Steam Power Plants

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Department of Mechanical Engineering
Indian Institution of Technology Dharwad
Course: ME 307 Applied Thermodynamics

Credits: 3-0-0-6

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<th>Slot 3</th>
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Books

Lecture Plan

Steam Power Plants
- Rankine cycle
- Improving Performance: Superheat, Reheat, Regeneration

Refrigeration
- Vapor-compression cycle
- Refrigerant properties

Psychrometry
- Psychrometric principles
- Wet-bulb and dry-bulb temperatures
- Psychrometric charts
- Analyzing Air-conditioning processes
Electricity in India

- Imagine world without electricity or our campus with only 2 or 3 hours of electricity.
- Where do we get this electricity from?
- Most of the energy in India come from Coal or Natural Gas.
Electricity Generation in India

Total Electrical Energy: 753.7 MToe

- Coal
- Petroleum or Liquids
- Natural gas
- Nuclear
- Hydroelectricity
- Renewable sources

\(^0\)BP Statistical Review of World Energy 2018
Coal

- Coal is the major source of electric power generation in India.
- Abundant coal reserves and a rail system allowing for smooth distribution of coal to electricity producers.
- Causes significant human-health and environmental-impact issues associated with coal.
- Burning fossil fuels, coal-fired vapor power plants are the major sources for the concentration of CO$_2$.
- CO$_2$ emissions can be reduced by using fossil fuels more efficiently and avoiding wasteful practices.
- One option involves removal of CO$_2$ from the exhaust gas of power plants, oil and gas refineries, and other industrial sources followed by storage (sequestration) of captured CO$_2$.
- What to do with the stored CO$_2$?
- May be use for enhanced oil recovery, to produce algae, a tiny single-cell plant, and to use solar energy to break the molecule and produce hydrocarbon. All these concepts are in early stages of development.
The word "thermo-dynamic," used first by Thomson (later Lord Kelvin, 1824-1907)\(^1\), has Greek origin

- \(\theta\acute{e}\rho\mu\eta\), therme: heat
- \(\delta\acute{u}n\alpha\mu\zeta\), dynamis: power

Thermodynamics is based on empirical observation. These findings have been formalized into certain basic laws.

**Thermodynamics**

The science that deals with heat and work and those properties of matter that relate to heat and work.

Formalize the relationship between heat, work, and energy

\(^1\)W. Thomson, *An account of Carnot’s theory of the motive power of heat; with numerical results deduced from Regnault’s experiments on steam*, Transactions of the Royal Society of Edinburgh, 1849(16):541-574. Weblink
<table>
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<td>AD</td>
<td>Reported Thermal engines</td>
<td>Hero of Alexandria</td>
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</table>
Hero of Alexandria: **Reported thermal engines**

- c. 10–85 AD (no evidence)
- No biographies, only few altered manuscripts\(^2\)
- Mathematician, physicist, engineer
- Taught at Alexandria’s Musaeum
- Books on Mathematics, Geometry, Engineering,
- Aeolipile, the **first steam turbine**
- Windwheel
- **Automated machines** for temples & theaters;
  Surveying instruments; military machines & weapons

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Otto von Guericke: Vacuum Pump

- 1601–1674
- German scientist, inventor, politician
- Air pump & Electrostatic generator
- No scientific explanation provided
- Impressed people in his wizardry: great leader
- Received "von" title
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<td>Nicolas Léonard Sadi Carnot</td>
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Nicolas L.S. Carnot: Idealized Heat Engines

- 1796-1832 36 years old
- Educated in science, art, language, and music
- Instructors: Gay-Lussac, Poisson, Ampère
- Fellow students: Navier, Coriolis
- French Army, military engineer
- Exposed to steam engine with father at Germany
- Back to Paris, wanted to increase $\eta$ from 3%
  - Was the available heat unlimited?
  - Can $\eta$ be improved with a different fluid or gas?

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Nicolas L.S. Carnot: Idealized Heat Engines

- At the age of 27, he published "Reflections on the Motive Power of Fire," Paris, 1824
- Introduced the reversibility
- Died at 36 due to cholera epidemic
- Fear of contaminated, his writings were buried with him
- "Father of Thermodynamics"

![Carnot efficiency diagram](image)
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<td>1840</td>
<td>1\textsuperscript{st} law</td>
<td>Germain Henri Hess</td>
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<tr>
<td>1840s</td>
<td>Relates heat and work</td>
<td>James P Joule</td>
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<tr>
<td>1847</td>
<td>Energy conservation</td>
<td>Hermann von Helmholtz</td>
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<tr>
<td>1848</td>
<td>Absolute zero temp.</td>
<td>Lord Kelvin</td>
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<tr>
<td>1850</td>
<td>2\textsuperscript{nd} law</td>
<td>Rudolf J.E. Clausius</td>
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<tr>
<td>1865</td>
<td>Entropy</td>
<td>Clausius</td>
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<tr>
<td>1870s</td>
<td>Statistical thermodynamics</td>
<td>Maxwell &amp; Ludwig Boltzmann</td>
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Vindhyachal Thermal Power Station, MP

Biggest plant in India: 5000 MW
Steam Power Plant

Schematic of a steam power plant
Introducing Vapor Power Plants

The Rankine cycle is the basic building block of vapor power plants. The components of four alternative vapor power plant configurations are:

1. fossil-fueled
2. nuclear-fueled
3. solar thermal
4. geothermal
Rankine Cycle

1. Condenser
2. Pump
3. Boiler
4. Turbine

$q_{in}$
$w_{pump,in}$
$q_{out}$
$w_{turb,out}$
Rankine Cycle

The diagram illustrates the Rankine cycle, which is used in steam power plants. The cycle consists of four processes:

1. **Process 1 to 2**: This is the isentropic expansion in the turbine, where the working fluid expands from state 1 to state 2. The work done is given by $w_{turb, out}$.
2. **Process 2 to 3**: This is the isobaric process in the condenser, where the fluid is cooled and condensed. The heat rejected is given by $q_{out}$.
3. **Process 3 to 4**: This is the isentropic compression in the pump, where the fluid is compressed from state 3 to state 4. The work required is given by $w_{pump, in}$.
4. **Process 4 to 1**: This is the isobaric process in the boiler, where the fluid is heated and vaporized. The heat added is given by $q_{in}$.

The cycle is closed, and the energy balance must be conserved throughout the process.
Rankine Cycle
Steam Power Plant

**Process 1-2**  A pump boosts the pressure of the liquid water prior to entering the boiler. To operate the pump, an input of energy is required.

**Process 2-3**  Energy is added to the water in the boiler, resulting, first, in an increase in the water temperature and, second, in a phase change. The hot products of combustion provide this energy. The working fluid is all liquid at state 2 and all vapor (steam) at state 3.

**Process 3-4**  Energy is removed from the high-temperature, high-pressure steam as it expands through a steam turbine. The output shaft of the turbine is connected to an electrical generator for the production of electricity.

**Process 4-1**  The low-pressure steam is returned to the liquid state as it flows through the condenser. The energy from the condensing steam is transferred to the cooling water.
Steam Power Plant

Process 1-2  Isentropic expansion of the working fluid through the turbine from saturated vapor at state 1 to the condenser pressure

Process 2-3  Heat transfer from the working fluid as it flows at constant pressure through the condenser with saturated liquid at state 3

Process 3-4  Isentropic compression in the pump to state 4 in the compressed liquid region

Process 4-1  Heat transfer to the working fluid as it flows at constant pressure through the boiler to complete the cycle
Evaluating Principal Work and Heat Transfers

Fluid kinetic and potential energy changes are neglected.

\[
\dot{W}_{\text{pump,in}} = \dot{m}(h_2 - h_1)
\]

Boiler, \( \dot{Q}_{\text{in}} = \dot{m}(h_3 - h_2) \)

\[
\dot{W}_{\text{turbine,out}} = \dot{m}(h_3 - h_4)
\]

Condenser, \( \dot{Q}_{\text{out}} = \dot{m}(h_2 - h_3) \)

If it is an internally reversible process through the pump then

\[
\frac{\dot{W}_{\text{pump,in}}}{\dot{m}} = \int_{1}^{2} \nu dP \approx \nu_1(P_2 - P_1)
\]
Performance Parameters: Thermal Efficiency

Thermal Efficiency, $\eta_{th} = \frac{\text{useful work produced}}{\text{energy supplied}}$

\[
\eta = \frac{\dot{W}_{\text{turbine, out}} - \dot{W}_{\text{pump, in}}}{\dot{Q}_{\text{in}}} = \frac{(h_3 - h_4) - (h_2 - h_1)}{h_3 - h_2}
\]

\[
\eta_{th} = 1 - \frac{h_4 - h_1}{h_3 - h_2}
\]

\[
\eta = \frac{\dot{Q}_{\text{in}} - \dot{Q}_{\text{out}}}{\dot{Q}_{\text{in}}} = 1 - \frac{\dot{Q}_{\text{out}}}{\dot{Q}_{\text{in}}}
\]
Back Work Ratio, \( bwr = \frac{\text{pump work input}}{\text{work developed by the turbine}} \)

\[
= \frac{\dot{W}_{\text{pump,in}}}{\dot{W}_{\text{turbine,out}}}
\]

\[
bwr = \frac{h_2 - h_1}{h_3 - h_4}
\]
Problem

Steam is the working fluid in an ideal Rankine cycle. Saturated vapor enters the turbine at 8.0 MPa and saturated liquid exits the condenser at a pressure of 0.008 MPa. The net power output of the cycle is 100 MW. Determine for the cycle

1. the thermal efficiency, 37.1%
2. the back work ratio, 0.84%
3. the mass flow rate of the steam, in kg/h, $3.77 \times 10^5$ kg/h
4. the rate of heat transfer, $\dot{Q}_{in}$, into the working fluid as it passes through the boiler, in MW, 269.77 MW
5. the rate of heat transfer, $\dot{Q}_{out}$, from the condensing steam as it passes through the condenser, in MW, 169.75 MW
6. the mass flow rate of the condenser cooling water, in kg/h, if cooling water enters the condenser at 15°C and exits at 35°C. $7.3 \times 10^6$ kg/h
Determine the maximum possible thermal efficiency for an industrial steam power plant operating with a high pressure of 1 MPa and a low pressure of 5 kPa. The power plant operates on a Rankine cycle with the steam entering the turbine as saturated vapor. Also determine the ratio of the pump power to the turbine power.

\[ \eta = 29.15\%, \ bwr = 0.0013 \]
Problem

Determine the maximum possible thermal efficiency for an industrial steam power plant operating with a high pressure of 1.5 MPa and a low pressure of 5 kPa. The power plant operates on a Rankine cycle with the steam entering the turbine as saturated vapor. Also determine the ratio of the pump power to the turbine power.

\[ \eta = 31.1\% \]
Problem

Determine the maximum possible thermal efficiency for an industrial steam power plant operating with a high pressure of 1 MPa and a low pressure of 5 kPa. The power plant operates on a Rankine cycle with the steam entering the turbine as saturated vapor. Also determine the ratio of the pump power to the turbine power. The turbine has an isentropic efficiency of 0.90.

$$\eta = 26.2\%$$
Problem

Determine the maximum possible thermal efficiency for an industrial steam power plant operating with a high pressure of 1 MPa and a low pressure of 5 kPa. The power plant operates on a Rankine cycle with the steam entering the turbine as saturated vapor. Also determine the ratio of the pump power to the turbine power. The pump has an isentropic efficiency of 0.60.

\[ \eta = 29.1\% \]
Effects of Higher and Lower Pressures

Increase in $w_{net}$
Effects of Superheat

Increase in $w_{\text{net}}$
Comparison with Carnot Cycle

Cooling curve for the products of combustion
Principal Irreversibilities and Losses

\[ \eta_t = \frac{\dot{W}_t}{\dot{W}_{ts}} \]
\[ \eta_p = \frac{\dot{W}_{ps}}{\dot{W}_p} \]
Improving Performance: Superheat, Reheat

Diagram showing a thermodynamic cycle with labeled points:
- Boiler
- High-P turbine
- Low-P turbine
- Reheater
- Condenser
- Pump

Equation: \[ P_4 = P_5 = P_{\text{reheat}} \]

Graph showing temperature vs. entropy (T-s) with labeled points:
- High-pressure turbine
- Reheating
- Low-pressure turbine
Improving Performance: Supercritical
Steam is the working fluid in an ideal Rankine cycle with superheat and reheat. Steam enters the first-stage turbine at 8.0 MPa, 480°C, and expands to 0.7 MPa. It is then reheated to 440°C before entering the second-stage turbine, where it expands to the condenser pressure of 0.008 MPa. The net power output is 100 MW. Determine the thermal efficiency of the cycle, the mass flow of steam in kg/h, the rate of heat transfer from the condensing steam as it passes through the condenser, in MW. Discuss the effects of reheat on the vapor power cycle.

$$\eta_{th} = 40.3\%, \dot{m} = 2.363 \times 10^5 \text{ kg/h, } \dot{Q}_{out} = 148 \text{ MW}$$
Importance of Regenerator

- Low-temperature heat addition
- Steam entering boiler
- Steam exiting boiler
Open Feedwater Heaters

Diagram:

1. Condenser
2. Pump I
3. Open FWH
4. Pump II
5. Boiler
6. Turbine

Flows:
- 1 → 2
- 2 → 3
- 3 → 4
- 4 → 5
- 5 → 6
- 6 → 7
- 7 → 1
- y → 6
- (1 - y) → 7

Nodes:
- Boiler
- Open FWH
- Turbine
- Condenser
Open Feedwater Heaters
Open Feedwater Heaters

\[ y = \frac{\dot{m}_6}{\dot{m}_5} \]

\[
\dot{W}_{\text{pump, in}} = \dot{m}(h_2 - h_1) + (1 - y)\dot{m}(h_4 - h_3)\dot{Q}_{\text{out}} = (1 - y)\dot{m}(h_7 - h_1)
\]

\[
\dot{W}_{\text{turbine, out}} = \dot{m}(h_5 - h_6) + (1 - y)\dot{m}(h_6 - h_7)
\]

\[
\dot{Q}_{\text{in}} = \dot{m}(h_5 - h_4)
\]

\[
\dot{w}_{\text{pump, I}} = \nu_1(P_2 - P_1)
\]

\[
\dot{w}_{\text{pump, II}} = \nu_3(P_4 - P_3)
\]
Consider a steam power plant operating on the ideal regenerative Rankine cycle with one open feedwater heater. Steam enters the turbine at 15 MPa and 600°C and is condensed in the condenser at a pressure of 10 kPa. Some steam leaves the turbine at a pressure of 1.2 MPa and enters the open feedwater heater. Determine the fraction of steam extracted from the turbine and the thermal efficiency of the cycle.

\[
\frac{m_6}{m_5} = 0.2270, \eta_{th} = 46.3\%
\]
Closed Feedwater Heaters
Closed Feedwater Heaters

- The condensed steam is then either pumped to the feedwater line or routed to another heater or to the condenser through a device called a trap.
- A trap allows the liquid to be throttled to a lower pressure region but traps the vapor.
- The enthalpy of steam remains constant during this throttling process.
Closed Feedwater Heaters
Open vs Closed Feedwater Heaters

**Open Feedwater Heater**
- Simple and inexpensive and have good heat transfer characteristics
- Brings the feedwater to the saturation state
- For each heater, however, a pump is required to handle the feedwater

**Closed Feedwater Heaters**
- More complex because of the internal tubing network, and thus they are more expensive
- Heat transfer in closed feedwater heaters is also less effective since the two streams are not allowed to be in direct contact
- However, closed feedwater heaters do not require a separate pump for each heater since the extracted steam and the feedwater can be at different pressures
Most steam power plants use combination of open and closed FWHs.
Co-generation

Some industries rely heavily on process heat are chemical, pulp and paper, oil production and refining, steel making, food processing, and textile industries. Process heat in these industries is usually supplied by steam at 5 to 7 atm and 150 to 200°C.

The production of more than one useful form of energy (such as process heat and electric power) from the same energy source.
Combined Gas-Vapor Power Cycles

- The maximum fluid temperature at the turbine inlet is about 620°C for modern steam power plants, but over 1425°C for gas-turbine power plants and over 1500°C at the burner exit of turbojet engines.
- The use of higher temperatures in gas turbines is made possible by recent developments in cooling the turbine blades and coating the blades with high-temperature-resistant materials such as ceramics.
- Because of the higher average temperature at which heat is supplied, gas-turbine cycles have a greater potential for higher thermal efficiencies.
- However, the gas-turbine cycles have one inherent disadvantage: the gas leaves the gas turbine at very high temperatures (usually above 500°C), which erases any potential gains in the thermal efficiency.
- The situation can be improved somewhat by using regeneration, but the improvement is limited.
Combined Gas-Vapor Power Cycles
Combined Gas-Vapor Power Cycles

- Energy is recovered from the exhaust gases by transferring it to the steam in a heat exchanger that serves as the boiler.
- In general, more than one gas turbine is needed to supply sufficient heat to the steam.
- Also, the steam cycle may involve regeneration as well as reheating.
- Energy for the reheating process can be supplied by burning some additional fuel in the oxygen-rich exhaust gases.
- Recent developments in gas-turbine technology have made the combined gas–steam cycle economically very attractive.
- The combined cycle increases the efficiency without increasing the initial cost greatly.
- Consequently, many new power plants operate on combined cycles, and many more existing steam- or gas-turbine plants are being converted to combined-cycle power plants.
- Thermal efficiencies well over 40 percent are reported as a result of conversion.
A 1350-MW combined-cycle power plant built in Ambarli, Turkey, in 1988 by Siemens of Germany is the first commercially operating thermal plant in the world to attain an efficiency level as high as 52.5 percent at design operating conditions.

This plant has six 150-MW gas turbines and three 173-MW steam turbines.

Some recent combined-cycle power plants have achieved efficiencies above 60 percent.
Consider the combined gas–steam power cycle. The topping cycle is a gas-turbine cycle that has a pressure ratio of 8. Air enters the compressor at 300 K and the turbine at 1300 K. The isentropic efficiency of the compressor is 80 percent, and that of the gas turbine is 85 percent. The bottoming cycle is a simple ideal Rankine cycle operating between the pressure limits of 7 MPa and 5 kPa. Steam is heated in a heat exchanger by the exhaust gases to a temperature of 500°C. The exhaust gases leave the heat exchanger at 450 K.

Determine (a) the ratio of the mass flow rates of the steam and the combustion gases and (b) the thermal efficiency of the combined cycle.

\[
\frac{\dot{m}_s}{\dot{m}_g} = 0.131, \eta = 48.7\%
\]
Problem