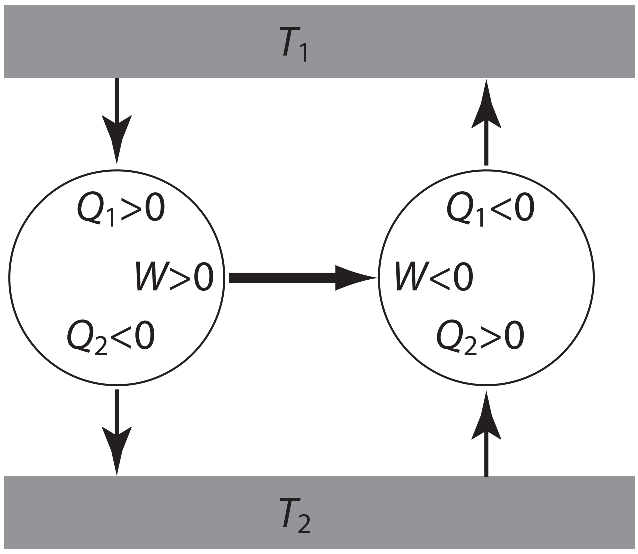
General Physics II at EPFL

(2018-2019 SS, Wed 17:15-19:00 and Thu 8:15-10:00, Exercise Thu 10:15-12:00)

Thermodynamic (9th week)

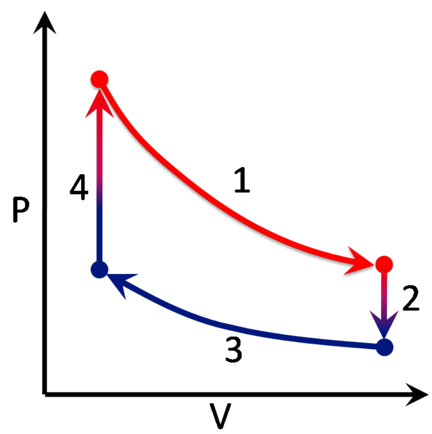
Perpetual motion with two Carnot engines

The first low of thermodynamics does not allow drawing work from nothing. The second law of thermodynamics does not allow to covert 100% of heat to work. Now we consider two Carnot engines where the first one works in a normal way producing a positive work, W, to the outside. Those work is then fed to the second Carnot engine operates in the reverse direction. The thermal energy transferred from the high temperature heat reservoir to the low temperature by the first engine is restored by the second one. Thus the two engines seem to work forever. This third kind of perpetual motion is not allowed by the energy losses such as the frictions and heat losses of a real machine.

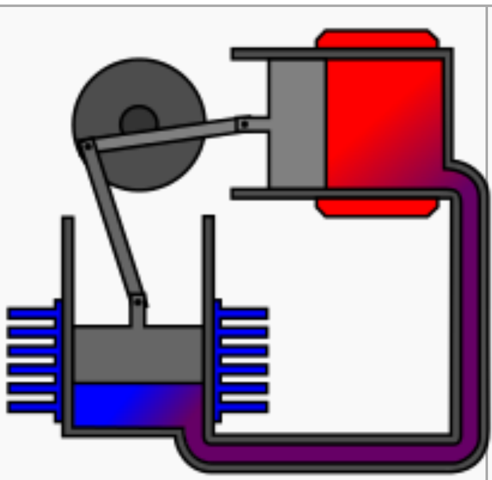


Starling Engine

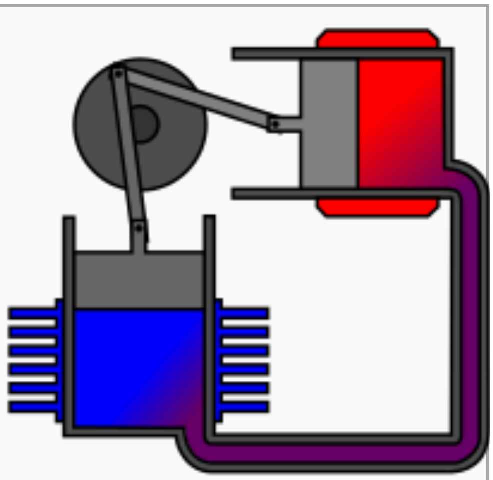
Starling thermal cycle consists of the following four steps: 1) isothermal expansion, 2) isovolumetric heat exhaustion, 3) isothermal compression, 4) isovolumetric heat absorption.



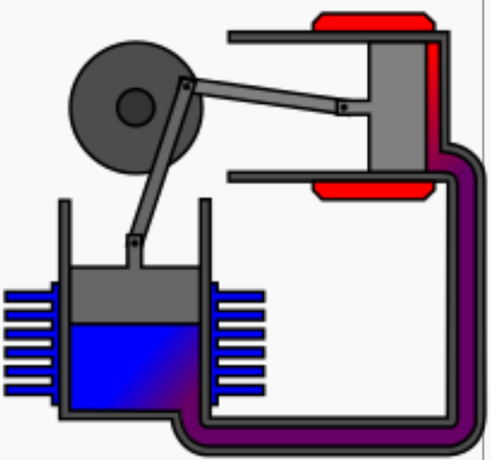
The next figure shows how a real Starling engine works:



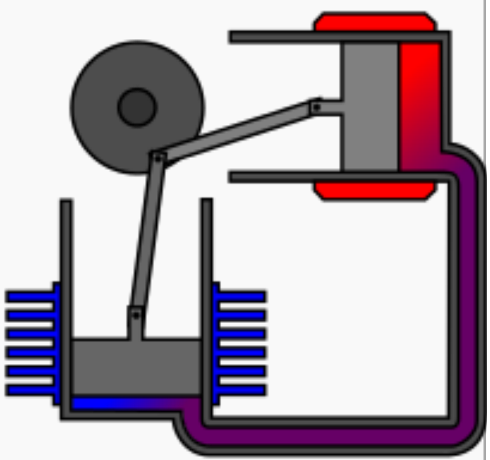
1. Most of the working gas is in the hot cylinder and has more contact with the hot cylinder's walls. This results in overall heating of the gas. Its pressure increases and the gas expands. Because the hot cylinder is at its maximum volume and the cold cylinder is at the top of its stroke (minimum volume), the volume of the system is increased by expansion into the cold cylinder.



2. The system is at its maximum volume and the gas has more contact with the cold cylinder. This cools the gas, lowering its pressure. Because of flywheel momentum or other piston pairs on the same shaft, the hot cylinder begins an upstroke reducing the volume of the system.

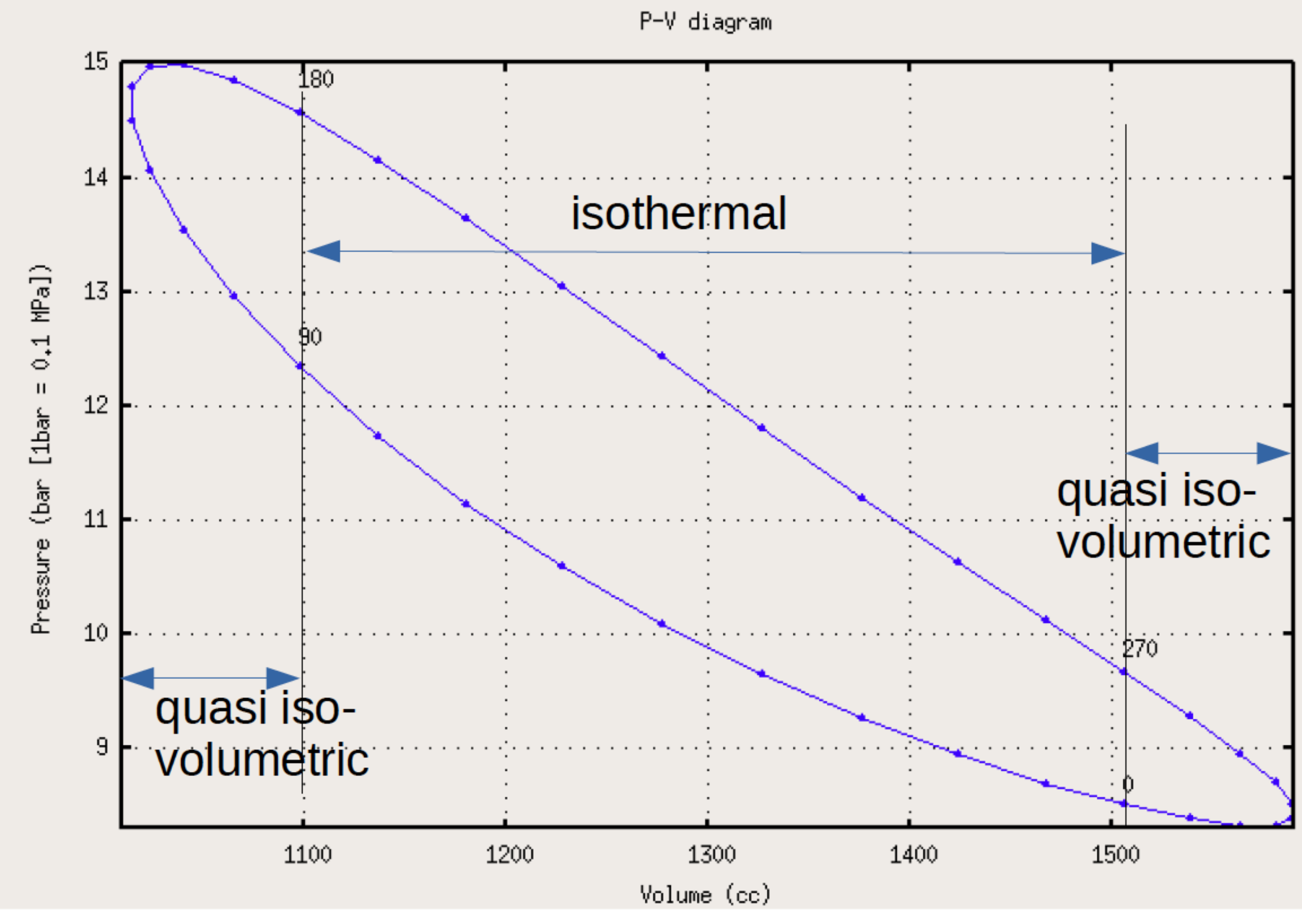


3. Almost all the gas is now in the cold cylinder and cooling continues. This continues to reduce the pressure of the gas and cause contraction. Because the hot cylinder is at minimum volume and the cold cylinder is at its maximum volume, the volume of the system is further reduced by compression of the cold cylinder inwards.



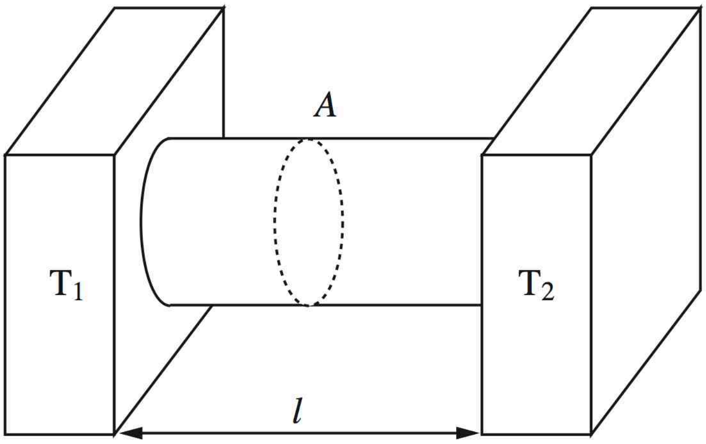
4. The system is at its minimum volume and the gas has greater contact with the hot cylinder. The volume of the system increases by expansion of the hot cylinder.

The previously shown Starling cycle is ideal and the P-V diagram for a real Starling engine looks more like



Heat generation: Conduction, Convection and Radiation (373, 328, 326, 386, 401)

Conduction: Thermal energy transfers through direct contact of materials with different temperatures.



The rate of energy transfer from object-1 to -2 is given by the Fourier's law:

$$\frac{\Delta Q}{\Delta t} = kA\frac{T_1 - T_2}{l}$$

A: cross-section area of the object

l: distance between the two ends

T_1 and T_2: temperatures of the object-1 and object-2, respectively.

k: thermal conductivity

and $\Delta Q/\Delta t > 0$ means that the thermal energy flows out from 1, this if $T_1 - T_2 > 0$, the thermal energy flows out from the object-1. If we chose the origin of the coordinate system to be the edge of the object-1, we have $dT/dx < 0$ for $T_1 - T_2 > 0$. Therefore, for an infinitesimal small length, this leads to

$$\frac{dQ}{dt} = -kA\frac{dT}{dx}.$$

Material with large k, thermal conductor

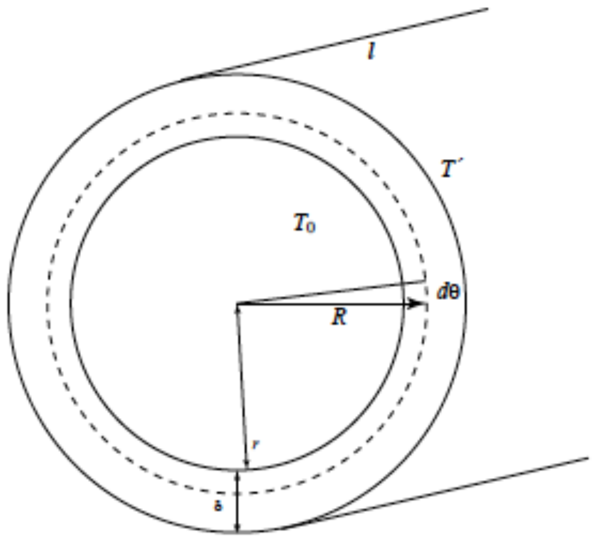
Material with small k, thermal insulator

Application for cylindrical pipes

A cylindrical pipe has inner radius r with a wall thickness of δ. The pipe carries hot water inside at a temperature of T_0. The temperature outside is T'. Let us consider a small wedge of the cylinder with a length l, as shown in the figure. For the formula for the heat transfer

$$\frac{dQ}{dt} = -k \cdot A \cdot \frac{dT}{dx}$$

which means that the rate of heat transfer is proportional to the temperature gradient, the direction of the heat is in R and area A at R is given by $l \cdot R \cdot d\theta$. Therefore it leads to the heat rate for this small wedge, $d\left(dQ/dt\right)$, is given by



$$d\left(\frac{dQ}{dt}\right) = -k \cdot l \cdot R \cdot d\theta \cdot \frac{dT}{dR}$$

The total rate is then obtained by integrating the left side of the equation for θ from 0 to 2π and

$$\frac{dQ}{dt} = -2\pi \cdot k \cdot l \cdot R \cdot \frac{dT}{dR}$$

When the temperatures inside and outside remain constant, the temperature gradient remains constant, thus dQ/dt is also constant, and it follows that $R \cdot dT/dR = c$, and

$$dT = \frac{c}{R}dR \rightarrow T = c\ln R + c'$$

where c and c' are unknown constants. Since at $R=r$, $T = T_0$ and $R=r+\delta$, $T = T'$, c can be obtained as

$$c = \frac{T' - T_0}{\ln\frac{r+\delta}{r}}$$

For $\delta/r << 1$, we obtain

$$\ln\frac{r+\delta}{r} = \ln\left(1+\frac{\delta}{r}\right) \approx \frac{\delta}{r}$$

thus

$$\frac{dQ}{dt} = 2\pi k\left(T_0 - T'\right)l\frac{r}{\delta}$$

Convection: for gas and liquid

Change of density with temperature and gravitational force generate the flow of matter with different temperatures.

Radiation: energy transfer without medium, through electromagnetic wave.

Radiation rate from an object with a temperature T is found to follow the Stefan-Boltzmann equation

$$\frac{\Delta Q}{\Delta t} = \varepsilon\sigma A T^4$$

where σ is the Stefan-Boltzmann constant, $\sigma = 5.67 \times 10^{-8}\ \mathrm{W}/\left(\mathrm{m}^2 \cdot \mathrm{K}^4\right)$ and ΔQ is the flow of thermal energy from the object. The constant ε is called the emissivity of the object, a number between 0 and 1: $\varepsilon = 1$ corresponds to "black body". An object can also absorb energy with radiation. When the body has a temperature T_1 is placed in an environment with a temperature T_2, the energy flow into the object is given by

$$\frac{\Delta Q}{\Delta t} = \varepsilon\sigma A\left(T_1^4 - T_2^4\right)$$

i.e. if $T_1 = T_2$ there is no energy flow. If $T_1 > T_2$, we have $\Delta Q/\Delta t > 0$, thus thermal energy is flowing out from the body to the environment.