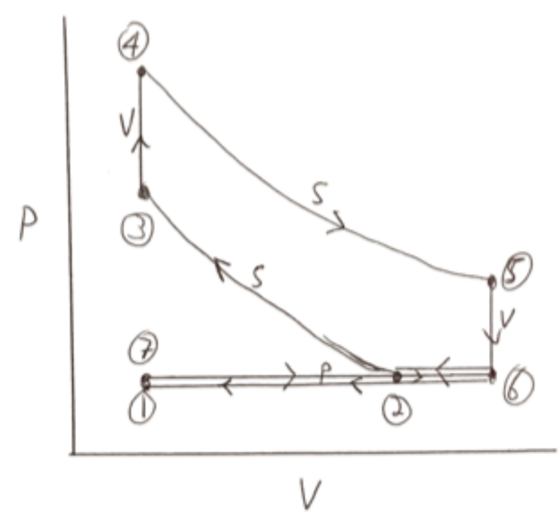
Chemical Engineering Thermodynamics
Quiz 2 January 22, 2020

The Toyota Prius hybrid engine introduced the concept of using an Atkinson cycle (or Complete Expansion cycle) engine coupled with an electric motor in a hybrid design. The Atkinson engine has a larger power stroke (3 to 5 below) compared to the compression stroke (2 to 3 below). These strokes are equal in volume change for a traditional four-cycle Otto engine.
Prof. Roney at USC (http://ronney.usc.edu/AME436/Lecture8/?C=M;O=A) provides the following specification for an Atkinson engine:

Stroke	Process	Name	Constant	Mass in cylinder	Other info
A	$1 \rightarrow 2$	Intake	P	Increases	$P_2 = P_1$; $T_2 = T_1$ At 1, exhaust valve opens, intake valve closes
B	$2 \rightarrow 3$	Compression	s	Constant	At 2, intake valve closes
---	$3 \rightarrow 4$	Combustion	P	Constant	At 3, fuel is injected
C	$4 \rightarrow 5$	Expansion	s	Constant	
---	$5 \rightarrow 6$	Blowdown	V	Decreases	At 5, exhaust valve opens, exhaust gas "blows down" as with Otto
D	$6 \rightarrow 7$	Exhaust	P	Decreases	

Below is a sketch of the *P*/*V* behavior in this engine. Notice that 2 to 3 has a smaller ΔV compared to 4 to 5. The length of 1 to 2 decides the amount of fuel consumed by a cylinder in the four cycles. Steps 4 to 5 determine the work output (steps 2 to 4 consumes work in compression). The advantage of the Atkinson engine is that it returns to the intake manifold the fuel taken in from 2 to 6 in the intake cycle during the first part of the compression cycle (6 to 2).
V = Isochoric; S = Adiabatic reversible; P = Isobaric.



Consider that the material in the cylinder is 10% isooctane and 90% air with $\boldsymbol{C_p = 5.4R}$.
Ignore the increase in number of moles with combustion.

a) ***Fill in the table below*** (grey areas cannot be solved). (60 points ~2 pts each) assuming an ideal gas.

b) -***Calculate the efficiency*** of this engine (net work/enthalpy input) if the fuel/air mixture had a combustion enthalpy of 22.4 kJ/mole (accounting for 10% isooctane in air) ignoring the work from 1 to 2.
-Also ***calculate the efficiency*** as the ***net*** work output divided by the net enthalpy input ignoring the work from 1 to 2. (The net work includes both the wasted and used work.)
-***Compare*** these values with the normal value for efficiency of an Atkinson engine of 30 to 40%. Comment on how the added moles from combustion would impact the efficiency (13.5 moles in 17 moles out $C_8H_{18} + 12.5\ O_2 \Rightarrow 8CO_2 + 9\ H_2O$).

c) The Atkinson engine has high efficiency but low power density (power per engine mass). ***Comment*** on why this engine might be useful in a Hybrid vehicle.

	Intake (Mass Changes)	Compression	Combustion	Expansion	**Blowdown (Mass Changes)**	**Exhaust (Mass Changes)**
	isobaric	adibatic, rev	isochoric	adibatic, rev	isochoric	isobaric
Stage	1-2	2-3	3-4	4-5	5-6	6-7
Ti K	313	313		750		
Tf K	313		750			313
Pi MPa	0.1	0.1				0.1
Pf Mpa	0.1				0.1	0.1
*V*i cm3	100	1000	100	100	1300	1300
*V*f cm3	1000	100	100	1300	1300	100
moles i						
moles f						
W_{EC} kJ/mole						
ΔH kJ/mole						
ΔU kJ/mole						
Q kJ/mole						

1 atmosphere is 14.7 psi, 1.01 bar, 0.101 MPa, 760 mmHg, 29.9 inHg

Gas Constant, R

$= 8.31447$ J/mole-K $= 8.31447$ cm^3-MPa/mole-K $= 8.31447$ m^3-Pa/mole-K

$= 8{,}314.47$ cm^3-kPa/mole-K $= 83.1447$ cm^3-bar/mole-K $= 1.9859$ Btu/lbmole-R (see note 1)

$= 82.057$ cm^3-atm/mole-K $= 1.9872$ cal/mole-K (see note 2) $= 10.731$ ft^3-psia/lbmole-R

Process Type	Work Formula (ig)
Isothermal	$W_{EC} = -\int P dV = -RT\int \frac{dV}{V} = -RT\ln\frac{V_2}{V_1}$ (ig)
Isobaric	$W_{EC} = -\int P dV = -P(V_2 - V_1)$ (ig)
Adiabatic and reversible	$W_{EC} = -\int P dV = -\int \text{const}\frac{dV}{V^{(C_P/C_V)}}$ (*ig) or $\Delta U = C_V(T_2 - T_1) = W_{EC}$ (*ig) $\frac{T_2}{T_1} = \left(\frac{P_2}{P_1}\right)^{(R/C_P)} = \left(\frac{V_1}{V_2}\right)^{(R/C_V)}$ (*ig)

$Q_{rev} = \Delta U$ for isochoric (constant volume) 4.17

$dU = C_v\, dT$ for isochoric (constant volume)

$C_p = C_v + R$ (exact for ideal gas)

$\Delta H = \Delta U + \Delta(PV) = \Delta U + R(\Delta T)$ (exact for ideal gas)

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	Intake (Mass Changes)	Compression	Combustion	Expansion	Blowdown (Mass Changes)	Exhaust (Mass Changes)
	isobaric	adibatic, rev	isochoric	adibatic, rev	isochoric	isobaric
Stage	1-2	2-3	3-4	4-5	5-6	6-7
T i K	313	313	**528**	750	**419**	
T f K	313	**528**	750	**419**		313
P i MPa	0.1	0.1	**1.69**	**2.4**	**0.103**	0.1
P f Mpa	0.1	**1.69**	**2.4**	**0.103**	0.1	0.1
V i cm3	100	1000	100	100	1300	1300
V f cm3	1000	100	100	1300	1300	100
moles i		**0.0384**	**0.0384**	**0.0384**	**0.0384**	
moles f	**0.0384**	**0.0384**	**0.0384**	**0.0384**		
W_{EC} kJ/mole		**7.87**	**0**	**-12.1**		
ΔH kJ/mole		**9.65**	**9.96**	**-14.9**		
ΔU kJ/mole		**7.87**	**8.12**	**-12.1**		
Q kJ/mole		**0**	**8.12**	**0**		

b) Efficiency = (12.1 kJ/mole – 7.87 kJ/mole)/22.4 kJ/mole = 0.189 or 18.9 % efficiency.
Efficiency = Net Work/Enthapy input = (12.1 kJ/mole – 7.87 kJ/mole)/(9.65 + 9.96) kJ/mole = 0.216 or 21.6% efficiency.
Typically, the Atkinson Engine has an efficiency of about 30-40%.

c) In a hybrid vehicle the electric motor adds torque when it is needed for acceleration and climbing hills. Coupling the Atkinson with high efficiency and the added power from the electric motor makes a functional high mileage car.

a) 1-2 $$n_2 = \frac{P_2 V_2}{R T_2} = \frac{0.1\,MPa\ 1000\,cm^3}{8.31\,\frac{cm^3 MPa}{K\,mol}\ 313\,K} = 0.0384 \text{ moles}$$

2-3 Adiabatic $Q = 0$ $$T_2 = T_1 \left(\frac{V_1}{V_2}\right)^{R/C_v} = 313K(10)^{1/4.4} = 528K$$

$$\Delta U = W_{EC} = \int C_v\, dT$$

$$= (4.4)\ 8.31 \frac{J}{mol\,K} (528K - 313K)$$

$$= 7.87\ kJ/mole$$

$$\Delta H = \Delta U \frac{5.4}{4.4} = 9.66\ kJ/mole$$

$$= \Delta U \left(\frac{C_p}{C_v}\right)$$

$$P_f = \frac{nRT}{V_f} = \frac{0.0384\,mole\ 8.31 \frac{J}{mol\,K}\ 528K}{100\,cm^3} = 1.69\,MPa$$

3-4 Isochoric

$$P_f = P_i\, T_f / T_i = 1.69\,MPa\ 750K/528K = 2.40\,MPa$$

$$W_{EC} = 0 \quad (\Delta V = 0)$$

$$\Delta U = Q = \int C_v\, dT = 4.4\left(8.31 \frac{J}{mol\,K}\right)(750K - 528K)$$

$$= 8.12\ kJ/mole$$

$$\Delta H = \Delta U \frac{C_p}{C_v} = 8.12\,kJ/mole\ \frac{5.4}{4.4} = 9.96\ kJ/mole$$

4-5 Adiabatic $$T_2 = T_1 (V_1/V_2)^{R/C_v} = 750K\left(\frac{100\,cm^3}{1300\,cm^3}\right)^{1/4.4} = 419K$$

$$P_f = nRT/V_f = 0.0384\,mol\left(8.31 \frac{MPa\,cm^3}{mol\,K}\right) 419K / 1300\,cm^3 = 0.103\,MPa$$

$$\Delta U = W_{EC} = \int C_v\, dT = 4.4\left(8.31 \frac{J}{mol\,K}\right)(419K - 750K) = -12.1\ kJ/mol$$

$$\Delta H = \frac{C_p}{C_v} \Delta U = -12.1 \frac{kJ}{mol}\ \frac{5.4}{4.4} = -14.9\ kJ/mole$$