Heat Engines

Unit: Heat & Thermodynamics

NGSS Standards: HS-PS2-6

MA Curriculum Frameworks (2006): N/A

AP Physics 2 Learning Objectives: 5.B.5.4, 5.B.5.5, 5.B.7.3, 7.B.2.1

Knowledge/Understanding:

- definition of a heat engine
- different types of heat engines

Skills:

- calculate the energy produced by a heat engine
- calculate the efficiency of a heat engine

Language Objectives:

- Understand and correctly use the terms “heat engine,” “enthalpy,” “entropy”.
- Accurately describe and apply the concepts described in this section using appropriate academic language.
- Set up and solve word problems relating to the action of heat engines.

Labs, Activities & Demonstrations:

- Stirling engine

Notes:

heat engine: a device that turns heat energy into mechanical work.

A heat engine operates by taking heat from a hot place (heat source), converting some of that heat into work, and dumping the rest of the heat into a cooler reservoir (heat sink).

A large number of the machines we use—most notably cars—employ heat engines.

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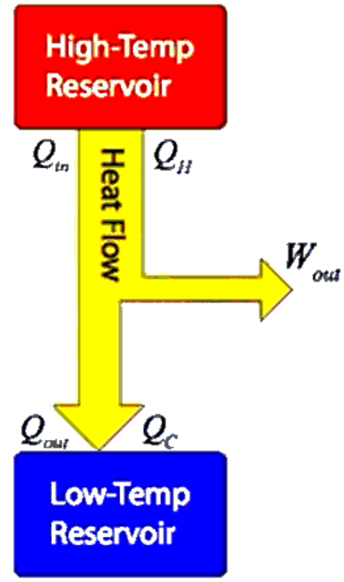

The basic principle of heat engine is the first law of thermodynamics (heat flows from a region of higher temperature to a region of lower temperature). Because heat is a form of energy, some of that energy can be harnessed to do work.

The law of conservation of energy tells us that all of the energy that we put into the heat engine must go somewhere. Therefore, the work done plus the heat that comes out must equal the heat we put in.

This means:

$$Q_{in} = Q_{out} + W_{out}$$

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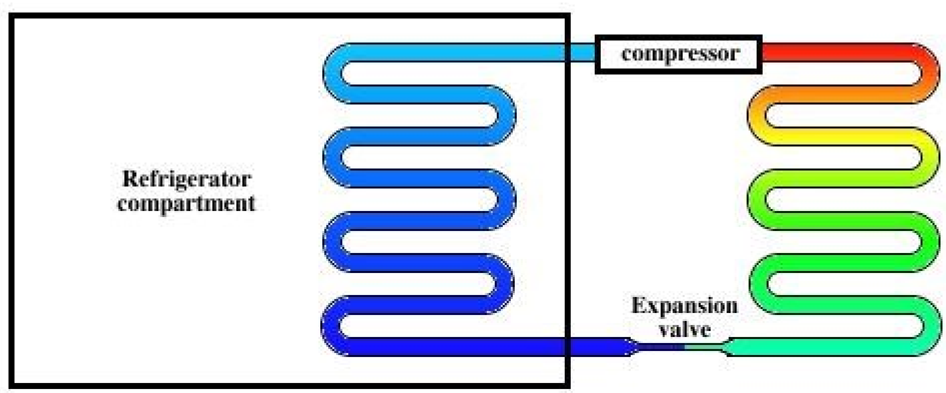
Heat Pumps

A heat pump is a device that "pumps" heat from one place to another. A refrigerator and an air conditioner are examples of heat pumps. A refrigerator uses a fluid ("refrigerant") to transfer (or "pump") heat from the inside of the refrigerator to the outside of the refrigerator (and into your kitchen). This is why you can't cool off the kitchen by leaving the refrigerator door open—if you had a 100% efficient refrigerator, the heat that you pumped out would mix with the cool air and you would be back where you started. Moreover, because refrigerators are only 20–40% efficient, the refrigerator loses a significant amount of heat into its environment, which means leaving the refrigerator door open will actually heat up the kitchen!

A refrigerator works by compressing a refrigerant (gas) until it turns into a liquid. The liquid is then pumped inside the refrigerator and allowed to expand to a gas, lowering the temperature. The increase in volume of the gas takes energy (heat) from the inside of the refrigerator, which lowers the temperature of the refrigerant to about −20°C. The gas is then pumped out of the refrigerator where it is compressed back to a liquid, which causes its temperature to increase to about 70°C. The hot liquid is then pumped through cooling coils, where it releases its heat into the kitchen until the refrigerant returns to room temperature (about 20°C).



Of course, a heater can operate under the same principle, by putting the cooling coils inside the room to be heated and having the expansion, which cools the refrigerant, occur outside the room. This cycle is the most efficient type of heat engine. The cycle is called the Carnot cycle, named after the French physicist Nicolas Carnot.

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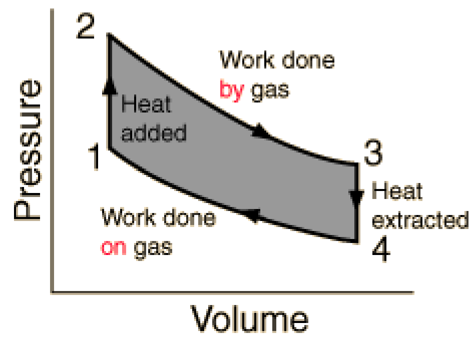
Heat Engines and PV Diagrams

On a PV diagram, a heat engine is a closed loop or cycle:



Recall that on a PV diagram, a curve that moves from left to right represents work done *by* the gas on the surroundings. (Work is leaving the system, so $\Delta W < 0$.) A curve that moves from right to left represents work done *on* the gas by the surroundings. (Work is entering the system so $\Delta W > 0$.)

A clockwise cycle means more work is done going to the right than to the left, which means there is a net flow of work out of the system (*i.e.,* the heat is being used to do work). (A counterclockwise cycle would represent a refrigerator.)

In the above diagram:

From 1 → 2 heat is added to the gas at constant volume. The temperature of the gas goes up, but no work is done.

From 2 → 3, the gas expands, doing work.

From 3 → 4, the gas is cooled at constant volume, extracting heat. The temperature of the gas goes down, but no work is done.

From 4 → 1 work is done on the gas to compress it.

Notice that the work done by the gas on the surroundings is at a higher temperature than the work done on the gas. (Isotherms are hyperbolas. The work done by the gas follows a higher isotherm.)

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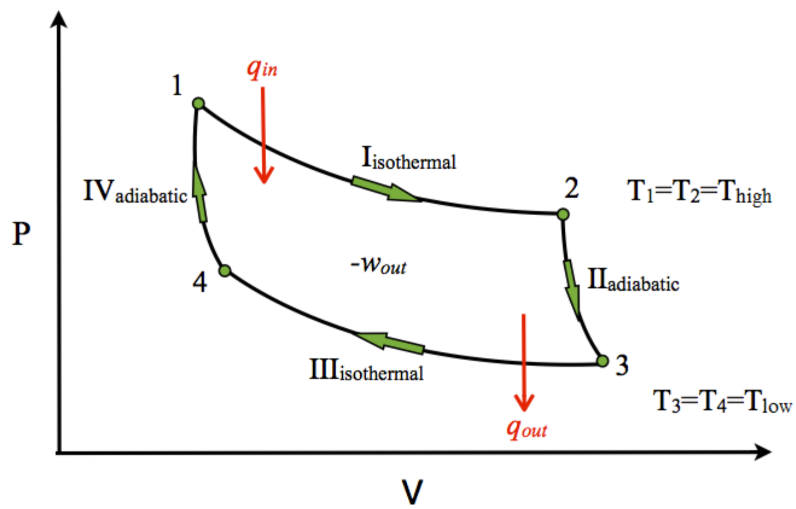
The most interesting type of heat engine is the Carnot cycle, which uses only adiabatic (no heat loss) and isothermal processes.



Heat pumps (including refrigerators) are based on the Carnot cycle.

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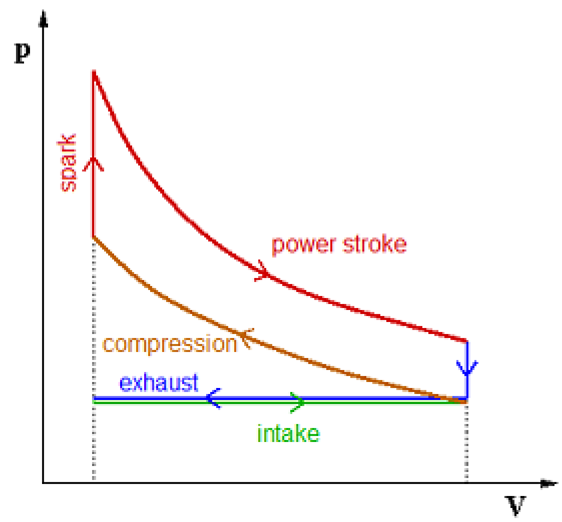
The internal combustion engine in a car is a type of heat engine. The engine is called a "four-stroke" engine, because the piston makes four strokes (a back or forth motion) in one complete cycle. The four strokes are:

1. The piston moves down (intake), sucking a mixture of gasoline and air into the cylinder.

2. The piston raises (compression), compressing the gases in the cylinder.



3. The spark plug creates a spark, which combusts the gases. This increases the temperature in the cylinder to approximately 250°C, which causes the gas to expand (power stroke).

4. The piston raises again, forcing the exhaust gases out of the cylinder (exhaust).

Note that, at the end of the cycle, the gas is hotter than its original temperature. The hot gas from the cylinder is dumped out the exhaust pipe, and fresh (cool) gas and fuel is added.

The energy to move the piston for the intake and exhaust strokes is provided by the power strokes of the other pistons.

This cycle—constant temperature compression, constant volume heating (spark), constant temperature expansion (power), and constant volume gas exchange (exhaust) is called the Otto cycle, named after Nikolaus August Otto, who used this type of heat engine to build the first successful commercial internal combustion engine.

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