Lecture 12 (Energy). EngGen 140

Recall :

Overview of Part II [Energy/Material

Split into three related sections

✓ 5. Basic Physics of Energy (~4/5 Lectures)

- Sources & consumption of energy
- Forms of energy, units etc
- Basic balance calculations

Here → 6. Basics of Energy Transfer (~6/7 Lectures)

- Thermodynamics
- More sophisticated balance calculations etc.

7. Basics of Biological Energetics (~4 lectures)

- How do animals, cells etc store & use energy

Lecture 12 Energy Transfer: Basics of thermodynamics

Topics - Case study

- energy transformations in a car, including...
- Otto cycle for an Otto engine

what you should be able to do

- understand how the principles devel. in prev. lectures apply to case study
- understand & sketch Otto cycle & fill in details of PV process

Examples

(Worksheet 2017)

Draw the idealised Otto Cycle on a PV diagram. On this diagram label the area that corresponds to adiabatic expansion work done by the gas.

(Exam 2017)

35) As an engineer, you have been asked to fully characterise a new, experimental combustion engine, that works on an idealised Otto cycle. You have measured various points of the cycle, as indicated in the table below. Calculate the four missing entries and enter them into the table. Show all of your working.

(3 marks)

Table 1. Otto cycle data

	1	2	3	4
T (K)	250.0	651.4	1342.0	515.4
P (Pa)	7.93×10^5			1.64×10^6
V (m^3)	2.6×10^{-4}			2.6×10^{-4}
n = 0.103, adiabatic constant $\gamma = 1.4$, $R = 8.314\ J\ mol^{-1}\ K^{-1}$, compression ratio = 11.0				

Calculations for missing entries:

6.8 Case study: Energy transformations in a car

An internal combustion engine provides a good example of the various energy transformations that provide us with useful energy and work from chemical energy→heat→work→kinetic energy (Figure 21). Let's explore these in more detail to check your understanding of the general energy concepts we have covered.

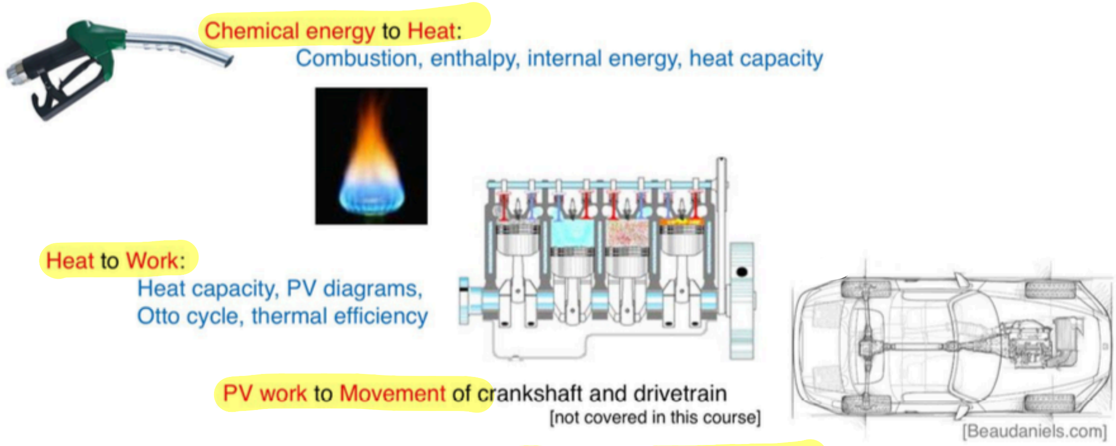


Figure 21: Energy transformations of a four-stroke internal combustion engine car and the general energy concepts.

We will assume our car runs on kerosene[21]. The combustion of kerosene is given by:

$$C_{12}H_{26}\ (g) + 18.5O_2\ (g) \longrightarrow 12CO_2\ (g) + 13H_2O\ (l) + \text{heat}\ (Q)$$

Calculate the standard enthalpies of combustion for kerosene (dodecane), $C_{12}H_{26}$ (ΔH_f^o $C_{12}H_{26}$ (g) = -353.5 kJ/mol). Is this reaction endo- or exothermic?

$$\Delta H = \Delta H^{products} - \Delta H^{reactants}$$

$$= [12 \times (-393.5) + 13 \times (-285.83)] - [(-353.5) + 0]$$

$$\approx -8084 \text{ kJ}$$

$\Rightarrow$ exothermic, $\Delta H = Q^{in} = -8084 \text{ kJ/mol}$

Table 6: Example enthalpy of formation values at 298 K and 1 atm.

Substance	Phase	Chemical Formula	ΔH_f^o (kJ.mol^{-1})
Water	liquid	H_2O	-285.83
Water	gas	H_2O	-241.8
Oxygen	gas	O_2	0
Hydrogen	gas	H_2	0
Carbon dioxide	gas	CO_2	-393.5
Lead	solid	Pb	0
Lead sulfate	solid	$PbSO_4$	-919.94
Lead oxide	solid	PbO_2	-274.47
Sulfuric acid	liquid	H_2SO_4	-909.27

= reactants

= products

Pop Quiz

What is the energy source for the heat released in a chemical reaction? Where does the energy go when heat is absorbed in a chemical process (i.e. endothermic reactions)?

Both: internal energy (chemical energy stored in/ released from bonds etc)

If energy is released as heat and work, what happens to the internal energy (U)?

↳ exothermic : decreases internal energy. (also $\Delta H \downarrow$)

True of False, internal energy does not depend on P, T, and V?

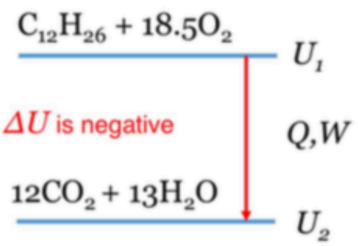
False. ($dU = -pdV + TdS$)

True or False, internal energy (U) cannot be measured direct~~ion~~ly, however, ΔU can be?

True. (Relative to a reference)

Car Cont'd

Consider the products and reactants of the above reaction in the figure below. Describe ΔU in terms of U_1 and U_2, as well as heat (Q) and work (W).



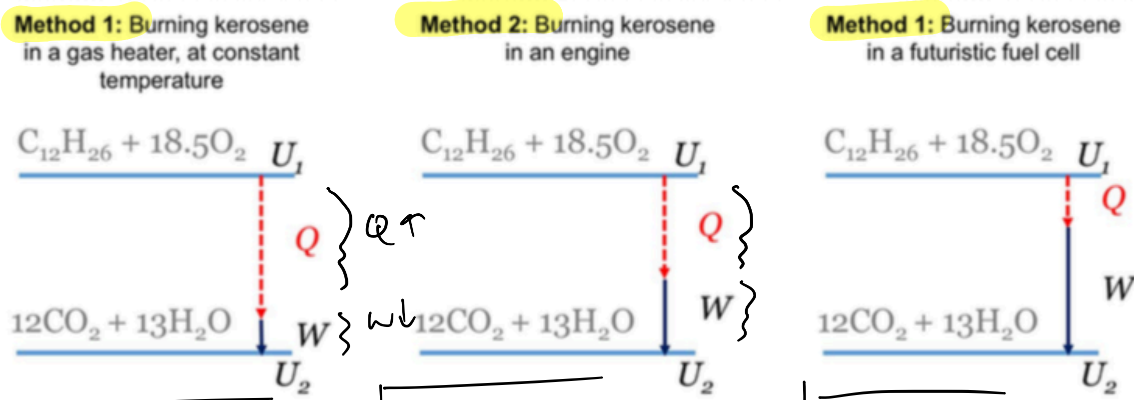
$$\boxed{\begin{aligned}\Delta U &= U_2 - U_1 < 0 \\ \Delta U &= Q - W \quad (W = W^{by})\end{aligned}}$$

(first law)

True or False, the relative amounts of heat and work depend on how the process is carried out?

True – process vars are path dependent. BUT $Q - W = \Delta U$ indep. of path!

Consider the burning of kerosene using the following three methods and describe the work done.



Method 1: Q↑, W↓. Most of energy transfered as heat, minimal work.

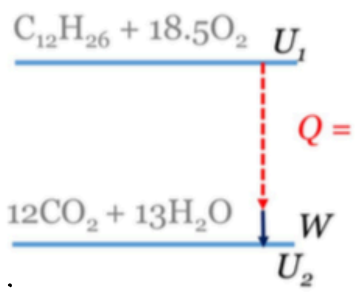
Method 2: Work done by expanding a piston.

Method 3: Q↓, W↑. Improved engineering reduces waste heat.

What is the term used to describe the amount of heat (Q) of the reaction?

(Max) amount of heat absorbed by syst. during reaction = Δ Enthalpy

Heat engines convert this to work.



ΔH (or $-\Delta H$) dep. on signs.

What is the energy density (in MJ/kg) of kerosene if its molar mass is 170.3 g.mol[-1]?

From before (combustion): $\Delta H = Q_{max} = -8084 \frac{kJ}{mol} \times \frac{1\ mol}{0.1703\ kg} \simeq 47.5 \frac{MJ}{kg}$

What are the units of energy density in terms of SI base units?

energy density = energy/vol $[=]$ $J/m^3 = kg \cdot \frac{m^2}{s^2} \cdot \frac{1}{m^3} = \boxed{kg \cdot m^{-1} s^{-2}}$ Base SI units for energy density

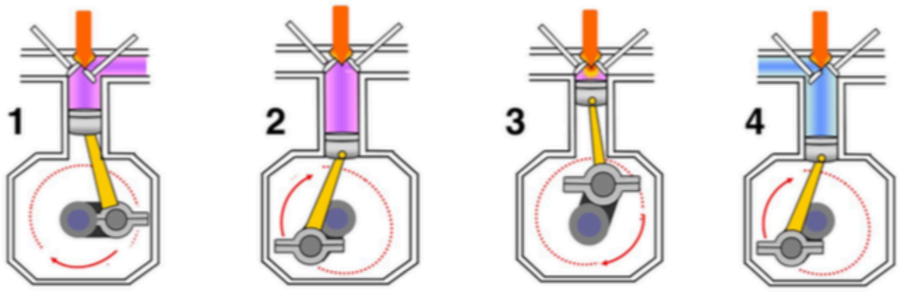
(we've been using specific energy $[=]$ J/kg

$= \frac{kg \cdot m^2}{s^2} \cdot \frac{1}{kg} = m^2 \cdot s^{-2}$ → base SI units for specific energy)

Otto engine

6.8.1 The four stroke Otto engine

To understand the *PV work* part of the energy transformation of this case study, we will take a quick diversion to discuss the common, four stroke *Otto engine*, named after its German inventor, Nikolaus Otto[22] and the four movements (strokes) required to complete one cycle (Figure 22).



Intake stroke: intake valve opens and gas-air mixture enters cylinder

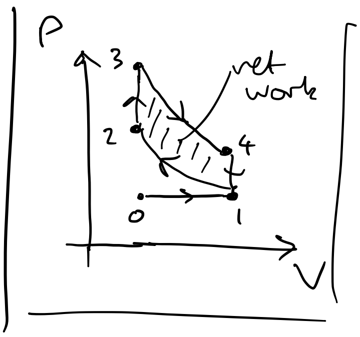
Compression stroke: intake and exhaust valves closed. Gas-air mixture compressed (ratio V_i/V_f = 8 to10)

Power stroke: Spark plug fires. Compressed gas-air ignites and expands (T>750°C). Piston forced down

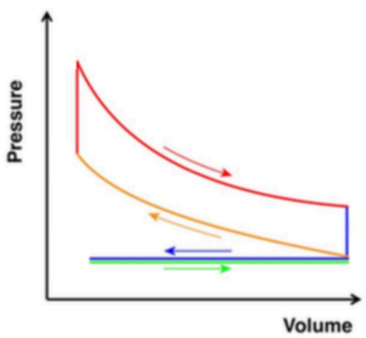
Exhaust stroke: Exhaust valve opens and combusted products are swept out of cylinder.

Figure 22: The four strokes of the Otto engine. A car generally runs on 4, 6, or 8 cylinders.

Typical sketch.



Throughout the Otto cycle, work is performed under compression and expansion, which can be characterised by the area within the pressure-volume diagram (Figure 23) (recall Section 6.5.1). Heat is transferred to and lost by the gas.



0-1 Fuel-air mixture is drawn in

1-2 Fuel-air mixture is compressed: V decreases, P increases and T increases; Work is done on the gas

2-3 Heat released by combustion is transferred to air plus combustion gases. T and P increase, V is constant

3-4 The gas expands adiabatically and does work on the piston (piston movement rotates crankshaft and wheels)

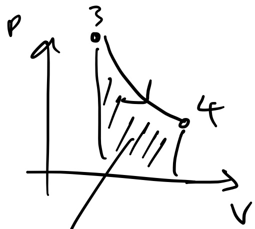
4-1 Waste heat removed

1-0 Exhaust gases removed

Key

Figure 23: Pressure-volume diagram of the Otto cycle. The movements of a piston create a PV-work loop. This is an idealised diagram and approximates the real process. The gases involved are air and air + combustion products.

ie 3-4



adiabatic work (not net work!)

Recall the equation from Section 6.5.3 that describes the work done due to adiabatic compression or expansion.

$$W^{adiabatic} = \underbrace{\int_{V_1}^{V_2} p\,dV}_{\text{general}} = \underbrace{\left(\frac{P_iV_i - P_fV_f}{\gamma - 1}\right)}_{\text{adiabatic}} ; \quad \gamma = \frac{c_p}{c_v} = 1.4$$

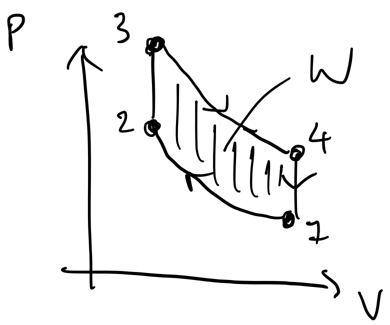
[22] It took Otto 14 yrs to successfully create a compressed charge internal combustion engine in 1896. He found a way to layer the fuel mixture into the cylinder resulting in a progressive, as opposed to explosive, combustion..

An engine is operating under the following conditions. Assuming this follows the Otto cycle, calculate the Work of compression, Work of expansion, and Net work. Also calculate the heat transferred to and lost by the gas.

compression → expansion → exhaust →

	1	2	3	4
Temperature, K	323	742	1173	511
Pressure, Pa	1.1×10^5	2.02×10^6	3.19×10^6	1.74×10^5
Volume, m³	8.0×10^{-4}	1.0×10^{-4}	1.0×10^{-4}	8.0×10^{-4}
Compression ratio = 8	Cylinder volume = 0.8L	c_v = 20.78 Jmol-1K-1	n=0.0327	

Note: check for consistent units and calculate any missing P, T, V, and n using Ideal Gas Law; PV = nRT



(assume $\gamma = 1.4$).

1-2: either use $V_2 = \frac{nRT_2}{P_2}$

or $V_2 = \frac{V_1}{8}$ ← compression ratio

$\Rightarrow V_2 = 1.0 \times 10^{-4}\ m^3$

2-3: $V_3 = V_2$

3-4: $V_4 = \frac{nRT_4}{P_4}$

$= \frac{0.0327 \times 8.314 \times 511}{1.74 \times 10^5}$

$\approx 8.0 \times 10^{-4}\ m^3$

Calculate the thermal efficiency of the engine.

assume 1-2 & 3-4 adiabatic

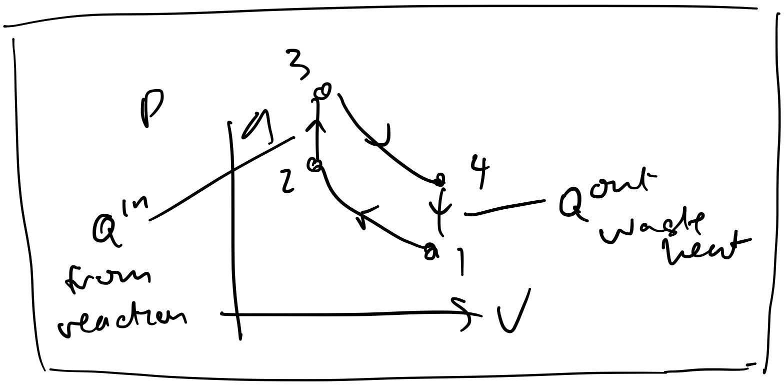
$$W_{1\to2} = \left(\frac{V_1P_1 - V_2P_2}{\gamma - 1}\right) = \frac{8 \times 11 - 202}{1.4 - 1} = -285\ J$$

$$W_{3\to4} = \left(\frac{V_3P_3 - V_4P_4}{\gamma - 1}\right) = \frac{319 - 8 \times 17.4}{0.4}$$

$$= +450\ J$$

$$W_{Net} = 450 - 285$$
$$= 165\ J$$

Heat input & output



- $Q^{2\to3} = m \cdot C_V \, \Delta T^{(3-2)}$

$$= \underbrace{0.0327 \text{ mol}}_{\text{amount}} \times 20.78 \frac{J}{mol \cdot K} \times \overset{T_3 - T_2}{(1173 - 742)}$$

$$\approx \underline{293 J} \quad (+\text{ve in} \Rightarrow Q^{in} = Q^{2\to3})$$

- $Q^{4\to3} = m \cdot C_V \, \Delta T^{(1-4)}$

$$= 0.0327 \times 20.78 \times (323 - 511)$$

$$= \underline{-128 J} \quad (-\text{ve in i.e. +ve out}) \quad \underline{Q^{out} = 128 J}$$

Efficiency

$$\eta = \frac{W^{out}}{Q^{in}} = \frac{165}{293} \approx 56\%$$

OR, equivalently

$$\eta = 1 - \frac{Q^{out}}{Q^{in}} = 1 - \frac{128}{293} \approx 56\%$$