**AGENDA:**

I. Introduction to Thermodynamics
II. First Law Efficiency
III. Second Law Efficiency
IV. Property Diagrams and Power Cycles
V. Additional Material, Terms, and Variables
VI. Practice Problems

## I. INTRODUCTION TO THERMODYNAMICS

Why study thermodynamics?

Much of thermodynamics concerns the transformation of heat into mechanical energy. At the heart of this transformation is the *heat engine*, a device that converts heat into mechanical energy (think about trying to convert heat to work directly). Regardless of whether the heat engine is a spark ignition engine, a natural gas-fired power plant, a nuclear reactor… the basic principles governing heat engines are the same and we will devote much of this week to understanding heat engines and their thermal (First Law), Carnot, and Second Law efficiencies.

Thermodynamics is useful for:

- Comparing different energy sources (efficiency, amount of fuel needed, pollution produced)
- As a tool for improving energy systems (analyze each part of power plant: pumps, heat exchangers, etc.)
- Analyzing alternative energy scenarios (ethanol, biodiesel, hydrogen)

Laws of thermodynamics, simplified:

- Zeroth: "You must play the game."
- First: "You can't win."
- Second: "You can't break even."
- Third: "You can't quit the game."

Laws of thermodynamics, actual:

- Zeroth: If two systems are both in thermal equilibrium with a third then they are in thermal equilibrium with each other.
- **First: The increase in internal energy of a closed system is equal to the heat supplied to the system minus work done by it.**
- **Second: The entropy of any isolated system never decreases. An isolated system evolves towards thermodynamic equilibrium — the state of maximum entropy of the system.**
- Third law of thermodynamics: The entropy of a system approaches a constant value as the temperature approaches absolute zero.

## II. FIRST LAW EFFICIENCY

The first law states that energy cannot be created or destroyed, but can be converted from one form to another. As an equation, this is simply:

$$E_{system} = 0 = E_{in} - E_{out}$$

Thermal energy can be increased within a system by adding thermal energy (heat) or by performing work in a system. For a closed system its change in energy will be the balance between the heat transferred *to* ($Q_{in}$) and the work done *on* ($W_{in}$) the system, and the heat transferred *from* ($Q_{out}$) and work done *by* ($W_{out}$) the system. As an equation, this can be expressed by:

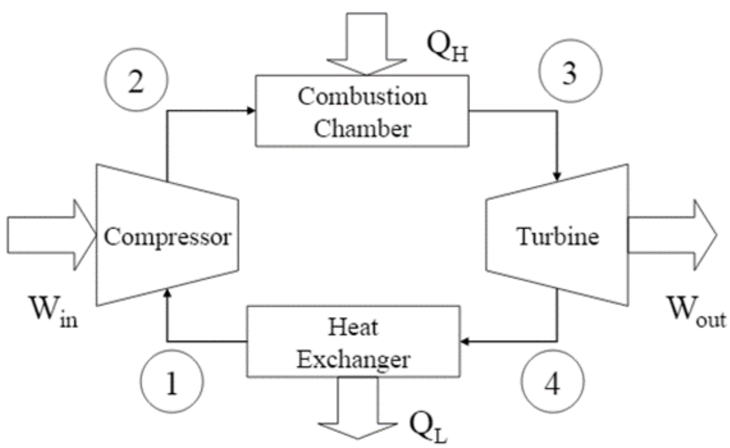
$$\Delta E = (Q_{in} - Q_{out}) - (W_{out} - W_{in}) = Q_{net,in} - W_{net,out}$$

or

$$W_{net,out} = Q_{in} - Q_{out}$$

A heat engine (think of it like a basic power plant) works as such:

1) Air is compressed ($W_{in}$);
2) Heat is added ($Q_H$ or $Q_{in}$);
3) Air turns turbine ($W_{out}$);
4) Exhaust gases cool ($Q_{out}$ or $Q_L$).




Thermal efficiency is defined as:

$$\text{Thermal efficiency} = \frac{\text{Net work output}}{\text{Total heat input}} \quad \text{or} \quad \eta_{th} = \frac{W_{net,out}}{Q_{in}}$$

Note from the diagram above that $Q_{in}$ is the heat absorbed from the high temperature source. Also note that you can substitute the $W_{net,out} = Q_{in} - Q_{out}$ equation into the $\eta_{th}$ definition.

$$\eta_{th} = \frac{W_{net,out}}{Q_{in}} = \frac{Q_{in} - Q_{out}}{Q_{in}} = 1 - \frac{Q_{ou}}{Q_{in}}$$

We are going to spend most of our time talking about heat engines that operate in a thermodynamic cycle (*e.g.*, a power plant) – most power producing devices do. Closed systems (*e.g.*, a steam power plant) have a working fluid (*e.g.*, water or air), and the heat is transferred to and from this fluid as it cycles through the system. In open systems (*e.g.*, an internal combustion engine), the working fluid (*e.g.*, air) is continuously brought in from outside the system and released as exhaust outside the system.

## III. SECOND LAW EFFICIENCY

The second law states that, due to the increase in entropy, heat cannot be converted to work without creating some waste heat. There due important efficiency equations with respect to this concept:

1. *Carnot Efficiency*
   Carnot efficiency is the theoretical maximum efficiency that a heat engine can achieve operating between hot and cold reservoirs with temperatures $T_H$ and $T_L$, respectively:

$$\eta_c = \frac{T_H - T_L}{T_H} = 1 - \frac{T_L}{T_H}$$

   The temperatures here should be in Kelvin → K = ºC + 273.15 or Rankin = 460 + ºF.

2. *Second Law Efficiency*
   Second Law efficiency is a measure of how much of the theoretical maximum (Carnot) you achieve, or in other words, a comparison of the system's thermal efficiency to the maximum possible efficiency. The Second Law efficiency will always be between the Carnot and First Law efficiencies.

$$\eta_s = \frac{\eta_{th}}{\eta_c}$$

## IV. PROPERTY CYCLES AND THE POWER DIAGRAM

It's important to understand what's happening to temperature (T), pressure (P), volume (V), entropy (S), and heat exchange ($\Delta Q$) in energy conversion systems. For P, V, and T, the ideal gas law is a helpful guide:

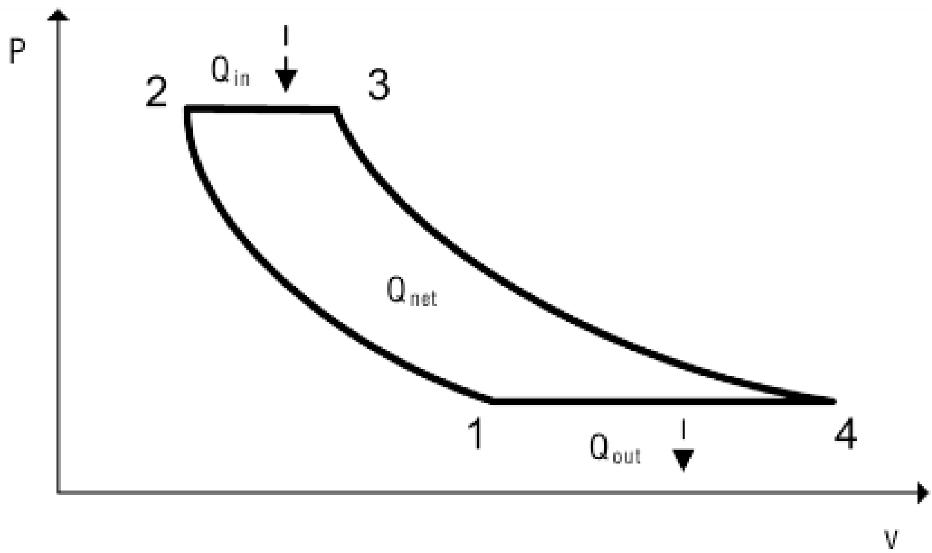
$$PV = nRT$$

where R is the ideal gas constant, which has a value of 8.314 J/K-mol. For instance, in a constant-pressure process an expansion in volume will lead to an increase in temperature. Expansion in an isothermal process requires a drop in pressure, etc.

We're going to look at a gas power cycle (the Brayton cycle in section, but the same general principles and approaches apply to vapor power cycles as well (*e.g.*, the Rankine cycle). The diagram below is a Pressure-Volume (P-V) diagram for the Brayton cycle, which shows how pressure changes with changes in volume during the cycle.

As the diagram shows, there are four processes (the line segments) in the Brayton cycle:

- 1-2 Isentropic compression (compressor)
- 2-3 Constant-pressure heat addition (combustion chamber)
- 3-4 Isentropic expansion (turbine)
- 4-1 Constant-pressure heat rejection (exhaust or heat exchanger)




See the discussion about reversible processes in the Cengel and Bowles to get a better sense of what isentropic means here.

## V. ADDITIONAL MATERIAL, TERMS, AND VARIABLES

Another commonly used thermodynamic equation has to do with thermal energy transfer. It can be expressed as:

$$Q = m\,C\,\Delta T$$

Q = energy transfer (Joules)
m = mass of the material (kilograms)
C = specific heat capacity of the material (J / kg °C)
ΔT = temperature difference (°C)

For solids and liquids the above equation is a fair representation, but gases often involve work done in expansion and compression ("boundary work") in addition to changes in internal energy. The notion of enthalpy (H) was created to account for this boundary work:

$$H = Q + PV$$

For the change in enthalpy:

$$\Delta H = mc_p \Delta T + P\Delta V$$

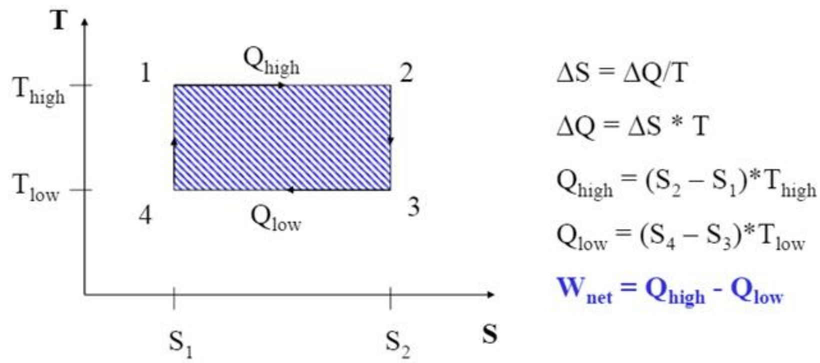
where this time the system is assumed to be at constant pressure. Note that if the PΔV term is zero, as it will be for solids and liquids, ΔH = ΔQ and $c_p = c_v = c$. The value of c for water, which is the substance that you'll be most interested in for this course, is 4.184 J/g-°C.

Using the ideal gas law and a bit of manipulation you can also show that the change in enthalpy is a function of temperature only, which means that:

$$h_2 - h_1 = mc_p(T_2 - T_1)$$

where the lower case h's are specific enthalpy (h = H/m, in units of kJ/kg). This equation is very useful in analyzing power cycles, as we will see below. This equation is also useful when we want to determine how many degrees a nearby power plant increases the temperature of a river or other body of water.

Lastly, entropy is calculated as: $\Delta S = \Delta Q/T$. Here is a diagram showing a Carnot temperature/entropy diagram.




| Symbol | Term | Definitions and Subscripts |
|---|---|---|
| U | Internal Energy | Internal energy is the sum of all forms of microscopic energy for a substance, which depend on molecular structure and molecular activity. |
| C | Specific Heat | Specific heat is the amount of energy needed to raise a unit mass of a substance by 1 degree, with SI units of kJ/kg-ºC. The subscript tells you whether the specific heat is at constant pressure ($c_p$) or constant volume ($c_v$) |
| H | Enthalpy | From the Greek enthalpien (to heat), enthalpy is the sum of internal energy and the absolute pressure times the volume (*i.e.*, the flow work) of a system, H = U + PV. We use enthalpy to account for boundary work (expansion or compression) done by the system. |
| Q | Heat | Heat is energy transferred between two systems by virtue of a temperature difference. The subscript tells you the direction of heat transfer. $Q_{in}$, in other words, is heat transfer into the system; $Q_{out}$ is heat transferred out of the system. |
| W | Work | Work is defined as force acting over a distance in the direction of the force (W = Fd), typically in units of J or Btu. The subscript characterizes work and gives a direction. Wnet,out, for instance, is the net work done by the system. |
| S | Entropy | Entropy is a measure of disorder in a system, defined formally as: $\Delta S = \Delta Q/T$. |
| η (eta) | Efficiency | The subscript tells you what kind of efficiency eta represents. $\eta_{th}$ is thermal efficiency, for instance. |

| Term | Formal Definition | Descriptive Definition |
|---|---|---|
| Adiabatic | $\Delta Q = 0$ | No transfer of heat |
| Isentropic | $\Delta S = 0$ | No change in entropy; for a process to be isentropic it must be adiabatic and reversible |

| | | |
|---|---|---|
| Isothermal | $\Delta T = 0$ | Constant temperature |
| Isobaric | $\Delta P = 0$ | Constant pressure |

## VI. PRACTICE PROBLEMS

1. A steam power plant with a power output of 150 MW consumes coal at a rate of 60 tons/h. If the heating value of the coal is 30,000kJ/kg, determine the overall efficiency of this plant (from Cengel and Bowles).

   With the coal consumption rate and the heating value you can find the total rate of thermal output:

$$\frac{60\text{ tons}}{\text{hour}} \times \frac{1{,}000\text{ kg}}{\text{ton}} \times \frac{30{,}000\text{ kJ}}{\text{kg}} \times \frac{1\text{ hour}}{60\text{ min}} \times \frac{1\text{ min}}{60\text{ sec}} = 500\text{ MW}$$

   Since you know that your electrical output is 150 MW, the overall efficiency is:

$$\eta_{th} = \frac{W_{net,out}}{Q_{in}} = \frac{150\text{ MW}}{500\text{ MW}} = 30\%$$

2. A heat engine takes in energy at a rate of 1600 W at a temperature of 1000 K. It exhausts heat at a rate of 1200 W at 400 K. What is the actual efficiency and maximum theoretical efficiency of this engine?

   The actual efficiency of this heat engine is:

$$\eta_{th} = \frac{Q_{in} - Q_{out}}{Q_{in}} = \frac{1600\text{ W} - 1200\text{ W}}{1600\text{ W}} = \frac{400\text{ W}}{1600\text{ W}} = 0.25 = 25\%$$

   However, its maximum theoretical efficiency is:

$$\eta_c = 1 - \frac{T_L}{T_H} = 1 - \frac{400\text{ W}}{1000\text{ W}} = 0.60 = 60\%$$

   So 2nd law efficiency is:

$$\eta_s = \frac{\eta_{th}}{\eta_c} = \frac{0.25}{0.60} = 0.42 = 42\%$$

3. Consider a power plant with typical efficiency of 33% and plant electrical output of 1000 MW. Suppose 15% of waste heat goes up the smokestack and 85% is taken away by cooling water drawn from a nearby river, which has a flow rate of 100 $m^3$/sec and a temperature of 20°C. Environmental guidelines suggest the plant limit coolant water temperature rise to 10 °C. What flow rate is needed from the river to carry the waste heat away? What will be the rise in river temperature?

   $mc\Delta T = Q = 1700\text{ MW} = 1.7\text{x}10^9\text{ J/s}$

   $m = 1.7\text{x}10^9\text{ J/s} / [(4184\text{J/ kg °C})(10\text{ °C})] = 40.6\text{x}10^3\text{ kg/s}$ of water

   so $40.6\text{x}10^3\text{ kg/s}(1\text{ m}^3/10^3\text{ kg H20})$ = **41 $m^3$/s of water**

You need 41 $m^3/s$ of water with the water heating 10 °C
The river has a flow of 100 $m^3/s$
Thus the river temperature will rise 41x10/100 = 4.1°C
The final river temperature will be 24.1 °C

4. Which segments in the P-V diagram for the Brayton Cycle are adiabatic? Isobaric?

   Under the diagram, it tells you that segments 1-2 and 3-4 are isentropic, which means that they have to be adiabatic as well. Segments 2-3 and 1-4 are isobaric.

5. Where in the P-V diagram for the Brayton Cycle is T the highest?

   T will be the highest at point 3, after the combustion stage is complete.

6. Based on the discussion in Energy and Energy Balances (in the section handout), how would you write the equation for the changes in enthalpy between 2 and 3? If $h_3$ is 1400 kJ/kg, $h_2$ is 500 kJ/kg, $T_2$ is 500 K, and $c_p$ (for air) is 1.005 kJ/kg-K, what is the value of $T_3$?

   This question is somewhat more challenging to set up, and we wouldn't ask you to do something like this on an exam. From the section handout you know that:

$$\Delta h = c_p(\Delta T) \quad \text{or} \quad h_3 - h_2 = c_p(T_3 - T_2)$$

   Solve for $T_3$:

$$T_3 = \frac{h_3 - h_2}{c_p} + T_2 = \frac{1400 kJ/kg - 500 kJ/kg}{1.005 kJ/kgK} + 500K = 1400K$$