Topics:

Combustion

Thermodynamics

Heat Engines

Steam Engines-Stationary
Energy is Useful Work
Work=Force x Distance

Constant pressure

Work done by an expanding gas, constant pressure:

\[
W = P \Delta V \quad \text{(constant pressure)}
\]

\[
W = P \Delta V = \frac{F}{A} (A \Delta x) = F \Delta x \quad \text{(Lbs-Ft)}
\]

Basis for Steam Engines
Combustion

- **Combustion** is the sequence of exothermic chemical reactions between a fuel and an oxidant accompanied by the production of heat and conversion of chemical species.
- Fuels of interest often include organic compounds in the gas, liquid or solid phase.
- In a complete combustion reaction, a compound reacts with an oxidizing element, such as oxygen, and the products are compounds of each element in the fuel with the oxidizing element.
Combustion

- **Combustion** is the sequence of exothermic chemical reactions between a fuel and an oxidant accompanied by the production of heat and conversion of chemical species.
- Fuels of interest often include organic compounds in the gas, liquid or solid phase.
- In a complete combustion reaction, a compound reacts with an oxidizing element, such as oxygen, and the products are compounds of each element in the fuel with the oxidizing element.
- Complete combustion is almost impossible to achieve.
- Actual combustion reactions yield a wide variety of major and minor species such as carbon monoxide and pure carbon.
- Any combustion in air, which is 78% nitrogen, will also create nitrogen oxides.
- Some source of heat is necessary to start combustion.
- Once combustion gets started, we don't have to provide the heat source because the heat of combustion will keep things going.
Combustion

- Liquid fuels do not actually combust
- It is the gas phase of the liquid fuel that is catching on fire, and so can only happen above a certain temperature
- The temperature at which a given liquid fuel can ignite is known as its **flash point**, and is the point at which there is enough volatile fuel in the air to catch fire
- Different fuels yield different products when they undergo a combustion reaction
  - $\text{C} + \text{O}_2 \rightarrow \text{CO}_2(g) + \text{heat}$
  - $\text{CH}_4 + 2 \text{O}_2 \rightarrow \text{CO}_2 + 2 \text{H}_2\text{O}(g) + \text{heat}$
  - $2 \text{H}_2 + \text{O}_2 \rightarrow 2 \text{H}_2\text{O}(g) + \text{heat}$
  - The result is water vapor or "steam"
Combustion

- Liquid fuels do not actually combust
- It is the gas phase of the liquid fuel that is catching on fire, and so can only happen above a certain temperature
- The temperature at which a given liquid fuel can ignite is known as its flash point, and is the point at which there is enough volatile fuel in the air to catch fire
- Different fuels yield different products when they undergo a combustion reaction
  
  C+O2 → CO2(g) + heat
  CH4 + 2 O2 → CO2 + 2 H2O(g) + heat
  2 H2 + O2 → 2 H2O(g) + heat
  
  The result is water vapor or "steam"

- Early man used the burning of wood and other biomass for heating living spaces and cooking food
  - Open fires
  - Fireplaces-directs products of combustion and most of the heat up and out
  - Furnaces-capture most of the heat- exhaust the products of combustion

- Source of thermal energy for most heat engines is combustion
  - Wood or other biomass
  - Coal
  - Natural gas
  - Refined petroleum products
  - Gasoline
  - Diesel Fuel
  - Jet Fuel
## Combustion

### Energy content of some fuels

<table>
<thead>
<tr>
<th>Fuel</th>
<th>BTU/LBS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Butane</td>
<td>21,200</td>
</tr>
<tr>
<td>Coal (Anthracite)</td>
<td>14,000</td>
</tr>
<tr>
<td>Coal (lignite)</td>
<td>8,000</td>
</tr>
<tr>
<td>Diesel</td>
<td>19,300</td>
</tr>
<tr>
<td>Ethanol</td>
<td>12,000</td>
</tr>
<tr>
<td>Gasoline</td>
<td>20,000</td>
</tr>
<tr>
<td>Hydrogen</td>
<td>61,000</td>
</tr>
<tr>
<td>Natural Gas</td>
<td>23,000</td>
</tr>
<tr>
<td>Propane</td>
<td>21,000</td>
</tr>
<tr>
<td>Wood</td>
<td>6,000</td>
</tr>
</tbody>
</table>
Thermodynamics
Thermodynamics Heat Engines

- **Heat engine** is defined as a device that converts **heat energy** (thermal energy) into **mechanical energy**
- Or the reverse
- Refrigerators and Heat Pumps
  - Convert **work** into **heat energy**
- **External Combustion** engines-
  - combustion outside the engine
    - Steam Piston Engines
    - Steam Turbine Engines
    - Stirling Cycle Engines
Thermodynamics Heat Engines

- **Heat engine** is defined as a device that converts **heat energy** (thermal energy) into **mechanical energy**
  - Or the reverse

Refrigerators and Heat Pumps
  - Convert **work** into **heat energy**

**External Combustion** engines—combustion outside the engine
  - Steam Piston Engines
  - Steam Turbine Engines
  - Stirling Cycle Engines

- **Internal Combustion (IC) Engines**—combustion within the engine
  - Spark Ignition (SI) Piston Engines—Gasoline
  - Compression Ignition (CI) Piston Engines—Diesel Fuel

- Gas Turbine Engines
- Jet Engines
- Rocket Engines
Thermodynamics Heat Engine

- A **forward heat engine** has a **positive work output** such as an IC engine.
- Applying the First Law of Thermodynamics:
  \[ Q_1 - Q_2 - W = 0 \]
  \[ \eta = \frac{W}{Q_1} \]

- The Second Law of Thermodynamics states:
  The thermal efficiency of the cycle has an upper limit (thermal efficiency of the Carnot cycle)
  \[ \eta < \eta_c < 1.0 \]

- It can be shown that:
  \[ Q_1 > W \]
  which means that it is **impossible to convert the whole heat input to work** and

- \[ Q_2 > 0 \]
  which means that a **minimum of heat supply to the cold reservoir is necessary**

LER= Low Temperature Energy Reservoir
HTER= High Temperature Energy Reservoir

**Forward Heat Engine**

![Diagram of heat engine]
A reverse heat engine has a positive work input such as a heat pump or refrigerator.

Applying the First Law of Thermodynamics:

$$Q_1 + Q_2 + W = 0$$

In case of a reverse heat engine the Second Law of Thermodynamics is as follows:

It is impossible to transfer heat from a cooler body to a hotter body without any work input i.e.

$$W > 0$$

Which means that the Coefficient of Performance (COP) for a reverse heat engine is greater than unity.

For a refrigerator,

$$\text{COP} = \frac{Q_2}{W}$$

For a heat pump,

$$\text{COP} = \frac{Q_1}{W}$$
Laws of Thermodynamics

• **Thermodynamics** is the science concerned with the relations between heat and mechanical energy or work, and the conversion of one into the other

• **Laws of Thermodynamics** apply to all heat engines
  – Engines that convert thermal energy into mechanical energy
  – Engines that convert mechanical energy into thermal energy
Laws of Thermodynamics

• **Thermodynamics** is the science concerned with the relations between heat and mechanical energy or work, and the conversion of one into the other

• **Laws of Thermodynamics** apply to all heat engines
  – Engines that convert thermal energy into mechanical energy
  – Engines that convert mechanical energy into thermal energy

• **Classical thermodynamics** describes the exchange of work and heat between systems

• It has a special interest in systems that are individually in states of Thermodynamic equilibrium, a condition of systems which are adequately described by only macroscopic variables

• The laws of thermodynamics are important fundamental laws in physics and they are applicable in other natural sciences
Laws of Thermodynamics

• Define **fundamental physical quantities** (*temperature, energy and entropy*) that characterize thermodynamic systems and how these quantities behave under various circumstances

• **First Law**: Heat and work are forms of energy transfer

• While energy is invariably conserved, the *internal energy* of a closed system changes as *heat* and *work* are transferred in or out of it

$$\Delta U = Q - W$$

*Change in internal energy*  *Heat added to the system*  *Work done by the system*
Laws of Thermodynamics

• Define fundamental physical quantities (temperature, energy and entropy) that characterize thermodynamic systems and how these quantities behave under various circumstances

• First Law: Heat and work are forms of energy transfer

• While energy is invariably conserved, the internal energy of a closed system changes as heat and work are transferred in or out of it

\[ \Delta U = Q - W \]

• Second Law: The entropy of any closed system not in thermal equilibrium almost always increases

• Closed systems spontaneously evolve towards thermal equilibrium -- the state of maximum entropy of the system

• Third Law: The entropy of a system approaches a constant value as the temperature approaches absolute zero

• The entropy of a system at absolute zero is typically zero

  — The universe is “running own”
Laws of Thermodynamics Entropy

- **Entropy** is a measure of the lack of useful energy (work) available in a system.
- It is the change in entropy that has the real meaning.
- If the energy transfer in a system is not *reversible*, almost always the case, the system’s entropy will increase with time.
- As entropy increases the randomness or disorder of the system increases.
- Heat flows from hot to cold bodies - not the other way around.
- Heat is a measure of randomness - atomic/molecular motions.
Laws of Thermodynamics Entropy

- **Entropy** is a measure of the lack of useful energy (work) available in a system.
- It is the change in entropy that has the real meaning.
- If the energy transfer in a system is not *reversible*, almost always the case, the system’s entropy will increase with time.
- As entropy increases the randomness or disorder of the system increases.
- Heat flows from hot to cold bodies - not the other way around.
- Heat is a measure of randomness - atomic/molecular motions.
- For a bounded system entropy increases – it never decreases.
- The universe is a bounded system, in that nothing exists outside it.
- For the universe as a whole, energy is conserved, and entropy must always increase.
- Mathematical definition of entropy is: \( S = \frac{dQ}{T} \).
Entropy Example-Ice Melting in a Room of Air

• 1 lb of ice at 32F=492R in a room full of air at 70F=530R
• Heat required to melt ice, is 144BTU/lb so dQ=144BTU
• Energy is conserved—heat flows to ice(+) from air(-)
• The room with the ice is a closed system—no heat goes out or into the room
• Entropy is defined as : \( S = \frac{dQ}{T} \)
• Change in entropy of the system is:
  
  \[ dS_{\text{system}} = S_{\text{ice}} + S_{\text{air}} = \left( \frac{dQ}{T} \right)_{\text{ice}} + \left( -\frac{dQ}{T} \right)_{\text{air}} = \left( \frac{144}{492} \right) + \left( -\frac{144}{530} \right) = 0.021 \text{ btu/R} \]
• Entropy of the system increases

\[ \text{Molecules of liquid water are more disordered than molecules of ice} \]

• The system as a whole is less ordered than before the ice melts
Department of Entropy
Laws of Thermodynamics Carnot Cycle

• By using the Second Law of Thermodynamics it is possible to show that no heat engine can be more efficient than a reversible heat engine working between two fixed temperature limits.

• This heat engine is known as Carnot cycle and consists of the following processes:

- The supplied heat to the cycle per unit mass flow is:
  \[ Q_1 = T_1 \]
- The rejected heat from the cycle per unit mass flow is:
  \[ Q_2 = T_2 \]

By applying the First Law of Thermodynamics to the cycle, we obtain:

\[ Q_1 - Q_2 - W = 0 \]

And the thermal efficiency of the cycle will be:

\[ \eta = \frac{W}{Q_1} = 1 - \frac{T_2}{T_1} \]

Due to mechanical friction and other irreversibilities no cycle can achieve this efficiency.
Laws of Thermodynamics Carnot Cycle

- The **Carnot cycle** can be thought of as the most efficient heat engine cycle allowed by physical laws.
- The Second law of Thermodynamics states that *not all the supplied heat in a heat engine can be used to do work*.
- The **Carnot efficiency** sets the limiting value on the fraction of the heat which can be so used.
- In order to approach the Carnot efficiency, the processes involved in the heat engine cycle must be reversible and involve no change in *entropy*.
Laws of Thermodynamics Carnot Cycle

- The **Carnot cycle** can be thought of as the most efficient heat engine cycle allowed by physical laws.
- The Second law of Thermodynamics states that *not all the supplied heat in a heat engine can be used to do work*.
- The **Carnot efficiency** sets the limiting value on the fraction of the heat which can be so used.
- In order to approach the Carnot efficiency, the processes involved in the heat engine cycle must be reversible and involve no change in entropy.
- This means that the Carnot cycle is an idealization, since no real engine processes are reversible and all real physical processes involve some increase in entropy.
- The conceptual value of the Carnot cycle is that it establishes the maximum possible efficiency for an engine cycle operating between $T_H$ and $T_C$.
- It is not a practical engine cycle because the heat transfer into the engine in the isothermal process is too slow to be of practical value.
Steam Engines

- In 1679 Denis Papin a French experimental physicist invented a type of pressure cooker, a closed vessel with a tightly fitting lid that confined steam until high pressure was generated.
- He observed that the steam in the vessel raised the lid suggesting the use of steam to power a piston and cylinder engine.
Steam Engines

- In 1679 Denis Papin a French experimental physicist invented a type of pressure cooker, a closed vessel with a tightly fitting lid that confined steam until high pressure was generated.
- He observed that the steam in the vessel raised the lid suggesting the use of steam to power a piston and cylinder engine.
- Papin’s 1690 atmospheric steam engine.
- The generation of steam, the power stroke of the piston, and the condensation of the steam takes place in the same cylinder.
- The working cylinder is also the steam boiler and the condenser.
Steam Engines

- **Thomas Savery**, an English inventor and military engineer, studied Papin’s work and built a steam-driven suction machine for removing water from coal mines.
- Savery’s machine (patented in 1698) consisted of a boiler, a closed, water-filled reservoir, and a series of valves.
- Steam was introduced into the reservoir, and the pressure of the steam forced the water out through a one-way outlet valve until the vessel was empty.
- Water was then sprayed over the surface of the vessel to condense the steam and create a vacuum capable of drawing up more water through a valve below.
- The vacuum created was not perfect, and so water could only be lifted to a limited height.
Steam Engines

- Around 1712 another English engineer, **Thomas Newcomen**, developed a more efficient steam pump consisting of a cylinder fitted with a piston—a design inspired by Papin’s idea.
- When the cylinder was filled with steam, a counterweighted pump plunger moved the piston to the extreme upper end of the stroke.
- With the admission of cooling water, the steam condensed, creating a vacuum.
- The atmospheric pressure in the mine acted on the piston and caused it to move down in the cylinder, and the pump plunger was lifted by the resulting force.
Steam Engines

- Savery had a broad patent so Newcomen did not patent his steam engine.
- Newcomen entered into a partnership with Savery, and together they built, in 1712, the first piston-operated steam pump.
- Several years later Smeaton improved the Newcomen engine, almost doubling its efficiency.
- Engines of this kind converted only about 1 percent of the thermal energy in the steam to mechanical energy, they remained unrivaled for more than 50 years.

http://www.animatedengines.com/newcomen.html
Steam Engines

• A Scottish instrument maker, **James Watt**, noted in 1763 how inefficient the Newcomen engine was
• In 1765 Watt conceived the idea of a separate condensation chamber
• Watt's idea was to equip the engine with a second, small cylinder, connected to the main one
• In Watt's design, the cold water was injected only into the condensation chamber
• This type of condenser is known as a *jet condenser*
• Because the chambers were connected, this caused condensation without significant loss of heat
Steam Engines

- A Scottish instrument maker, James Watt, noted in 1763 how inefficient the Newcomen engine was.
- In 1765 Watt conceived the idea of a separate condensation chamber.
- Watt's idea was to equip the engine with a second, small cylinder, connected to the main one.
- In Watt's design, the cold water was injected only into the condensation chamber.
- This type of condenser is known as a jet condenser.
- Because the chambers were connected, this caused condensation without significant loss of heat.

- The condenser remained cold and under less atmospheric pressure than the cylinder, while the cylinder remained hot.
- When the piston, forced by steam, reached the top of the cylinder, the steam inlet valve closed and the valve controlling the passage to the condenser opened.
- External atmospheric pressure pushed the piston towards the condenser.
Steam Engines

- Newcomen's engine used the steam chamber for condensation-introduced water.
- Watt added a separate condensation chamber—a small cylinder, connected to the main one—resulting in saving energy which was wasted by spraying cool water in main chamber for condensation.
- Watt also sealed the top of the cylinder and injected low-pressure steam into the upper part of the cylinder—thus making it a high pressure steam engine.
- This increased the power of the engine.
- Speed of Engine was controlled by a centrifugal governor regulating the amount of steam getting into pressure chamber.
Steam Engines

- **Double Action**
- An arrangement of valves could admit steam to either end, or connect either end with the condenser
- Consequently, the direction of the power stroke could be reversed
- The resulting **double action** gave a very even movement to the piston

http://www.animatedengines.com/locomotive.html
Steam Engines

• Watt had tried unsuccessfully for several years to have an accurately bored cylinder for his steam engines, and was forced to used hammered iron, which was out of round and caused leakage past the piston

• In 1774 John Wilkinson, the cannon maker, invented a boring machine with the shaft, which held the cutting tool, supported on both ends, extending through the cylinder, unlike the then used cantilevered borers

• True cylinders improved efficiency - less leakage around the piston
Steam Engines

• The use of steam engines to power various manufacturing factories was a major part of the **Industrial Revolution**

• Watt’s engine was able to convert only a little more than 2 percent of the thermal energy in steam to work

• Improvements (e.g., pressures and temperatures) increased the efficiency of the steam engine to roughly 17 percent by 1900

• Exponential improvement in steam engine efficiency over 300 years

• It doubled every sixty - from 32 pounds of coal per horsepower-hour down to one
Steam Engines

- Within the next decade after ~1900 the piston steam engine was supplanted by the more efficient **steam turbine**
- Technological advances and the use of high-temperature steam have allowed steam turbines to reach approximately 40% thermal energy conversion efficiency
- Steam turbines are used as the source of power for majority of electrical generation
  - Coal fired
  - Gas fired
  - Nuclear
• Steam Engines -
  – High pressure
  – Locomotives
  – Ships and boats
  – Automobiles
• Steam Turbines
  – Power generation