Existing Resources:


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1. **INTRODUCTION**

Energy Toolkit IV
2. **KEY CONCEPTS**

Our brief foray into thermodynamics will give us a more formal definition of energy, get us into enthalpy and entropy, and give us a foundation for understanding energy conversion. 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.

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Term</th>
<th>Definitions and Subscripts</th>
</tr>
</thead>
<tbody>
<tr>
<td>U</td>
<td>Internal Energy</td>
<td>Internal energy is the sum of all forms of microscopic energy for a substance, which depend on molecular structure and molecular activity.</td>
</tr>
<tr>
<td>C</td>
<td>Specific Heat</td>
<td>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·°C. The subscript tells you whether the specific heat is at constant pressure ($c_p$) or constant volume ($c_v$).</td>
</tr>
<tr>
<td>H</td>
<td>Enthalpy</td>
<td>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.</td>
</tr>
<tr>
<td>Q</td>
<td>Heat</td>
<td>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.</td>
</tr>
<tr>
<td>W</td>
<td>Work</td>
<td>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. $W_{net,out}$, for instance, is the net work done by the system.</td>
</tr>
<tr>
<td>S</td>
<td>Entropy</td>
<td>Entropy is a measure of disorder in a system, defined formally as: $ΔS = ΔQ/T$.</td>
</tr>
<tr>
<td>η (eta)</td>
<td>Efficiency</td>
<td>The subscript tells you what kind of efficiency eta represents. $\eta_{th}$ is thermal efficiency, for instance.</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Term</th>
<th>Formal Definition</th>
<th>Descriptive Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>Adiabatic</td>
<td>$ΔQ = 0$</td>
<td>No transfer of heat</td>
</tr>
<tr>
<td>Type</td>
<td>Change</td>
<td>Description</td>
</tr>
<tr>
<td>-----------</td>
<td>--------</td>
<td>--------------------------------------------------</td>
</tr>
<tr>
<td>Isentropic</td>
<td>$\Delta S = 0$</td>
<td>No change in entropy; for a process to be isentropic it must be adiabatic and reversible</td>
</tr>
<tr>
<td>Isothermal</td>
<td>$\Delta T = 0$</td>
<td>Constant temperature</td>
</tr>
<tr>
<td>Isobaric</td>
<td>$\Delta P = 0$</td>
<td>Constant pressure</td>
</tr>
</tbody>
</table>
3. **1st Law of Thermodynamics**

U = internal energy = function of (Q’s and W’s)

\[ dU = \Delta Q + \Sigma W \]

with \( \Delta Q \) a heat interaction, and \( \Sigma W \) all of the work interactions.

There are a range of work interactions that the system can undergo, such as:

<table>
<thead>
<tr>
<th>( \Delta W )</th>
<th>APPLICATION</th>
</tr>
</thead>
<tbody>
<tr>
<td>- PdV</td>
<td>expanding a substance, phase changes</td>
</tr>
<tr>
<td>( \Sigma \mu dn )</td>
<td>chemical, metallurgical interactions</td>
</tr>
<tr>
<td>VdQ</td>
<td>electrical charge transfer</td>
</tr>
<tr>
<td>FdL</td>
<td>elastic strain</td>
</tr>
</tbody>
</table>

For basic heat pumps, the starting ground is expansion of a gas, so

\[ \Delta Q = dU + PdV \]

which relates the amount of heat, \( \Delta Q \), to heat something at constant pressure.

For example, to boil a quantity of water where G is steam and L is liquid, then we transform \( \Delta Q = dU + PdV \) to:

\[ \Delta Q = \int (dU + PdV) = \int dU + P \int dV = U_G - U_L + P(V_G - V_L) \]

or,

\[ \Delta Q = (U + PV)_{steam} - (U + PV)_{liquid}. \]
4. 2\textsuperscript{ND} Law of Thermodynamics

Combining the First Law and the Second law gives perhaps the most useful equation of state:

\[ dU = TdS - pDV \]

This implies that the state of the system, \( U \), is a function of entropy (\( S \)) and volume (\( V \)), which leads to a special role that they will play in defining the state of a system in terms of its energy balance, or the ‘partition’ of energy. \( S \) and \( V \) are sometimes called the ‘natural’ variables.

From this equation we then naturally have that:

\[ dU = \left( \frac{\partial U}{\partial S} \right)_V dS + \left( \frac{\partial U}{\partial S} \right)_V dV \]

where the subscript, \( V \), or \( S \) mean that this quantity is held constant in the partial derivative. This is particularly helpful when thinking about the steps involved in operating a power plan (fossil fuel, or otherwise) when a fuel is combusted (at constant volume) or expanded (at constant temperature), etc. ....

From this equation it should be clear that

\[ \left( \frac{\partial U}{\partial S} \right)_V = T \]
5. **Heat Engines**

A heat engine comprises three characteristic processes:

1. Heat is absorbed from a high temperature source (reservoir)
2. Part of this heat is converted to work (usually a rotating shaft)
3. Heat is given off to a lower temperature sink (e.g., rivers, the atmosphere...)

![Diagram of the heat engine cycle]

Different heat engines work in different ways but this pattern is always the same. Note that a refrigerator is essentially a heat engine operating in reverse, *i.e.*, taking heat from a lower temperature sink and transferring it to a higher temperature source.

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.

Heat engines are governed by two general principles:

- **First Law of Thermodynamics**: Energy cannot be created or destroyed, but can be converted from one form to another.
- **Second Law of Thermodynamics**: It is impossible for any device that operates on a cycle to receive heat from a single reservoir and produce a net amount of work.

The Second Law definition is not particularly intuitive, but can be interpreted in two ways:

1. Heat transfer requires a temperature difference.
2. When work is done there is some inherent inefficiency.

We'll see what this means in practice in our exploration of efficiencies.
6. **CARNOT SYSTEM**

Refer to the lecture notes
7. **Efficiencies**

We’re going to focus on three primary efficiencies:

7.1. **First Law or Thermal Efficiency**

Thermal efficiency is derived from the First Law of Thermodynamics and is the ratio of useful energy – or the net work done by a system – to the total heat put into the system. First Law efficiency is what you use when you talk about the efficiency of a power; you can think of this ratio as describing how efficiently a heat engine converts heat input into work output.

\[ \eta_{th} = \frac{W_{net, out}}{Q_{in}} \]

Or in the symbols we’ve defined above:

\[ \eta_{th} = \frac{W_{net, out}}{Q_{in}} \]

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:

\[ \eta_{th} = \frac{W_{net, out}}{Q_{in}} = \frac{Q_{in} - Q_{out}}{Q_{in}} = 1 - \frac{Q_{out}}{Q_{in}} \]

7.2. **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 \( T_C \), respectively

\[ \eta_c = \frac{T_H - T_C}{T_H} = 1 - \frac{T_C}{T_H} \]

The temperatures here should be in Kelvin \( \rightarrow K = °C + 273.15 \) or Rankin \( = 460 + °F \).

7.3. **Second Law Efficiency**

Second Law efficiency is a measure of how much of the theoretical maximum (Carnot) you achieve. The Second Law efficiency will always be between the Carnot and First Law efficiencies.

\[ \eta_{II} = \frac{\eta_{th}}{\eta_c} \]
7.4. Sample 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).

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?
8. **Thermodynamics Diagrams**

It’s important to understand what’s happening to temperature (T), pressure (P), volume (V), entropy (S), and heat exchange (ΔQ) 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  Isenropic 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.
8.1. Sample Problems

1. Which segments in the P-V diagram are adiabatic? Isobaric?

2. Where in the P-V diagram is T the highest?

3. Based on the discussion in Energy and Energy Balances, 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 \( T_3 \)?
9. **Answers to Sample Problems**

**Section 7.4**

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

\[
\frac{60 \text{tons}}{\text{hour}} \times \frac{1000 \text{kg}}{\text{ton}} \times \frac{30000 \text{kJ}}{\text{kg}} \times \frac{1 \text{hour}}{3600 \text{sec}} = 500 \text{ MW}
\]

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

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

2. The actual efficiency of this heat engine is:

\[
\eta_{th} = \frac{Q_{in} - Q_{out}}{Q_{in}} = \frac{1600W - 1200W}{1600W} = 25\%
\]

However, its maximum theoretical efficiency is:

\[
\eta_{c} = 1 - \frac{T_{C}}{T_{H}} = 1 - \frac{400K}{1000K} = 60\%
\]

So 2\(^{\text{nd}}\) law efficiency is:

\[
\eta_{II} = \frac{\eta_{th}}{\eta_{c}} = \frac{25\%}{60\%} = 42\%
\]

**Section 8.1**

1. 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.

2. T will be the highest at point 3, after the heat addition in the combustion stage is complete.

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 \(T_{3}\):

\[
T_{3} = T_{2} + \frac{h_{3} - h_{2}}{c_{p}} = 500K + \frac{1400 \text{kJ/kg} - 500 \text{kJ/kg}}{1.005 \text{kJ/(kg·K)}} = 1400K
\]
10. REFERENCES