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THE POWER CYCLES SELF STUDY MODULE-Otto and Diesel Cycles

Objective

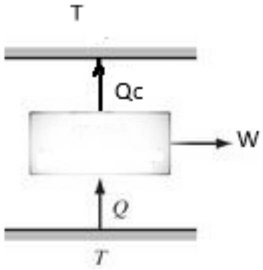
The objective of this module is to guide you in analyzing the power cycles. You will be able to differentiate the cycle efficiency from the process unit efficiency, you will learn about the energy conversion processes in general.

Reading assignment

Read Chapter 5 of Sandler's thermodynamics, 5th edition. Also read about other power cycles, such as the Steam engine, the Otto engine, the Diesel engine etc.

Remember

So far we have learned two perspectives of a power cycle. Let us first look at the general perspective of a power cycle. The general characteristics are:



1. The operation is cyclic, i.e. the process ends at the same state as it has started.
2. The cycle absorbs heat, Q_H, from the sink kept at constant T_H,
3. The cycle generates work, W
4. The cycle releases heat Q_C to the sink kept at constant temperature T_C. The cycle repeats itself.

Figure 1. The power cycle operating between a heat source at T_H and a heat sink operating at T_C

In this cycle the first law analysis reveals that

$\Delta U=Q_H-Q_C-W=0$ Because the operation is cyclic. Thus,

$W=Q_H-Q_C$ or, $Q_C= Q_H-W$

$\Delta S=0=\frac{Q_H}{T_H}-\frac{Q_C}{T_C}+S_{generated}$ (Self Test: Why is $\Delta S=0$?)

Substituting Q_C in terms of Q_H and W in the entropy balance yields

$0=\frac{Q_H}{T_H}-\frac{Q_H-W}{T_C}+S_{generated}$

If the cycle is reversible, i.e., $S_{gen}=0$, we obtain a relationship between the amount of work that we can obtain from this cycle in terms of the amount of the heat input and the difference between the source and the sink temperatures:

$$\eta=-\frac{W_H}{Q_H}=\frac{T_H-T_C}{T_H}$$

This general characteristics of a power cycle is reflected in the hypothetical Carnot cycle, shown below:

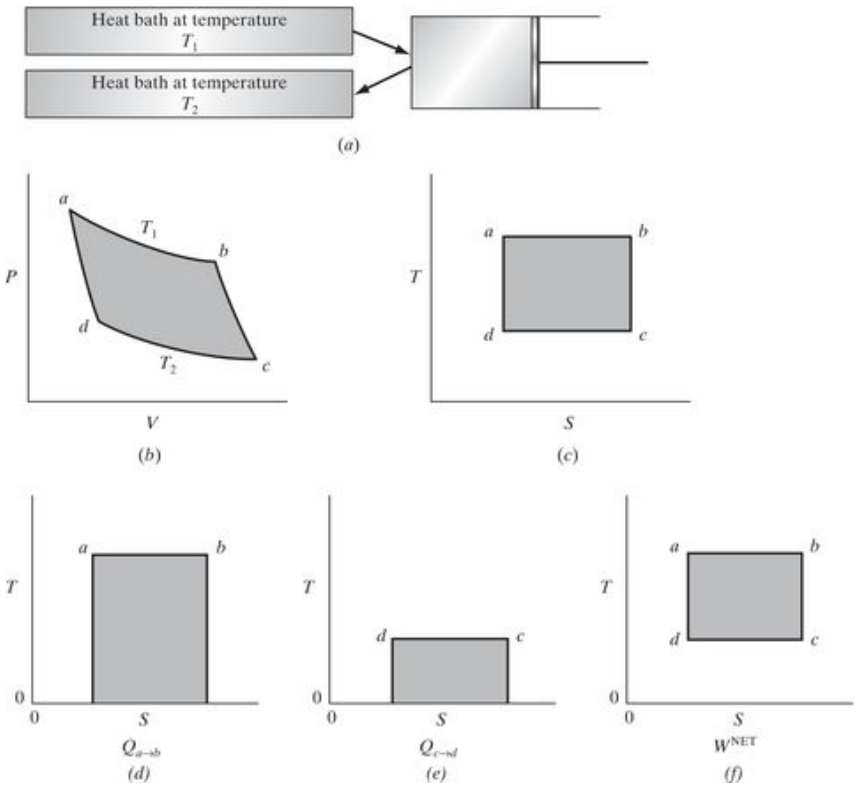


Figure 2. Sandler Figure 4.3-2 The Carnot Cycle and the heat and work interactions shown on a PV and TS diagrams.

The Internal Combustion Engines

The general perspectives of the power cycle will prevail through all of the power cycles. We will have a high temperature source, a low temperature sink and while heat flows from hot to cold, we can convert some of it to work. Now let us remember the thermodynamic landscape, we have four different independent variables, as seen in the sketch on the right side, P,V, T,S. In the Carnot cycle we have navigated in the T, S domain of the processes. The Carnot cycle followed a route with constant T, constant S, constant T, constant S, in other words, TSTS sequence. In this module, we will have two examples of the internal combustion engines.

The Diesel cycle

The Diesel Cycle has the following features:

Reversible adiabatic, i.e. isentropic compression of the fresh air, S

I. Constant pressure combustion, P

II. Reversible adiabatic, i.e. isentropic expansion, S

III. Constant volume exhaust, V

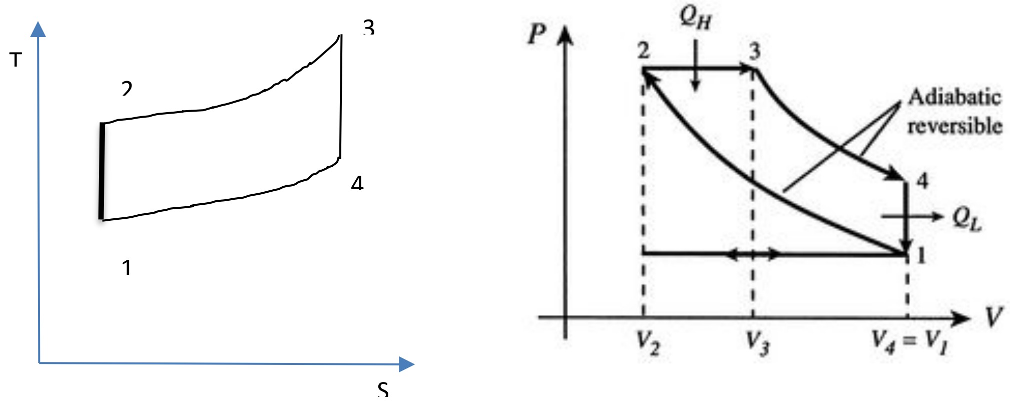


Figure 3. The Diesel cycle on a TS and a PV (web.mit.edu) diagram.

In the figure shown above, the horizontal line connecting to state 1 in the PV diagram corresponds to the intake of fresh air and the exhaust of the combustion gases. Now we will analyze they cycle step by step. We do not have to know much, when we know the initial state of the incoming air, atmospheric pressure and room temperature, and the heat input in the combustion zone, we can construct the complete cycle. Now we will design our own power cycle by selecting our own temperatures and pressures for this process. Let us start filling the table below for the states indicated in Figure 3 with the information that is already available.

State	**T (°C)**	**P (MPa)**	$\underline{V}$ **(m^3/mol)**	$\underline{S}$ **(J/mol-K)**
1	Ambient	Ambient	V_1	S_1
2				S_1
3				S_3
4			V_1	S_3

For the information we need to calculate, we will use the energy balance and entropy balance wherever necessary.

I. System is selected between states 1 and 2. Here the process is adiabatic and reversible, i.e., isentropic (Self test: Why do we make such approximations?). The entropy balance dictates that the final entropy is equal to the initial entropy. However, we need another state variable to determine the state 2. This state variable is the pressure, it comes from the engine design. For this example, the compression ratio is selected such that P_2/P_1 is 50. Now, knowing that the entropy change is zero, a ratio of the pressures, the fina temperature can be calculated from

$$\Delta S = n\, C_p \ln\left(\frac{T_2}{T_1}\right) - n\, R \ln\left(\frac{P_2}{P_1}\right)$$

II. System is selected between points 2 and 3. This is the combustion process at constant pressure. Combustion at constant pressure provides the heat input to the cycle. For a closed system running at constant pressure, the fisrt law simplifies to

$\Delta U = Q - P\Delta V$

$Q = \Delta U + P\Delta V$. Remembering that the the process is at constant pressure, one can write

$$Q = \Delta H = C_p^*(T_3 - T_2)$$

Therefore, if we know the rate of heat input, we can calculate T3.

III. The process analysis continues between states 3 and 4. This is the adiabatic and reversible expansion of the combustion gases. We know the state variables in state 3, this process is isentropic (why?) and we know the volume of state 4 (how?)

$$\Delta S = n\,C_v \ln\left(\frac{T_4}{T_3}\right) + n\,R \ln\left(\frac{V_4}{V_3}\right)$$

IV. Between points 4 and 1 the system exhausts the gases at constant volume.

Below, the table is partially filled for ambeint gas intake at state 1, and for a heat input of 1000 J/mol air between states 2 and 3. As an exercise, fill the table below for the missing values.

State	**T (°C)**	**P (MPa)**	**$\underline{V}$ (m^3/mol)**	**$\underline{S}$ (J/mol-K)**
1	25	0.1	0.02	S_1
2	630	5		S_1
3	664	5		S_3
4			0.02	S_3

Now you can calculate the the heat and work interactions of all of the process steps, and determine the cycle efficiency.

Fill the table below for the hypothetical cycle we constructed above:

Process step	ΔH(kJ/mol)	Q(kJ/mol)	W(kJ/mol)	ΔS(kJ/mol)
Constant pressure combustion				
Adiabatic expansion				
Exhaust/intake				
Adiabatic compression				
Overall cycle				

The Otto cycle

The Otto Cycle, the cycle for the gasoline engines, has the following features:

I. Reversible adiabatic, i.e. isentropic compression of the fresh air, S

IV. Constant volume combustion, V

V. Reversible adiabatic, i.e. isentropic expansion, S

VI. Constant volume exhaust, V

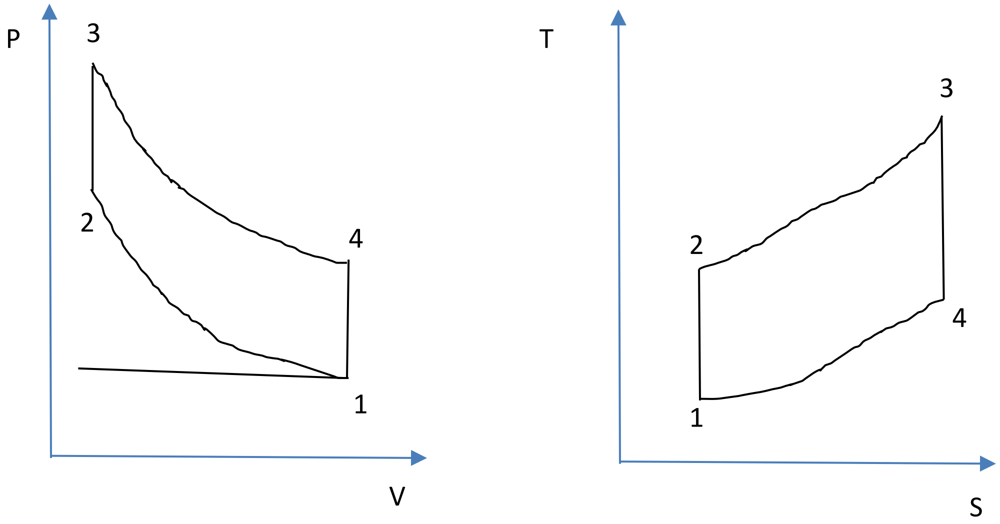


Figure 4. The Otto cycle on a TS and a PV diagram.

In the figure shown above, the horizontal line connecting to state 1 in the PV diagram corresponds to the intake of fresh air and the exhaust of the combustion gases. Now we will analyze they cycle step by step. Similar to the Diesel cycle, we do not have to know much, when we know the initial state of the incoming air, atmospheric pressure and room temperature, and the heat input in the combustion zone, we can construct the complete cycle. Now we will design our own power cycle by selecting our own temperatures and pressures for this process. Let us start filling the table below for the states indicated in Figure 4 with the information that is already available. Notice that the volumes are the stame in the states 1 and 4. Also, the volumes of states 2 and 3 are the same.

State	**T (°C)**	**P (MPa)**	**$\underline{V}$ (m^3/mol)**	**$\underline{S}$ (J/mol-K)**
1	Ambient	Ambient	V_1	S_1
2			V_2	S_1
3			V_2	S_3
4			V_1	S_3

For the information we need to calculate, we will use the energy balance and entropy balance wherever necessary.

I. System is selected between states 1 and 2. Here the process is adiabatic and reversible, i.e., isentropic (Self test: Why do we make such approximations?). The entropy balance dictates that the final entropy is equal to the initial entropy. However, we need another state variable to determine the state 2. This state variable is the self ignition temperature of the gasoline. We have to maintain the temperature at state 2 below the self ignition temperature of gasoline ~280 °C. If this is our **design constraint,** we should determine the pressure such that the temperatures are below this value. Now, knowing that the entropy change is zero, a ratio of the temperatures, the final pressure can be calculated from

$$\Delta S = n\, C_p \ln\left(\frac{T_2}{T_1}\right) - n\, R \ln\left(\frac{P_2}{P_1}\right)$$

II. System is selected between points 2 and 3. This is the combustion process at constant volume. Combustion at constant volume provides the heat input to the cycle. For a closed system running at constant pressure, the first law simplifies to ΔU=Q

$$Q = \Delta U = C_v^*(T_3 - T_2)$$

Therefore, if we know the rate of heat input, we can calculate T_3.

III. The process analysis continues between states 3 and 4. This is the adiabatic and reversible expansion of the combustion gases. We know the state variables in state 3, this process is isentropic (why?) and we know the volume of state 4 (how?)

$$\Delta S = n\, C_v \ln\left(\frac{T_4}{T_3}\right) + n\, R \ln\left(\frac{V_4}{V_3}\right)$$

IV. Between points 4 and 1 the system exhausts the gases at constant volume.

Below, the table is partially filled for ambeint gas intake at state 1, and for a heat input of 1000 J/mol air between states 2 and 3. As an exercise, fill the table below for the missing values.

State	**T (°C)**	**P (MPa)**	**$\underline{V}$ (m^3/mol)**	**$\underline{S}$ (J/mol-K)**
1	25	0.1		S_1
2	227	0.6		S_1
3	275	0.7		S_3
4				S_3

Now you can calculate the the heat and work interactions of all of the process steps, and determine the cycle efficiency.

Fill the table below with the values for the hypothetical cycle we constructed above:

Process step	ΔH(kJ/mol)	Q(kJ/mol)	W(kJ/mol)	ΔS(kJ/mol)
Constant pressure combustion				
Adiabatic expansion				
Exhaust/intake				
Adiabatic compression				
Overall cycle				

After filling the table with the relevant information and performing the necessary calculations, determine the cycle efficiency

$\eta=-W_{net}/Q_H$

Compare this efficiency with that of the Carnot cycle efficiency. Then discuss your results.

$\eta=\frac{T_H-T_C}{T_H}$

Calculate

1. Determine the effect of the ratio P_2/P_1 on the cycle efficiency for a Diesel cycle where the heat input is given as 1000 J/mol. Select different values for P_2/P_1 and determine the

cycle efficiency, then plot the efficiency as a function of P_2/P_1. Discuss whether there is a limit for the pressure ratio.

2. Determine the effect of changing the heat input on the Diesel cycle efficiency, for a given P_2/P_1. Select different values for the heat input and determine the cycle efficiency, then plot the efficiency as a function of heat input. How can you change the heat input to a Diesel engine? Is there a limit that you can change the heat input?
3. Repeat problem 1 for Otto engine.
4. Repeat problem 2 for Otto engine.

Evaluate yourself

What are the muddiest points, what are the points that you understood well? What should you do to clarify the parts that are not at all clear.

Why do we use TS diagrams for analyzing power cycles?

Why do we use PV diagrams for analyzing power cycles?

Why do we assume reversible operation in cycle analysis?