Lecture 12 : Combustion engines & Otto cycles

- application of ideas to:

$\boxed{\text{chemical energy} \rightarrow \text{heat} \rightarrow \text{work}}$

- Introduce Otto cycle & Otto engine
  - ↳ ideal gas in piston

Example questions

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:

+ calculate work for each stage
& hence overall work.

2.9 Case study: Combustion engines and Otto cycles

L12

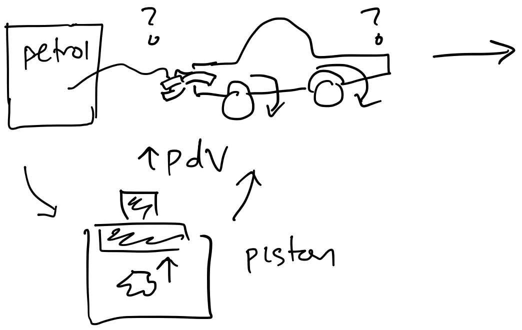
Problem background

In this case study we consider the basic ideas behind **combustion engines** i.e. the process of transforming: chemical energy → heat → work → kinetic energy.

A key part of this case study is learning about the **Otto cycle** which is the basis of the simple four stroke **Otto engine**, named after its inventor Nikolaus Otto.

~ took ~14 yrs.
'controlled combustion'

Concepts:



This course

Chemical energy to heat
(combustion, enthalpy, heat capacity)

↓

Heat to work
(heat capacity, PV diagrams, otto cycle, thermal efficiency)

↓

eg mechanical engineering

PV work to movement of crankshaft & drivetrain in car rockets & jets!

Fuel combustion and work extraction

We will assume our car runs on...kerosene! Let's calculate the enthalpy of combustion, the energy density etc, and then consider some different hypothetical methods of burning kerosene and extracting work.

1. Enthalpy of combustion

→ Combustion of kerosene:

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

$\Delta H_f^\circ = -353.5$ kJ/mol

table in course book.

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

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

$$\approx -8084 \text{ kJ (per mol)}$$

(exothermic, $\Delta H < 0$)

Some questions

Consider the following questions:

1. What is the energy source for the heat released in a chemical reaction?
2. What is the term used to describe the 'amount of heat' of the reaction?
3. Where does the energy go when heat is absorbed in a chemical process (i.e. in endothermic reactions)?
4. If energy is released as heat and work, what happens to the internal energy U.
5. True or False: internal energy does not depend on P, T and V?
6. True or False: internal energy cannot be measured directly, however ΔU can be?
7. What are the units of energy density in terms of SI base units?

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1. Internal energy – stored in/released from chemical bonds etc.
2. ΔH (change in enthalpy/enthalpy of reaction) → assuming constant pressure
3. Internal energy – stored in chemical bonds etc.
4. $\Delta U = W^{on} + Q^{in}$ if both <0 $\Rightarrow$ $\Delta U < 0$
5. False (eg $dU = -pdV + TdS$)
6. True (alway relative to a reference)
7. Energy density = energy/volume $[=]$ $\frac{J}{m^3} = kg \cdot \frac{m^2}{s^2} \cdot \frac{1}{m^3} = kg/m \cdot s^2$

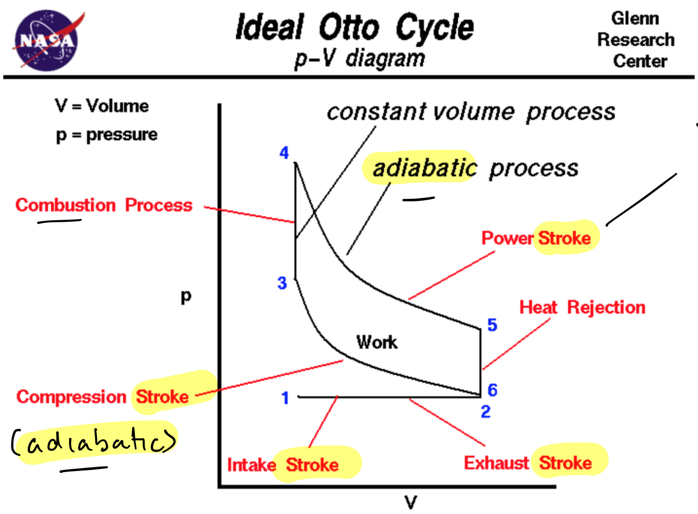
↳ (we've actually been using specific energy $[=]$ $J/kg = \cancel{kg} \cdot \frac{m^2}{s^2} \cdot \frac{1}{\cancel{kg}} = \frac{m^2}{s^2}$)

The Otto cycle and Otto engine

To understand in more detail how the heat released by combustion is converted into 'PV work', we look here at one of the simplest combustion engine types: the **Otto engine**. This operates according to...a (four stroke) **Otto cycle**. We assume this contains an *ideal gas*.

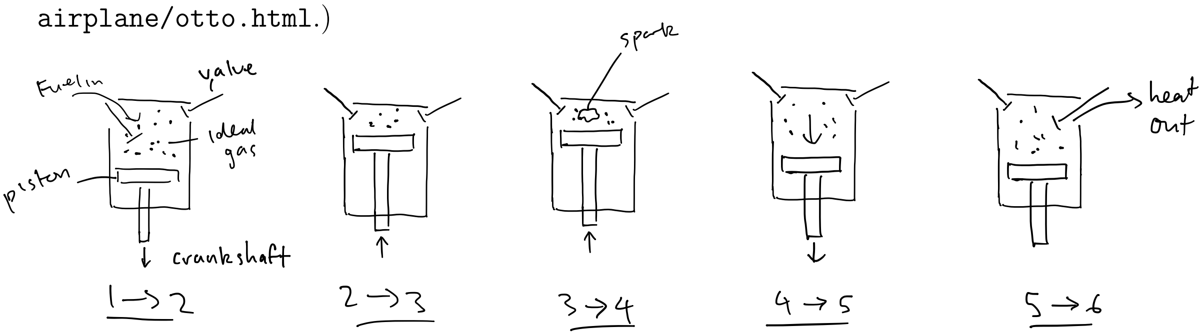
↳ NOT Carnot cycle (Otto is actually practical!)

A super glossy illustration of the Otto cycle is shown below.



'stroke': piston moves from top to bottom or vice-versa.

Figure 16: The ideal Otto cycle (From `https://www.grc.nasa.gov/www/k-12/airplane/otto.html`.)



Recall the expression for the *work done during adiabatic processes*:

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

Final calculations and 'conclusions'

Suppose our engine operates according to an Otto cycle under the conditions given in Table 5 below.

compression → combustion → power → heat rejection →

	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}			
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

$R = 8.314\ J/mol.K$

Table 5: Hypothetical Otto cycle data. (From notes by Thor Besier.)

Focus on 2 key 'strokes'

1→2
3→4

We can calculate the work of compression, the work of expansion and the net work done. We can also calculate the heat transferred to and lost by the gas, and hence calculate the $\boxed{\text{thermal efficiency}}$ of the engine.

• Table entries: volume

1→2: Either $PV = nRT$

OR $V_2 = \frac{1}{8} V_1$ ← compression ratio

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

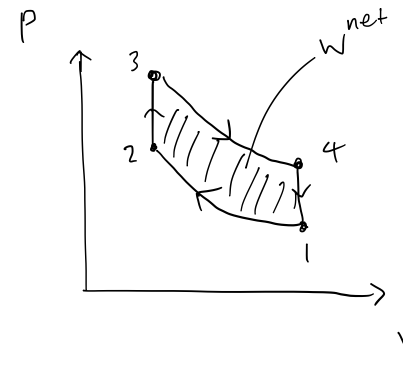
2→3: $V_3 = V_2$ (constant volume)

3→4: Either $V_4 = V_1$ or $PV = nRT$

fun: $V_4 = \frac{nRT_4}{P_4} = \frac{0.0327\ \cancel{mol} \times 8.314\ \cancel{J}/\cancel{mol \cdot K} \times 511\ \cancel{K}}{1.1 \times 10^5\ \cancel{J}/m^3}$

$\approx 8.0 \times 10^{-4}\ m^3 = V_1$ ✓

(Note: 1 Pa = 1 J/m³)



• Work? 1→2 & 3→4 } assumed adiabatic →

↳ Note though: $\Delta H_{1\to2} \neq Q$ ($P \neq$ const.)

↳ $dH = \underbrace{dU + PdV}_{=0\ \text{adiabatic}} + VdP$

$\Rightarrow dH = VdP \Rightarrow \underbrace{\Delta H = \int V dP}_{\text{adiabatic}}$.

Work strokes:

$$W^{by}_{1\to 2} = \left(\frac{V_1P_1 - V_2P_2}{\gamma - 1}\right) = \frac{\overbrace{8\times10^{-4}}^{m^3}\times \overbrace{1.1\times10^5}^{1\,Pa = 1\,J/m^3} - 1.0\times10^{-4}\times 2.02\times10^6}{1.4-1}$$

$$\approx \boxed{-285\ J} \quad \text{(−ve work by, since compression)}$$

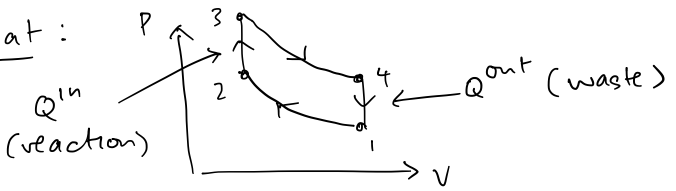
$$W^{by}_{3\to 4} = \left(\frac{V_3P_3 - V_4P_4}{\gamma - 1}\right) = \frac{1.0\times10^{-4}\times 3.19\times10^6 - 8\times10^{-4}\times 1.74\times10^5}{1.4-1}$$

$$\approx \boxed{+450\ J} \quad \text{(+ve work by, since expansion).}$$

$$\Rightarrow W^{by}_{Net} = W^{by}_{1-2} + W^{by}_{3\to4} = -285 + 450\ J$$

$$= \boxed{165\ J}$$

Heat:



(warning: $\Delta H_{1\to2} \neq Q$ again.)

$$Q_{2\to3} = m\cdot C_V\cdot \Delta T_{(3-2)} = 0.0327\ mol \times 20.78\ \frac{J}{mol\cdot K} \times (1173-742)\ K$$

note: constant volume here.

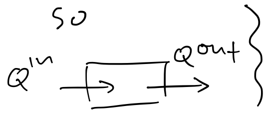
$$\approx \boxed{293\ J} \quad \text{(+ve heat into engine)}$$

$$Q_{4\to1} = m\cdot C_V\cdot\Delta T_{(1-4)} = 0.0327\times 20.78\times(323-511)$$

$$= \boxed{-128\ J} \quad \text{(−ve heat into engine).}$$

Efficiency?

so



$$\left.\begin{aligned} Q^{in} &= 293\,J \\ Q^{out} &= 128\,J \end{aligned}\right\}$$

Efficiency:

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

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

(equiv.)

(Bonus:
can show ideal eff. of Otto
$= 1 - \frac{1}{r^{\gamma-1}}$, r: compression ratio
$= 1 - \frac{1}{8^{0.4}} \approx 56\%$ ✓)

End L12