6. Cyclic Processes: Stringing Paths Together

A cycle is a process, or string of processes, that returns the system to its original state upon completion. The key is returning the system to its original state because that means the change in any property for a cyclic process is identically zero. That means $\Delta H = 0$, $\Delta U = 0$, $\Delta KE = 0$, $\Delta PE = 0$, $\Delta T = 0$, $\Delta p = 0$, etc. It’s now critically important that you remember $W$ and $Q$ are not properties. This means the work and heat transfer for a cyclic process are not zero. These two facts highlight the beauty of cyclic processes—their operation can result in the (partial) transformation of energy supplied by a temperature gradient (heat transfer) to mechanical work.

Not only are the work and heat transfer for a cyclic process not zero, but the 1st Law shows us that the net work of the cycle must equal the net heat transfer of the cycle.

An example of a cycle that transforms some of the energy supplied by a temperature difference to mechanical work is shown in Figure 6-1. It’s for an ideal gas (air) and consists of a constant pressure expansion, a constant volume pressure decrease, and an isothermal compression. There is no mass entering or exiting the system, and we can safely ignore $\Delta KE$ and $\Delta PE$. The 1st Law for each process in this cycle is therefore:
You should be able to look at the figure above and decide which paths have \( W \) associated with them and which do not. You also ought to be able to determine whether the sign of each \( W \) term is positive or negative. But what about \( Q \)?

To determine where \( Q \) occurs, and in which direction, we can analyze each of the three paths with the 1st Law:

1. **Constant pressure expansion.** By the ideal gas law, we know temperature must increase for expansion (i.e., volume increase) at constant pressure. \( \Delta U \) must also increase because internal energy depends only on \( T \) for an ideal gas like air. We can now determine the direction of \( Q \) from the 1st Law:

2. **Constant volume pressure decrease.** By the ideal gas law, we know temperature must decrease for a constant volume pressure decrease. \( \Delta U \) must also decrease because internal energy depends only on \( T \) for an ideal gas like air. We can now determine \( Q \) from the 1st Law:
3. Isothermal compression. \( \Delta U \) must be zero because \( \Delta T \) is zero and internal energy depends only on \( T \) for an ideal gas like air. We can now determine \( Q \) from the 1st Law:

\[
\Delta U = Q - W
\]

This same thought process should be applied to any cycle. An example is provided in the next section.

6.1 IC engines

Most of you are probably unfamiliar with the piston-cylinder combination that makes up an internal combustion (IC) engine and how it works. Examples of its operation can be seen at www.animatedengines.com. Note the repetitive, or cyclic, nature of operation. Cyclic operation means the system state returns to its original condition after one pass through the cycle. It also means that the individual process are not steady state.

You should know enough about IC engines to know that mass (fuel and air) flows in and exhaust (air and combustion products) flows out. You should also know that IC engines produce mechanical power via torque and rotational speed and reject heat (don’t put your hand on any of the high temperature surfaces!).

Using information from the paragraph above and the video, we can draw an EFD for an IC engine (Figure 6-2).
Note the presence of **energy transfer associated with mass flow entering** through the intake valve and **exiting** through the exhaust valve. Also note **energy transfer due to a temperature difference**, and rotational energy transfer associated with the crankshaft rotation (**engine output power**). How did we know these four contributions were present? When watching the engine animation, we saw the crankshaft rotating so we know there was rotational power produced by the engine. We also know engine surfaces are hot so there must be heat transfer. Finally, we can see from the animations that air/fuel enters the engine and air/combustion products exit so there must be energy transfer associated with mass flow.

[There could be energy accumulation inside our cyclic system if we analyze it during warmup, or energy loss if we analyze it after shutdown. But we won’t worry about that.]

A question to be asked is “What part of that diagram is the system?” You might not get this one right the first time because there is something flowing—the fuel/air that is transformed to
air/combustion products. The problem is that the flows are nowhere near steady, nor are the states of fuel and air inside the engine itself. How then do we relate the energy through the hot engine surfaces and power to the crankshaft to the combustion of fuel and air? We make modeling approximations.

The first approximation is to replace the air/fuel/combustion products with just air. We can do this because (i) the typical air-to-fuel ratio by mass (AFR) is about 15:1 so the fuel makes up only 7% of the total mass flow, and (ii) the combustion products, primarily CO₂ and H₂O, have thermodynamic properties fairly close to those of air.

Since we are ignoring the fuel and combustion products the next assumption is to artificially close the engine and pretend there is no mass flowing in or out. That approximation ignores any work associated with mass moving through the engine, but that turns out to be small compared to the expansion and contraction of the air during a typical IC engine cycle.

We now have to model the energy released when fuel and air combust to form products. We have eliminated any chemical energy corresponding to the fuel so we model the burning process as heat transfer from an external source.

Finally, we will pretend there are no hot surfaces on the outside of our engine (it is extremely well insulated) so the only heat transfer is the artificial one we use to model fuel-air combustion and product gas (air) expansion. Our EFD has become Figure 6-1.
If we consider our EFD further, we can see that the linearly moving piston is connected to the rotating crankshaft by the connecting rod. If there are no frictional or other losses between the piston and crankshaft motions, any work (or power) produced by the piston movement must be transferred out of the engine via the crankshaft rotation.

Given these modeling assumptions all we need do is compute the work related to the piston motion to find that produced by the engine. Again, if there are no frictional losses due to piston-cylinder wall and piston ring-cylinder wall interactions then the work associated with piston motion is equal to that resulting from the gas expansion and compression. How do we compute that? We model the gas expansion/compression using familiar Thermodynamic paths and make sure that whatever paths we choose result in a cycle, i.e. the air returns to its initial state.

To start, consider the pressure-volume cycle shown in Figure 6-4. It’s representative of a two-stroke Diesel engine. Don’t worry about the numbers and letters for now, we’re going to
build a model of this cycle using isothermal, isobaric and isochoric processes.

![Figure 6-4. pV diagram for two stroke cycle diesel engine (mechtech.blogspot.com).]

We’ll begin by modeling the process from state 2 to state 5 using an isothermal compression path. The process between 5 and 6 is best described by a constant volume pressure rise followed by a constant volume expansion. If we ignore the small dog-leg between 6 and 2 we can approximate that path as another isothermal process. Finally, there is a short vertical path at 2 that we’ll model as isochoric. Our model cycle is shown in Figure 6-5.

![Figure 6-5. pV diagram for model of two stroke cycle diesel engine]
We have removed the inlet and outlet so those energy flow terms in the 1st Law are zero. In addition, we are most interested in the behavior along each of the five paths so we integrate the 1st Law with respect to time. We then need to evaluate only $Q$, $\Delta U$ and $W$ for each path.

The constant volume temperature rise and constant volume temperature fall both have $W = 0$. Consequently, $Q = \Delta U$ in each case. From above we determined that $\Delta U > 0$, $W < 0$ and $Q > 0$ for the constant pressure process. The remaining two paths, both isothermal, must have $\Delta U = 0$ so $W = Q$. We have $W < 0$ for the compression and $W > 0$ for the expansion with $W = mRT \ln(V_{final} / V_{initial})$. 
6.2 Examples

6.2.1 Turbofan engine

Consider the aircraft gas turbine turbofan engine shown below. Assume that the high pressure turbine drives the compressor and the low pressure turbine drives the fan. Also assume level flight and that the speed is low enough to ignore kinetic energy changes.

a) Calculate the specific work and heat transfer interactions for each of the four rotating components. Report all answers in kJ/kg.

b) In addition, find the specific heat transfer supplied in the combustor. Report all answers in kJ/kg.