A short Course in Energy Conversion
Session 4

Jim Rauf
• Steam Engines-
  – High pressure
  – Locomotives
  – Ships and boats
  – Automobiles

• Steam Turbines
  – Power generation
Steam Engines

- James Watt’s patent expired in 1800
- The consequence was an enormous mass of inventions with steam as their basis
- James Watt already mentioned the idea of a high-pressure steam engine in his patent of 1769
- He did not intend to build such an engine, but he wanted to be sure nobody else would either
- Watt thought that it was impossible to create cylinders and pistons that did not leak under high pressure

- Richard Trevithick already thought early about building high-pressure steam engines
- His most significant contribution was to the development of the first high pressure steam engine, he also built the first full-scale working railway steam locomotive
Steam Engines

- **The reason for high pressure**
  - Maximizing the efficiency of a heat engine depends upon getting the temperature at which heat is accepted (steam in the boiler) as far as possible from the temperature at which it is rejected (the steam when it leaves the cylinder).
  - Two options:
    - *raise the inlet temperature*
    - *lower the outlet temperature*
  - The former means raising steam at higher pressure and temperature.
  - The latter means bigger cylinders to allow the exhaust steam to expand further.

- High-pressure is the way to go to improve steam engine fuel efficiency.
- High-pressure locomotives were much more complicated than conventional designs.
- It was not simply a matter of building a normal fire tube boiler with suitably increased strength and stoking harder. Structural strength requirements in the boiler shell make this impractical; it becomes impossibly thick and heavy. For high steam pressures the water tube boiler is universally used.
Steam Engines

High pressure Steam Engines Use Water Tube Boilers

Fire Tube Boiler

Water Tube Boiler

Stress = Pressure x Radius/Wall thickness
Steam Locomotives

• On February 21, 1804 the world's first locomotive-hauled railway journey took place as Trevithick's unnamed steam locomotive hauled a train along the tramway of the Penydarren Ironworks, in Wales.

The first locomotive in the world by Richard Trevithick 1804
Steam Engines

- **George Stephenson** designed his first locomotive in 1814, a travelling engine designed for hauling coal on the Killingworth wagonway, and named *Bluecher* after a Prussian general.
- This locomotive could haul 30 tons of coal up a hill at 4 mph and was the first successful flanged-wheel adhesion locomotive.
  - Its traction depended only on the **contact** between its **flanged wheels** and the rail-friction.
- The new engines were too heavy to be run on wooden rails, and iron rails were in their infancy, with cast iron exhibiting excessive brittleness.
- Together with William Losh, Stephenson improved the design of cast iron rails to reduce breakage.
- For the Stockton and Darlington Railway, Stephenson would use only wrought iron rails.
Steam Engines

• In 1829, there was a decision to build a railway line between the two main cities of trade in England, Liverpool and Manchester
  – The line had been finished before deciding on how to move the wagons!
• The favored approach was to use a stationary steam-engine to pull the wagons by means of rope
  – Like canal barges were pulled by horses
• George Stephenson wanted them to do a competition with locomotives
• In 1829, Stephenson built *The Rocket* which was entered in and won the Rainhill Trials

• The great advantage of this engine was its **tube boiler**
• *The Rocket* used tube boiler and was able to pull a 30 passenger wagon at a speed of 28 mph
• The Liverpool and Manchester Railway opened in 1830
• Stephenson’s company became the pre-eminent builder of steam locomotives used in the UK, US and Europe
Steam Locomotives

- A modern steam engine consists of a **double acting** steam engine, which works directly on the driving wheels.
- Water is heated in a **water tube** boiler to produce steam.
- The water flows thru spiral formed tubes over the fire to enlarge the surface.
- The flow of steam, therefore power, is regulated by a **slide-gate valve**
- The valve can be adjusted to operate the engine forward or backwards

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

• Steam locomotives have been replaced by diesel electric powered locomotives
Steam Automobiles

Early Steam Vehicle actually Built 1760

- 1760 French Cugnot
- Steam powered 3 wheel vehicle
- Intended to haul Artillery
- Difficulty steering-crashed into a building on its first run on the Paris streets

Replica of Cugnot 1760 Steam Vehicle
Steam Engines

- **Locomobile** Company produced steam automobiles from 1899 to 1929
- Early steam Locomobiles were:
  - Unreliable
  - Finicky to operate
  - Prone to paraffin fires
  - They had small water tanks (getting only 20 mi per tank)
  - They took 20-30 minutes to raise steam
Steam Automobiles

1902 Stanley Steamer

1924 Stanley Steamer model 750A
Steam Engines

- In early **Stanley** cars steam was generated in a **boiler**, mounted beneath the seat, with a vaporizing gasoline (later, kerosene) burner underneath.
- The boiler was reinforced by several layers of piano wire wound around it, which gave it a strong, yet relatively light-weight, shell.
- The boilers were fitted with safety valves, and even if these failed, a dangerous overpressure would rupture one of the many joints long before the boiler shell was in danger of bursting, and the resulting leak would relieve the boiler pressure.
- There was never been a documented case of a Stanley boiler exploding in use.
- The engine had **two double-acting cylinders** side-by-side, equipped with slide-valves, and was of the simple-expansion type.
- Drive was transmitted directly from the engine crankshaft to a rear-mounted differential by means of a chain.
- In order to improve range, **condensers** were used, beginning in 1915.
- A Stanley Steamer set the world record for the fastest mile in a car at 127.6 mph in 1906.
- This record was not broken by any automobile until 1911.
- Production rose to 500 cars in 1917 and ended in 1924.
Steam Engines

• Stanley steam engine was similar to steam locomotive
• The 20 horsepower car had two 4” diameter cylinders with 5” stroke
• Steam pressure was 600 psi
• Each piston provided over 3 ½ ton force
• Engine is double acting
• Engine provided same number of power impulse per revolution as an 8 cylinder internal combustion engine
• The Stanley steam engine developed maximum power from a standstill
• Steam powered cars could not compete with gasoline powered cars
  • Convenience of electric starters and “no wait” driving
Steam Ships

- Almost as soon as the steam engine was invented there were attempts to use it as motive power to drive ships.
- In the early 1700's the Frenchman, Denis Papin, was the first to try to put a steam engine into a ship.
- His idea was to use the steam to drive a paddle wheel.
- Papin was defeated by the design problem of turning the to and fro motion of the piston into the circular motion needed for the paddle.
- Added to this was the fact that the boilers could not produce enough pressure to provide sufficient power.
- In Britain, Thomas Newcomen worked on the same problem, but he came up against the same difficulties as Papin.
- Newcomen did find a way to produce rotary motion, but his steam engine was too large and bulky to fit into a ship.
- The first ship to be powered by steam was the Pyroscaphe which was built by the Marquis de Jouffroy d'Abbans in 1783.
- It ran on the River Soane but it proved to be unreliable.
Steam Ships

- The first successful steamship was *the Charlotte Dundas* which was built in 1802 by **William Symington**
  - This ship was used as a tug boat on the Forth-Clyde canal
- American, **Robert Fulton**, was present on one of her sailings and he saw the potential for further development
- In 1803 Fulton demonstrated a steam driven boat on the River Seine
- In 1807, he developed a bigger paddle steamer, driven by a Boulton and Watt engine, which he shipped to America
  - This steamer was capable of long-distance river travel and was so successful that a much larger ship was built using the same design
- In Britain, a Scottish engineer, **Henry Bell**, designed a small steamship called the *Comet* which he ran on the River Clyde in 1812
Steam Ships

• The success of *the Charlotte Dundas* and *the Comet* showed that steam power was possible on water
• This started a general drive towards the production of steam powered river boats
• By 1818 steam powered, sea-going ships were being developed
• In 1820 a steamship called the *James Watt* was launched
• At 43 metres long, this was the biggest steamship of the time
• She was powered by two Boulton and Watt engines, each driving a paddle wheel
• In 1822 the *Aaron Manby* was the first iron ship to be steam powered
• She ran between Britain and France at first, but was later used as a pleasure cruiser on the Seine
Steam Ships

• All these developments ultimately led to the idea of building a ship large enough to cross the Atlantic under steam
• The Savannah had made the crossing in 1819, but the journey had been made largely under sail
• It was Isambard Kingdom Brunel who designed and built the first successful steam powered ship capable of an Atlantic crossing
• His ship, the Great Western, was a paddle-driven steamship
• It was built in Bristol, launched in 1837 and crossed the Atlantic in 1845

• The Great Western sailed from Bristol to New York in 15 days at sea
  – Atlantic crossing under sail 30-40 days
  – Modern record 3 days 10 hours
Steam Ships

• In 1854 John Elder invented the **compound steam engine**
• In a compound engine steam is expanded in two or more stages
• Steam is first expanded in a high-pressure cylinder then having given up heat and losing pressure, it exhausts directly into one or more larger volume low-pressure cylinders
• **Multiple-expansion** engines employ additional cylinders, of progressively lower pressure, to extract further energy from the steam
• The same principal is used in steam turbines

High-pressure steam (red) enters from the boiler and passes through the engine, exhausting as low-pressure steam (blue) to the condenser

Steam Ships

• Elder designed triple expansion quadruple expansion engines

• One ton of coal was now doing as much work as three tons had done in 1845

• The development of sea-going steamships in the 18th and 19th centuries led to the rapid expansion of the British Industrial Revolution
  – Trade within the Empire and beyond

• Within 50 years the cost of carrying goods by ship had fallen by over seventy percent
  – Globalization

• Once the Atlantic had been crossed using steam power the potential for long distance travel at an economic price allowed many emigrants to travel from Europe to the New World

• Technology developments can have great effects on society and geopolitical relationships
Steam Ships

- In 1811, the "New Orleans" was built at Pittsburgh, designed by Robert Fulton and Robert Livingston
- The New Orleans had a passenger and freight route on the lower Mississippi River
- By 1814, Fulton and Livingston were offering regular steamboat and freight service between New Orleans, Louisiana and Natchez, Mississippi.
  - Their boats traveled at 8 mph downstream and 3 mph upstream
- By 1853 a trip from New Orleans took 4 ½ days - down from 25 days in 1816
- Between 1814 and 1834, New Orleans steamboat arrivals increased from 20 to 1200 a year
- The boats transported cargo and passengers contributing greatly to the nation’s economy
- By the 1870s, railroads had begun to supplant steamboats as the major transporter of both goods and passengers

OLLI Fall 2019
Steam Turbines

• The modern steam turbine was invented in 1884 by the Sir Charles Parsons, whose first model was connected to a dynamo that generated 7.5 kW (10 hp) of electricity
• His patent was licensed and the turbine scaled-up shortly after by George Westinghouse
• The Parsons turbine also turned out to be easy to scale up.
• A number of other variations of steam turbines have been developed
• The de Laval turbine (invented by Gustaf de Laval) accelerates the steam to full speed before running it against a turbine blade. Hence the (impulse) turbine is simpler, less expensive and does not need to be pressure-proof. It can operate with any pressure of steam, but is considerably less efficient than reaction turbines
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Steam Power Plant

Energy Conversion Process in Thermal Power Plants

Chemical Energy is Converted into Thermal Energy by Combustion In Boiler

Thermal Energy is Converted into Mechanical Energy In Turbine

Mechanical Energy is Converted into Electrical Energy In Generator

Electrical Energy
Steam Power Plant

Energy Conversion...

- Fuel, Air and water produce steam in the boiler by combustion
- Steam of high temperature and pressure is expended from high pressure to low pressure in the turbine
- Thermal energy is converted into kinetic energy and finally mechanical energy
- This mechanical energy derives the generator to produce electricity

Efficiency...

Efficiency = Heat Equivalent of Electrical output / Heat of Combustion

- Normally $\eta = 29\%$
- Losses:
  1. Boiler House Losses:
     a. To Dry Fuel Gases 5%
     b. To moisture in gases 5%
     c. To ash and unburnt carbon 1%
     d. To radiation and leakage 2.5%
     e. Unknown losses 2.5%
  TOTAL 16%

- Turbine Losses:
  a. To condenser 54%

3. Alternator or Generator Loss 1%
  TOTAL 55%

Grand Total 71%

So Efficiency = (100% - Losses)
  = 100% - 71% = 29%
Thermal energy in steam is converted by turbine (as pressure and temperature decrease) into mechanical energy (rotational energy)

- **Blades** are to produce maximum rotational energy by directing the flow of the steam along their surface
- The blades are designed to effectively tap both the impulse and reaction force of the steam for higher efficiency
Steam Turbines

Rankine cycle with superheat

1-2: The working fluid (water) is pumped from low to high pressure.
2-3: The high pressure liquid enters a boiler where it is heated at constant pressure by an external heat source to become a dry saturated vapor.
3-3’: The vapor is superheated.
3-4 and 3’-4’: The dry saturated vapor expands through a turbine, generating power.
This decreases the temperature and pressure of the vapor, and some condensation may occur.
4-1: The wet vapor then enters a condenser where it is condensed at a constant pressure to become a saturated liquid.
Steam Turbines
Steam Turbine Power Plant

Efficiency ~ 30 to 45%

Zimmer Power Station
Coal fired
1,300 MW
In service 1991

1. Cooling tower
2. Cooling water pump
3. Transmission line (3-phase)
4. Unit transformer (3-phase)
5. Electric generator (3-phase)
6. Low pressure turbine
7. Boiler feed pump
8. Condenser
9. Intermediate pressure turbine
10. Steam governor valve
11. High pressure turbine
12. Deaerator
13. Feed heater
14. Coal conveyor
15. Coal hopper
16. Pulverized fuel mill
17. Boiler drum
18. Ash hopper
19. Superheater
20. Forced draught fan
21. Reheater
22. Air intake
23. Economizer
24. Air preheater
25. Precipitator
26. Induced draught fan
27. Chimney Stack
Steam Power Plant

Cooling Tower-used to transfer heat from the condenser to the atmosphere
Steam Turbines

Diagram simplified:
Shaft seal and other minor extractions and returns not shown; thus mass rates do not balance exactly.

### FIG. 1.19 Heat balance. Ravenswood No. 3 Steam Power Plant. Nominal rating: 1000 MW. Data from Consolidated Edison Co. of New York.
Steam Power Plant

- Edison’s “jumbo dynamo” at the world’s first power station in Lower Manhattan
- Commercial operation of Pearl Street Station began on September 4, 1882
- The power plant’s efficiency was 1.6 percent

- Rheinhafen-Dampfkraftwerk (RDK)
- in Karlsruhe, Germany
- The 912 facility using GE technology achieved a 47.5 percent net thermal efficiency
- The steam pressure is 4,000 pounds per square inch
- The steam temperature is 1,112 degrees Fahrenheit
Steam Power Plant

- Rheinhafen-Dampfkraftwerk (RDK) in Karlsruhe, Germany

- The boiler is brown
- The horizontal water feeder white
- The ultra supercritical turbine is purple
- The generator (in yellow) is attached to the turbine
- It can produce 912 megawatts

A 3D rendition of the power plant
Internal Combustion Engines
Fire, Smoke and Noise

• Piston engines
  – Otto Cycle-Spark Ignition
  – Diesel Cycle-Compression Ignition

• Brayton Cycle engines
  – Gas Turbines
  – Jet engines

• Rocket Engines
  – Liquid Fuel
  – Solid Fuel

• Fire Arms