Carnot cycle—between two energy reservoirs is the most efficient engine possible.

- Such an ideal engine establishes an upper limit on the efficiencies of all other engines.

Nicolas Léonard Sadi Carnot (1796-1832)

Image Source: http://upload.wikimedia.org/wikipedia/commons/thumb/8/80/Sadi_Carnot.jpeg/300px-Sadi_Carnot.jpeg

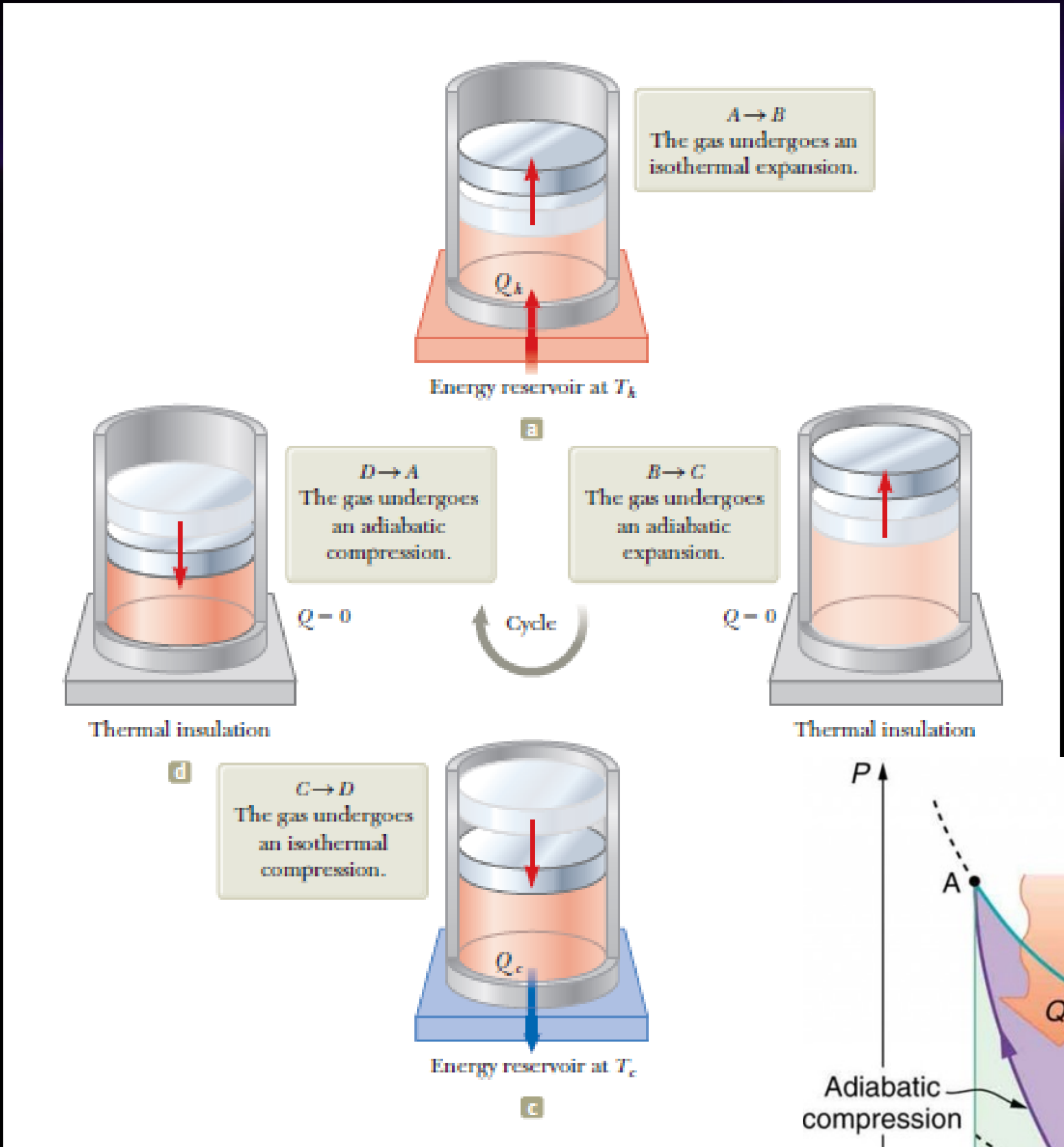
The Carnot Cycle



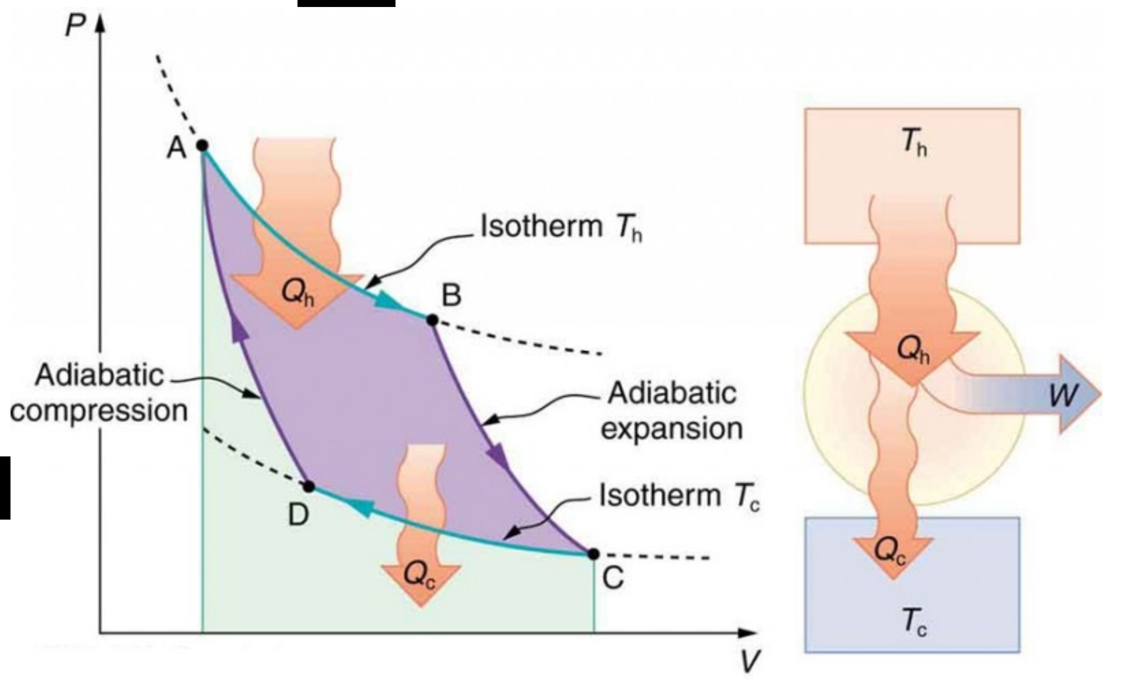
An ideal Carnot cycle consists of four processes.

1. Isothermal expansion of gas
2. Adiabatic expansion of gas
3. Isothermal compression of gas
4. Adiabatic compression of gas

Image Source: http://www.kshitij-school.com/Study-Material/Class-11/Physics/Second-law-of-thermodynamics/Carnot-engine/1.jpg



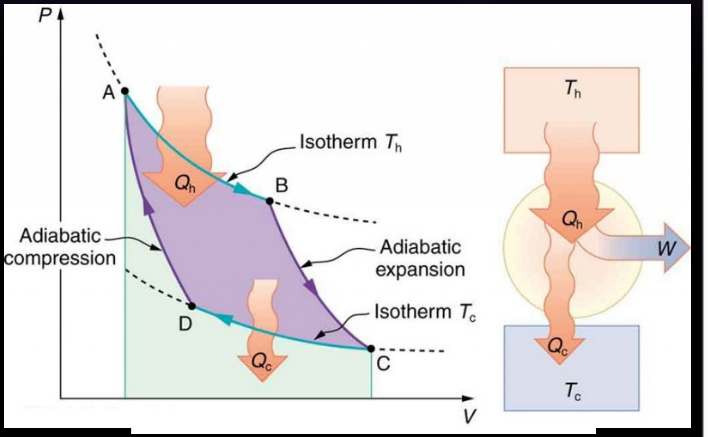
A → B
The gas undergoes an isothermal expansion.
Q_h
Energy reservoir at T_h
a
D → A
The gas undergoes an adiabatic compression.
B → C
The gas undergoes an adiabatic expansion.
Q = 0
Cycle
Q = 0
Thermal insulation
Thermal insulation
d
C → D
The gas undergoes an isothermal compression.
Q_c
Energy reservoir at T_c
c



P
A
Isotherm T_h
Q_h
B
Adiabatic compression
Adiabatic expansion
D
Isotherm T_c
Q_c
C
V
T_h
Q_h
W
Q_c
T_c

The Carnot Cycle

To describe the Carnot cycle taking place between temperatures *Tc* and *Th* , we assume that the working substance is an ideal gas contained in a cylinder fitted with a movable piston at one end. The cylinder's walls and the piston are thermally nonconducting. The Carnot cycle consists of two adiabatic processes and two isothermal processes, all reversible:



Process *A* →*B* is an isothermal expansion at temperature T_h . The gas is placed in thermal contact with an energy reservoir at temperature *Th* . During the expansion, the gas absorbs energy Q_h from the reservoir through the base of the cylinder and does work W_{AB} in raising the piston.

Process *B* → *C* the base of the cylinder is replaced by a thermally nonconducting wall, and the gas expands adiabatically—that is, no energy enters or leaves the system. During the expansion, the temperature of the gas decreases from T_h to T_c and the gas does work W_{BC} in raising the piston.

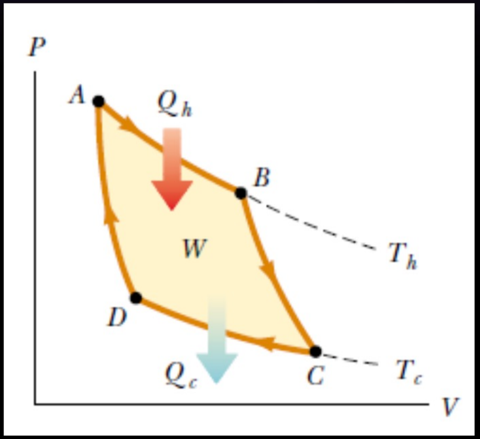
Process *C* → *D* , the gas is placed in thermal contact with an energy reservoir at temperature *Tc* and is compressed isothermally at temperature *Tc* . During this time, the gas expels energy *Qc* to the reservoir, and the work done by the piston on the gas is W_{CD}.

Process *D* → *A* , the base of the cylinder is replaced by a nonconducting wall, and the gas is compressed adiabatically. The temperature of the gas increases to T_h , and the work done by the piston on the gas is W_{DA} :

The Carnot Engine

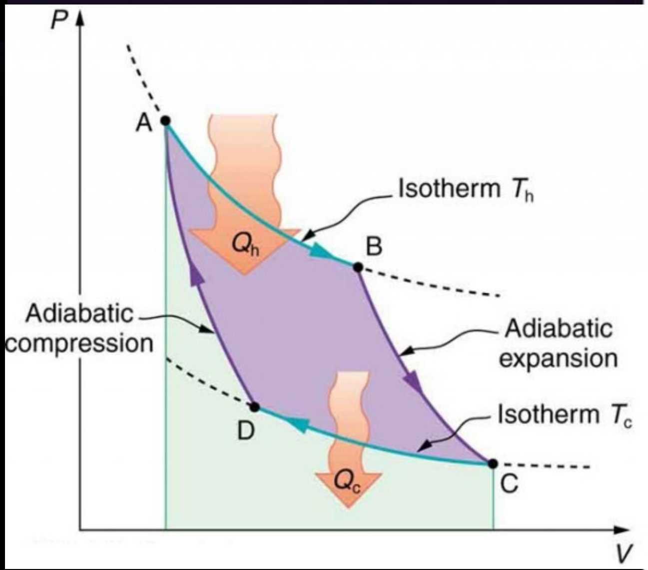
The net work done in this reversible, cyclic process is equal to the area enclosed by the path *ABCDA*. The change in internal energy is zero, thus the net work *W* done in one cycle equals the net energy transferred into the system, $|Q_h| - |Q_c|$. The thermal efficiency of the engine is given by

$$\eta = \frac{W}{|Q_h|} = \frac{|Q_h| - |Q_c|}{|Q_h|} = 1 - \frac{|Q_c|}{|Q_h|}$$



- Work done for path AB: $W_{AB} = |Q_h| = \mathcal{N}RT_h \ln(V_B/V_A)$
- Work done for path CD: $W_{CD} = |Q_c| = \mathcal{N}RT_c\ (V_C/V_D)$

$$\Rightarrow \frac{|Q_c|}{|Q_h|} = \frac{T_c}{T_h}\frac{\ln\,(V_C/V_D)}{\ln(V_B/V_A)}$$



- Now for an adiabatic process,

$$PV^\gamma = constant = \frac{nRT}{V}V^\gamma$$

$$\Rightarrow V^{\gamma-1}T = Constant.$$

- Applying for BC and DA,

$$V_B^{\gamma-1}T_h = V_C^{\gamma-1}T_c \text{ and } V_A^{\gamma-1}T_h = V_D^{\gamma-1}T_c$$

- Divide, $(V_B/V_A)^{\gamma-1} = (V_C/V_D)^{\gamma-1} \Rightarrow (V_B/V_A) = (V_C/V_D)$

- Thus

$$\Rightarrow \frac{|Q_c|}{|Q_h|} = \frac{T_c}{T_h}$$

- And hence efficiency of the Carnot engine

$$\eta_C = 1 - \frac{|Q_c|}{|Q_h|} = 1 - \frac{T_c}{T_h}$$

- This result indicates that all Carnot engines operating between the same two temperatures have the same efficiency.

Practice Problems

1. 5000 J of heat are added to two moles of an ideal monatomic gas, initially at a temperature of 500 K, while the gas performs 7500 J of work. What is the final temperature of the gas?

Solution

$$\Delta U = Q - W = 5000\,J - 7500\,J = -2500\,J$$

$$\Delta U = -2500\,J = (3/2)\,nR\Delta T = (3/2)(2)(8.31)\,\Delta T$$

$$\rightarrow \Delta T = -100\,K$$

$\rightarrow T_f =$ **500 K -100 K = 400 K**

comment : the gas does more work than it takes in as heat, so it must use 2500 J of its internal energy.

Practice Problems

2. Compute the internal energy change and temperature change for the two processes involving 1 mole of an ideal monatomic gas.

(a) 1500 J of heat are added to the gas and the gas does no work and no work is done on the gas

(b) 1500 J of work are done on the gas and the gas does no work and no heat is added or taken away from the gas

Solution

(a)

$$\Delta U = Q - W = 1500\,J - 0 = 1500\,J$$
$$\Delta U = 1500\,J = (3/2)nR\Delta T = (3/2)(1)(8.31)\Delta T$$
$$\rightarrow \Delta T = 120\,K$$

(b)

$$\Delta U = Q - W = 0 - (-1500\,J) = +1500\,J$$
$$\Delta U = 1500\,J = (3/2)nR\Delta T = (3/2)(1)(8.31)\Delta T$$
$$\rightarrow \Delta T = 120\,K$$

Notice that in both processes, the change in internal energy is the same. We say that the internal energy is a "state function". A state function depends only on the state of the system and not on the process that brings the system to that particular state.

Practice Problems

Q1. Practical steam engines utilize 450ºC steam, which is later exhausted at 270ºC. (a) What is the maximum efficiency that such a heat engine can have? (b) Since 270ºC steam is still quite hot, a second steam engine is sometimes operated using the exhaust of the first. What is the maximum efficiency of the second engine if its exhaust has a temperature of 150ºC? (c) What is the overall efficiency of the two engines? (d) Show that this is the same efficiency as a single Carnot engine operating between 450ºC and 150ºC.

5. (a)

$$Eff_1 = 1 - \frac{T_{\mathrm{c},1}}{T_{\mathrm{h},1}} = 1 - \frac{543\ \mathrm{K}}{723\ \mathrm{K}} = 0.249 \text{ or } 24.9\%$$

(b)

$$Eff_2 = 1 - \frac{423\ \mathrm{K}}{543\ \mathrm{K}} = 0.221 \text{ or } 22.1\%$$

(c)

$$Eff_1 = 1 - \frac{T_{c,1}}{T_{h,1}} \Rightarrow T_{c,1} = T_{h,1}\left(1, -, eff_1\right) \text{ similarly, } T_{c,2} = T_{h,2}\left(1 - Ef\right.$$

using $T_{h,2} = T_{c,1}$ in above equation gives

$$T_{c,2} = T_{h,1}\left(1 - Eff_1\right)\left(1 - Eff_2\right) \equiv T_{h,1}\left(1 - Eff_{\text{overall}}\right)$$

$$\therefore \left(1 - Eff_{\text{overall}}\right) = \left(1 - Eff_1\right)\left(1 - Eff_2\right)$$

$$Eff_{\text{overall}} = 1 - (1 - 0.249)(1 - 0.221) = 41.5\%$$

(d)

$$\text{Eff}_{\text{overall}} = 1 - \frac{423\ \text{K}}{723\ \text{K}} = 0.415 \text{ or } 41.5$$