Thermodynamics
Third Law
Heat Engines

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May 11, 2018

Last time

- heat engines
- heat pumps
- Carnot engines

Overview

- efficiency of Carnot engines
- the Third Law
- real engines

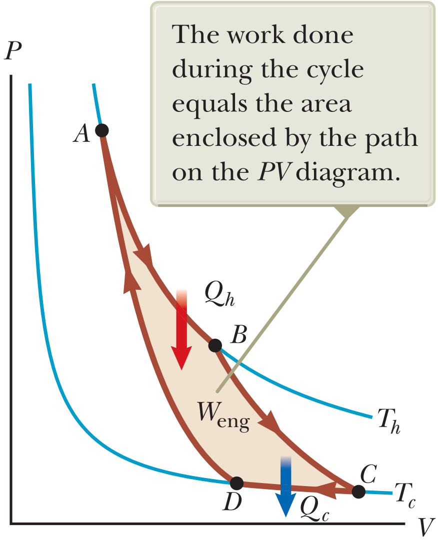
Heat Engine Recap

Steam engines and later incarnations of the engine run on a very simple principle: heat is transferred from a hot object to a colder object and mechanical work is done in the process.

Heat engines run in a cycle, returning their *working fluid* back to its initial state at the end of the cycle.

In practice, usually some chemical energy (burning fuel) is used to raise the temperature of one object, and the colder object remains at the ambient temperature.

The Carnot Cycle



Maximum Efficiency of an Engine

$$e > e_C \quad \Rightarrow \quad \frac{|W|}{|Q_h|} > \frac{|W|}{|Q_{hC}|}$$

This means

$$|Q_h| < |Q_{hC}|$$

We also know that $|W| = |Q_h| - |Q_c|$ (energy conservation). Since the works are equal:

$$\begin{aligned} W &= W_c \\ |Q_h| - |Q_c| &= |Q_{hC}| - |Q_{cC}| \end{aligned}$$

Rearranging:

$$|Q_{hC}| - |Q_h| = |Q_{cC}| - |Q_c|$$

But the LHS is positive if $e > e_C$.

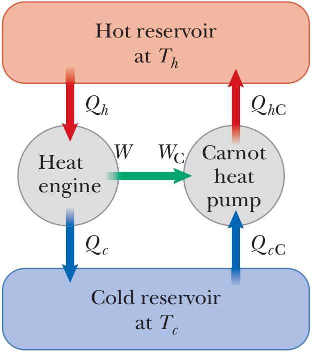
Heat arrives at the hot reservoir and leaves the cold one! $\Rightarrow$ Violates the Second Law.

Maximum Efficiency of an Engine

Putting the imagined engine and the Carnot heat pump together:

$|Q_{hC}| - |Q_h| > 0$

$|Q_{cC}| - |Q_c| > 0$



$\uparrow Q_{h,\text{net}}$

$\uparrow Q_{c,\text{net}}$

Violates the Second Law.

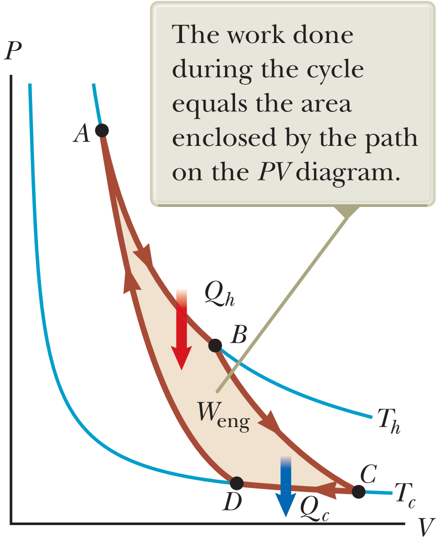
Carnot's Theorem

Carnot's Theorem

No real heat engine operating between two energy reservoirs can be more efficient than a Carnot engine operating between the same two reservoirs.

But how efficient is a Carnot engine?

The Carnot Cycle



Efficiency of a Carnot Engine

First, we can relate the volumes at different parts of the cycle.

In the first adiabatic process:

$$T_h V_B^{\gamma-1} = T_c V_C^{\gamma-1}$$

In the second adiabatic process:

$$T_h V_A^{\gamma-1} = T_c V_D^{\gamma-1}$$

Taking a ratio, then the $\gamma - 1$ root:

$$\frac{V_B}{V_A} = \frac{V_C}{V_D}$$

Efficiency of a Carnot Engine

First law: $\Delta E_{\text{int}} = Q + W = 0$ gives for the first isothermal process

$$|Q_h| = nRT_h \ln\left(\frac{V_B}{V_A}\right)$$

Second isothermal process:

$$|Q_c| = nRT_c \ln\left(\frac{V_C}{V_D}\right)$$

We will take a ratio of these to find the efficiency. Noting that $\frac{V_B}{V_A} = \frac{V_C}{V_D}$:

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

Efficiency of a Carnot Engine

Recall, efficiency of a heat engine:

$$e = 1 - \frac{|Q_c|}{|Q_h|}$$

Efficiency of a Carnot engine:

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

(T is measured in Kelvin!)

This is the most efficient that any heat engine operating between two reservoirs at constant temperatures can be.

Third Law of Thermodynamics

3rd Law

As the temperature of a material approaches zero, the entropy approaches a constant value.

The constant value the entropy takes is very small. It is actually zero if the lowest energy state of the material is unique.

Another way to express the third law:

3rd Law - alternate

It is impossible to reach absolute zero using any procedure and only a finite number of steps.

Entropy in the Carnot Cycle

Since the working fluid returns to its initial state along reversible paths, the change in the entropy for the whole cycle is

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We can see this from an analysis also:

$$\Delta S = \int \frac{1}{T} \, \mathrm{dQ_r}$$

In the reversible adiabatic processes $\Delta S = 0$.

In the reversible isothermal portions, T is constant so $\Delta S = \frac{Q}{T}$.

For the cycle

$$\Delta S = \frac{|Q_h|}{T_h} - \frac{|Q_c|}{T_c}$$

Entropy in the Carnot Cycle

For the cycle

$$\Delta S = \frac{|Q_h|}{T_h} - \frac{|Q_c|}{T_c}$$

We just found that

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

So

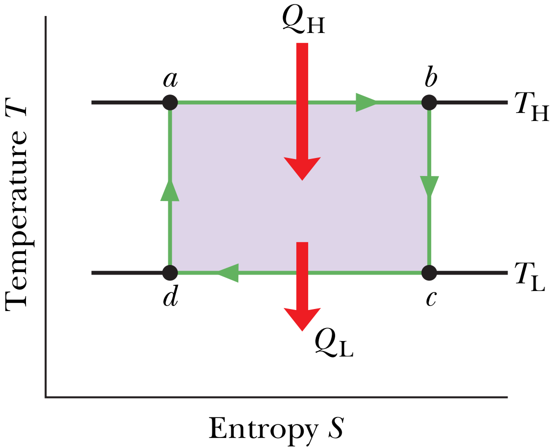
$$\frac{|Q_h|}{T_h} = \frac{|Q_c|}{T_c}$$

And for the cycle

$$\Delta S = 0$$

Entropy in the Carnot Cycle

We can represent the Carnot Cycle on a TS diagram:



Heat Engine question

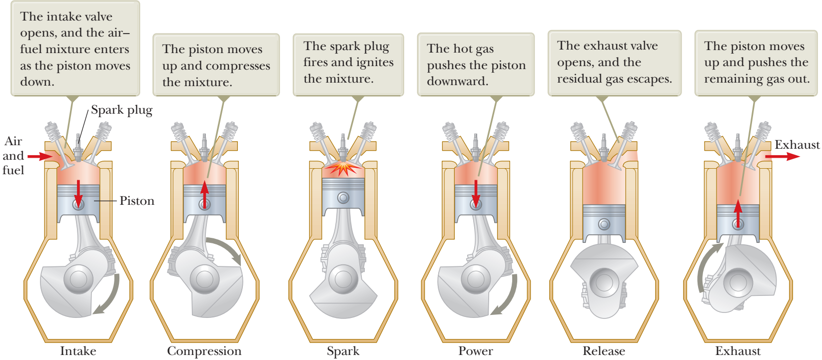
Consider and ocean thermal energy conversion (OTEC) power plant that operates on a temperature difference between deep 4°C water and 25°C surface water. Show that the Carnot (ideal) efficiency of this plant would be about 7%.

[0] Hewitt, page 331, problem 2.

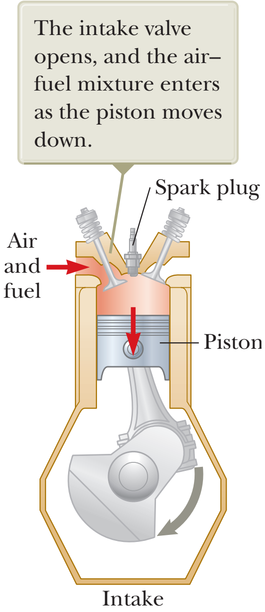
Car Engines

Car engines work by burning fuel in cylinders with pistons.

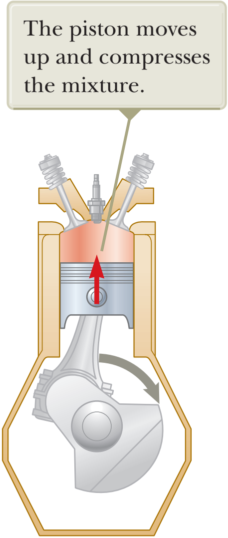
The four stroke cycle:



Car Engines

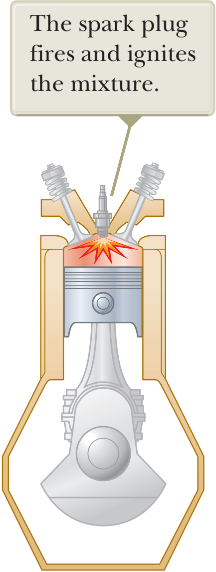

The intake valve opens, and the air–fuel mixture enters as the piston moves down.
Spark plug
Air and fuel
Piston
Intake

Car Engines



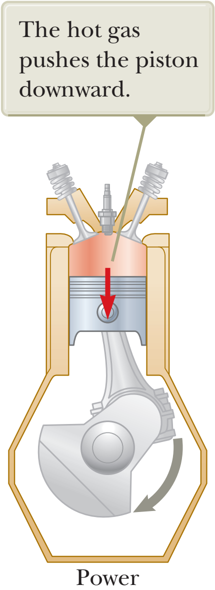
Compression

Car Engines

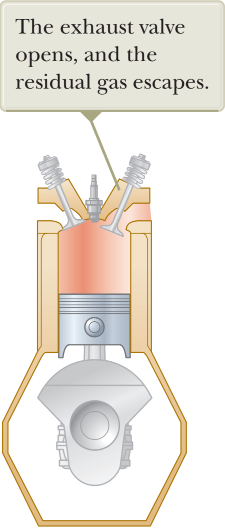


Spark

Car Engines

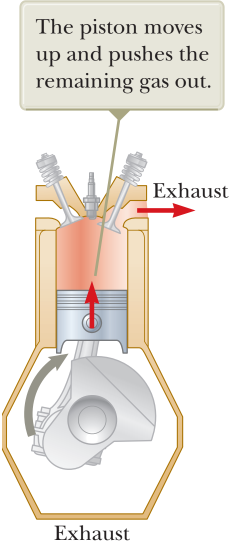


Car Engines



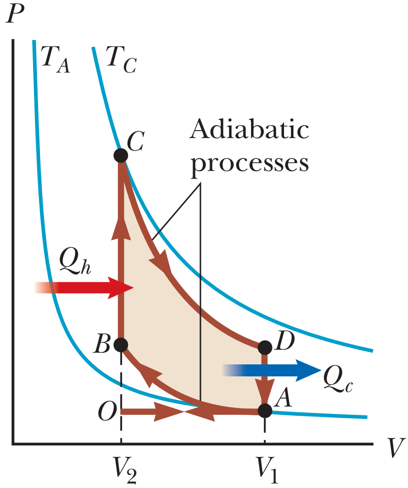
Release

Car Engines


The piston moves up and pushes the remaining gas out.
Exhaust
Exhaust

Car Engines and the Otto Cycle

The **Otto cycle** approximates the real 4-stroke cycle we just discussed.



Car Engines and the Otto Cycle

The efficiency of the Otto cycle is

$$e = 1 - \frac{1}{(V_1/V_2)^{(\gamma-1)}}$$

(See example 22.5 for a proof of this expression.)

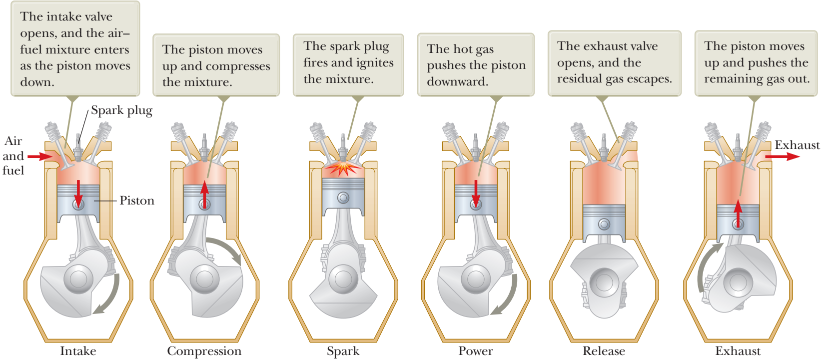
A typical value for the volume compression is $V_1/V_2 = 8$, which would give an efficiency of 56%.

Real efficiencies of car engines are much less than this, $\sim 20\%$.

There is heat loss, work lost overcoming friction, and imperfect combustion.

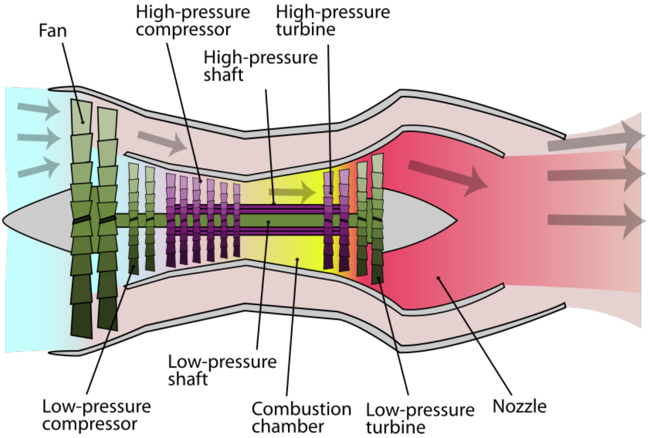
Car Engines

The four stroke cycle:



Jet Engines

Jet engines are even simpler and more efficient than car engines.

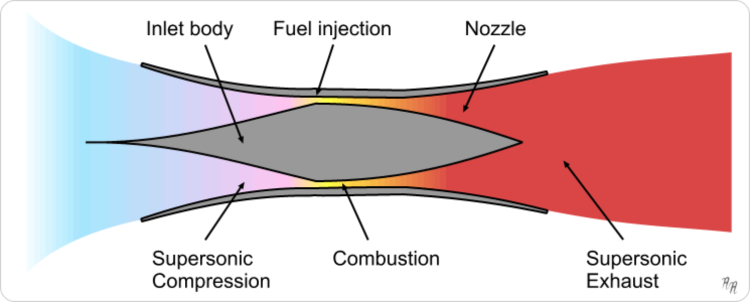


However, they require more advanced materials...

[1] Turbofan schematic from Wikipedia by K. Aainsqatsi.

Advanced Jets: Scramjet

...and higher speeds of operation.



[1]Scramjet schematic from Wikipedia by User:Emoscopes.

Summary

- Carnot engines
- real engines

Thermodynamics Test Monday, May 14.

Homework Serway & Jewett:

- Ch 22, OQs: 1, 3, 7; CQs: 1; Probs: 1, 3, 9, 15, 20, 23, 29, 37, 67, 73, 81