Institute for Green and Sustainable Science IGSS'09

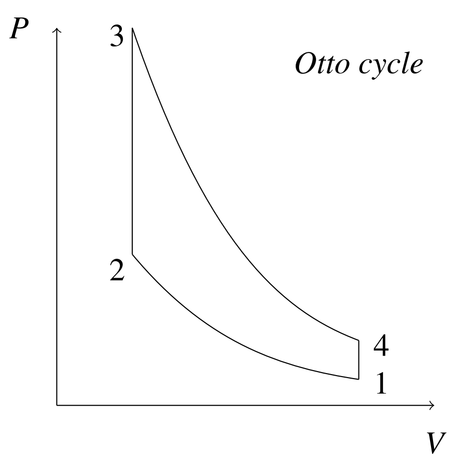
Marian University, Indianapolis

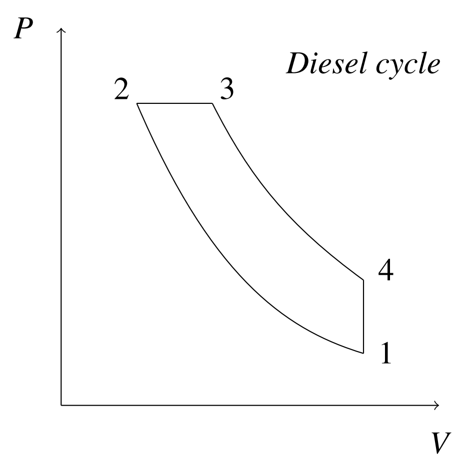
Supplementary notes - Engine efficiency

In David Mackay's book a figure of 25% is used for the efficiency of road vehicles - how accurate is this number, and what is its origin?

The efficiency with which road vehicles convert chemical energy from their (usually fossil) fuel into forward motion is compounded from several component factors: the ideal thermodynamic efficiency η (expressing the impossibility of complete conversion of *heat* into *work*), friction in the engine and other vehicle parts, turbulence of mixing gases influencing the combustion process, and work used to power water pumps, electrical generators, and other vehicle systems.

Thermodynamic analysis of ideal engines can be accomplished with the help of a pressure-volume phase diagram. The most common kinds of vehicle engine are the gasoline engine (a four-stroke spark ignition reciprocating engine), and the diesel engine (in which there is no spark, but ignition is accomplished during the compression cycle with the help of "glow plugs"). These are respectively described by the Otto cycle (named after Nikolaus Otto) and the Diesel cycle (named after Rudolf Diesel).





In the Otto cycle, step 1-2 is ingestion and adiabatic compression of the fuel-air mix (adiabatic: with no exchange of heat between the system and its surroundings; this implies that the process is also *isentropic*); step 2-3 is ignition and combustion of the mix at constant volume (implying that the process is effectively instantaneous) - this adds heat to the system; step 1-3 is adiabatic expansion (the component of the cycle that does *work*; and step 4 is constant volume cooling.

We can analyze all of these steps using straightforward thermodynamics, with the goal of obtaining the efficiency $\eta = \frac{w_{out}}{q_{in}}$, based on some assumptions.

We can calculate w_{out} straightforwardly from the First Law using the fact that the relevant steps are adiabatic, implying that $q = 0$ for that step. Hence we can write

$$w = \Delta U = c_V \left[(T_3 - T_4) - (T_2 - T_1) \right], \tag{1}$$

if c_V is assumed to be T-independent.

By some mathematical sleight-of-hand this can be converted to an expression given in terms of the compression ratio r, defined as the ratio of the cylinder volume at its largest capacity to its volume at its smallest. The resulting equation is

$$w = q_{in} \left(\frac{r^{\gamma-1} - 1}{r^{\gamma-1}} \right), \tag{2}$$

where $\gamma = c_P/c_V$, the ratio of the constant pressure and constant volume heat capacities. For a diatomic ideal gas (such as air), γ = 1.4, but a more realistic value for the gas mixture averaged over the combustion process is 1.27. From this equation we straightforwardly obtain the efficiency η by dividing by q_{in}, yielding

$$\eta = \frac{r^{\gamma-1} - 1}{r^{\gamma-1}}. \tag{3}$$

For a typical (good) compression ratio of 10, this yields a theoretical efficiency of 0.46, or 46%. To obtain a more realistic efficiency, we must multiply 0.46 by factors accounting for weaknesses in the model and other sources of energy loss. Weaknesses in the model include the assumption of instantaneous burning and constant gas composition, while other sources of energy loss include friction, inefficiency in the drivetrain, and the use of a component of the work produced to power systems such as the water pump and the electrical generator.

Analysis of the Diesel cycle is more complicated, because the (approximately) constant pressure heating step (as the gases ignite slowly under compression and the cylinder expands) involves the input of both heat and work.

The thermodynamic efficiency of the Diesel cycle can be expressed as

$$\eta = 1 - r^{1-\gamma}\left(\frac{\alpha^{\gamma} - 1}{\gamma\left(\alpha - 1\right)}\right), \tag{4}$$

where all other symbols have their previous meanings and α is the "cut-off ratio" V_3/V_2, which can be expressed as

$$\alpha = \left(\frac{T_3}{T_1}\right) r^{1-\gamma}. \tag{5}$$

This equation is fairly straightforward to apply if it is assumed that T_1 is the inlet air temperature and T_3 is the *adiabatic flame temperature* of the fuel, based on the actual fuel-air mixture used. (The adiabatic flame temperature is defined as the temperature the combustion product gases would reach if *all* of the combustion enthalpy were used to heat the product gases. It is therefore always an overestimate.)

The Diesel cycle is in fact *less* efficient than the Otto cycle for a given compression ratio. However, diesel engines are typically *more* efficient than gasoline engines because higher compression ratios (15-25) are typical, and because diesel engines are less susceptible to efficiency loss through gas turbulence in the cylinder.

Exercises

1) Graph η against r for an Otto cycle with a reasonable range of compression ratios (say, 5 to 15).

2) Calculate the adiabatic flame temperature for a stoichiometric diesel-air mixture, assuming diesel to be a C_{14} hydrocarbon with an energy density of about 48 MJ/kg, and with the following (constant pressure) heat capacities: nitrogen 29.12 J mol$^{-1}K^{-1}$, oxygen 29.38 J mol$^{-1}K^{-1}$, water vapor 37.42 J mol$^{-1}K^{-1}$, carbon dioxide 36.94 J mol$^{-1}K^{-1}$ (assumed to be T-independent).

3) Using the data from question 2, calculate η for a diesel engine with a compression ratio of 25.