University of Jordan
Chemical Engineering Department
Chemical Engineering Thermodynamics (1) –

Lecture 16: Power Generation Cycles

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Outline

- Sources for power generation.
- Power generation from fossil fuels
  - Idealized cycles.
  - Rankine: Steam power cycle.
  - Internal combustion engine: Otto and Diesel cycles.
  - Brayton: Gas-turbine engines.
  - Jet engines and rocket engines.

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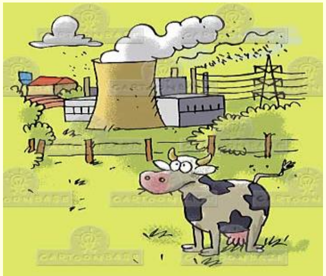
Energy Sources

- Energy Source
  - Nuclear
    - Fusion
    - Fission
  - Fossil fuels
    - Natural gas
    - Petroleum
    - Coal and derivatives
    - Other: tar sand, oil shale etc.
  - Electro-chemical
    - Fuel cells
  - Hydro-electric
  - Alternate
    - Solar: collectors & photovoltaic
    - Wind
    - Biomass
    - Geothermal, Tidal etc.



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Hierarchy of Power Production

- Power Generation
  - Steam power plant
    - Rankine Cycle
  - Internal combustion engine
    - Spark-ignition
      - Otto Cycle
    - Compression-ignition
      - Diesel Cycle
  - Gas-turbine engine
    - Brayton Cycle
  - Jet & rocket engines

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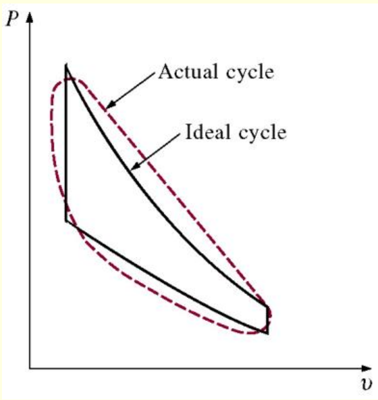
Ideal Cycles

- The majority of power production processes are operated cyclically.
- The analysis of real cycles is difficult. Consequently, resort to idealized cycles.
- **Ideal cycle**. A cycle that resembles an actual cycle closely but is made up totally of internally reversible processes



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Analysis of Power Cycles – Assumptions

- When treating idealized cycles, the following assumptions are implicitly involved:
  - Frictionless cycle i.e., the working fluid is not experiencing any pressure drop.
  - All expansion/compression processes take place in a quasi-equilibrium manner.
  - Heat transfer to the surroundings from the pipes in the process is assumed to be negligible.

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Analysis of Power Cycles – Efficiency

- The efficiency as always is defined as the desired output divided by the required input.
- For power generation cycles work is obtained by supplying energy.
- The efficiency of a power cycle is defined as the ratio of extracted work to the supplied heat i.e.,

$$\eta = \frac{W_{\text{net,out}}}{Q_{\text{in}}} \qquad (1)$$

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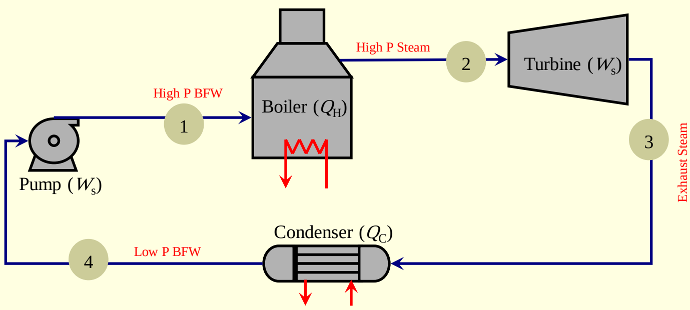
The Steam Power Plant (SPP)



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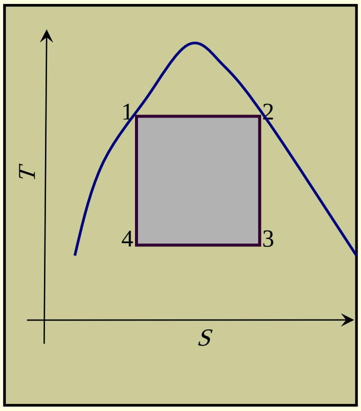
Pitfalls of the Carnot Engine for SPP

- There are practical limitations that makes operating a steam power plant as a Carnot engine infeasible:
  - Step 2→3. Turbines that takes in saturated steam, produce an exhaust with high liquid content, which in turn causes severe erosion.
  - Step 4→1. Very hard to design a pump which takes a wet steam stream and discharges a saturated liquid.



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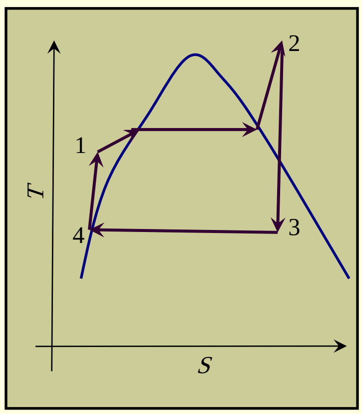
Rankine Cycle

- 1→2 Isobaric heating in the boiler
  - Heating a subcooled liquid to T^{sat}.
  - Isothermal-Isobaric vaporization.
  - Superheating of vapor.
- 2→3 Isentropic expansion to P in the condenser.
- 3→4 Isothermal-Isobaric condensation.
- 4→1 Isentropic compression of a saturated liquid to P in the boiler to get a subcooled liquid.



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Analysis for the Rankine Cycle

- Two work, and two heat contributions occur in the Rankine cycle:
  - Heat transfer in the boiler (**supplied**).
  - Heat transfer in the condenser (**rejected**).
  - Work in the turbine (**extracted**).
  - Work in the pump (**supplied**).

$$\begin{aligned} W_{s,\text{Rankine}} &= Q_{\text{Condenser}} - Q_{\text{Boiler}} \\ &= W_{s,\text{pump}} - W_{s,\text{Turbine}} \end{aligned} \qquad (2)$$

$$\eta = \frac{\left|W_{s,\text{Rankine}}\right|}{Q_{\text{Boiler}}} \qquad (3)$$

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Internal Combustion Engines

Steam power plant
- Working fluid (steam) is inert.
- Does not come into direct contact with the heat source/sink.
- Heat transfer occurs through walls that may impose a limit on the absorption/rejection of heat.

- Internal combustion engine (ICE)
  - Fuel is burned within the engine itself.
  - Combustion products serve as the working fluid.
  - High temperatures are internal and does not involve heat transfer surfaces.
  - Flow is continuous (**not cyclic**).

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Analysis of ICE

- The working medium in an ICE does not go through a cyclic process.
- Analysis uses cycles equivalent to the effects produced to the medium:
  - Cyclic engines with air replaces the ICE.
  - These cyclic engines are equivalent in performance to the actual ICE.
  - The combustion step is replaced by the addition of an equivalent amount of heat to the air.

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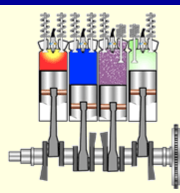
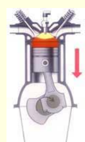
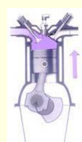
Steps in an ICE







Induction stroke	Compression stroke	Power stroke	Exhaust stroke
The inlet valve is open, the exhaust valve closed. The piston descends, inducing a flow of mixture. Soon after this stroke, the inlet valve is closed.	Both inlet and exhaust valves are closed. The rising piston compresses the mixture in the combustion chamber and compression heat vaporizes the mixture.	Both valves remain closed. The compressed gas is ignited by a spark from the spark-plug. Expansion of burning gas drives the piston down. Exhaust valve opens.	The inlet valve is closed, and exhaust valve open. The piston rises to expel burnt gases, inlet valve opens, exhaust valve closes. Then the cycle restarts.

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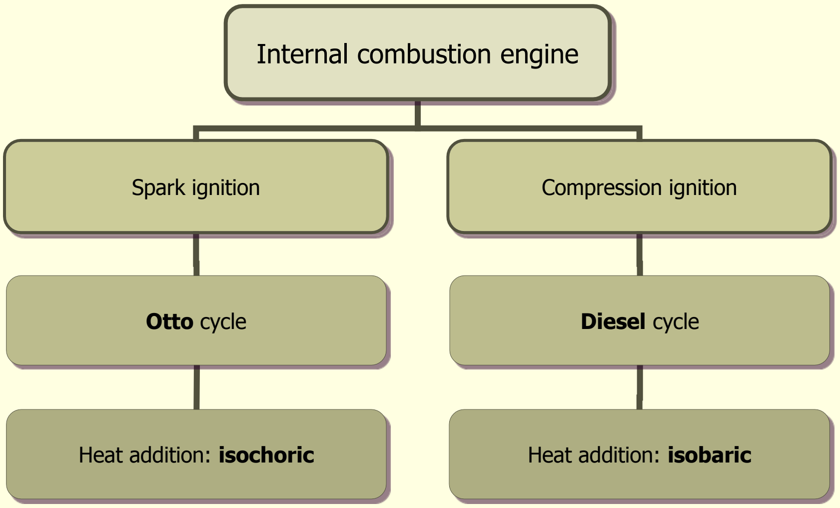
www.cybersteering.com/cruise-feature-engine-crankshaftrun_gif.htm

Air-Standard Otto and Diesel Engines



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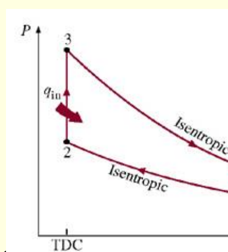
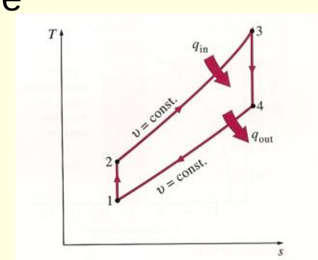
Air-Standard Otto Engine

- Four steps:
  - 1→2 Isentropic compression.
  - 2→3 ***Isochoric heating***.
  - 3→4 Isentropic expansion.
  - 4→1 Isochoric cooling.
- The compression ratio (r) is the ratio between the volumes at the beginning and end of the compression stroke.

$$r = \frac{V_{max}}{V_{min}} = \frac{V_1}{V_2} \qquad (4)$$





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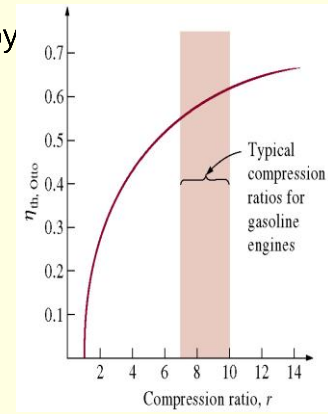
Thermal Efficiency of the Otto Engine

- The thermal efficiency of the Otto engine is the work output divided by the heat input i.e.,

$$\eta = \frac{|W_{s,\text{net}}|}{Q_{23}} = 1 - \frac{T_4 - T_1}{T_3 - T_2} \qquad (5)$$

- The thermal efficiency is related to the compression ratio by

$$\eta = 1 - \left(\frac{1}{r}\right)^{\gamma - 1} \qquad (6)$$



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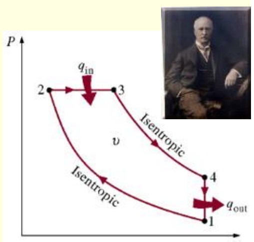
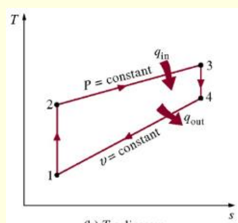
Air-Standard Diesel Engine

- Four steps:
  - 1→2 Isentropic compression.
  - 2→3 ***Isobaric heating***.
  - 3→4 Isentropic expansion.
  - 4→1 Isochoric cooling.
- The efficiency is a function of the compression ratio (r) and the expansion ratio (r_e)

$$r_e = \frac{V_4}{V_3} \qquad (7)$$



(a) P- v diagram



(b) T-s diagram

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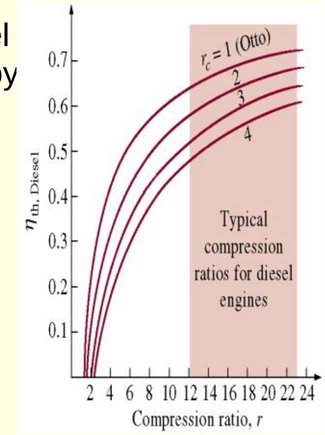
Thermal Efficiency of the Diesel Engine

- The thermal efficiency of the Diesel engine is the work output divided by the heat input i.e.,

$$\eta = \frac{\left|W_{s,\text{net}}\right|}{Q_{23}} = 1 - \frac{1}{\gamma}\frac{T_4 - T_1}{T_3 - T_2} \qquad (8)$$

- The thermal efficiency is related to the compression and expansion ratios by

$$\eta = 1 - \frac{1}{\gamma}\left(\frac{\left(1/r_e\right)^{\gamma-1} - \left(r_e/r\right)\left(1/r\right)^{\gamma-1}}{\left(1/r_e\right) - \left(1/r\right)}\right) \qquad (9)$$



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Efficiency of the Otto and Diesel Cycles

- For the same compression ratio, the Otto engine has a higher efficiency than the Diesel engine.
- Preignition limits the compression ratios attainable in the Otto engine. Therefore, the Diesel engine operates at higher compression ratios, and consequently at higher efficiencies.

The Gas-Turbine Engine

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- Otto and Diesel cycles
  - Apply direct energy of high-T, high-P gases acting on a piston within a cylinder.
  - No heat transfer with an external source is required
- **Turbines are more efficient than reciprocating engines**.
- Gas-turbine engine
  - Advantages of internal combustion engines are utilized
  - The advantage of the more efficient turbine is used instead of the piston and cylinder assembly.

Gas-Turbines as a Brayton Cycle

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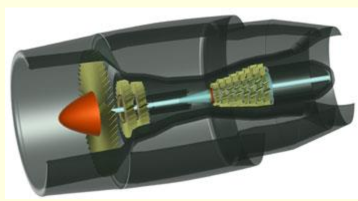
- Gas-turbines operate continuously. However, the Brayton cycle is used to describe them as was the case with the ICE.
- Two major substitutions
  - The combustion process is replaced by a constant-pressure heat-addition process.
  - The exhaust process is replaced by a constant-pressure heat-rejection process



The Brayton Cycle

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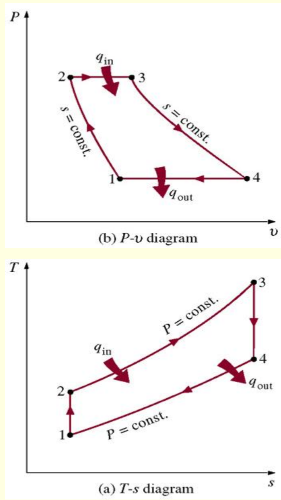

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Thermal Efficiency of the Brayton Cycle

- Thermal Efficiency

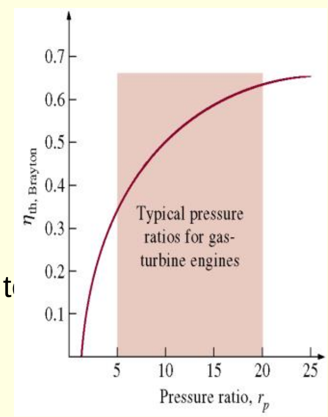
$$\eta = \frac{|W_{s,\text{net}}|}{Q_{23}} = \frac{|W_{34}| - |W_{12}|}{Q_{23}} \qquad (10)$$

- For an Air-standard cycle with the assumption of ideal gas being valid

$$\eta = 1 - \frac{T_4 - T_1}{T_3 - T_2} \qquad (11)$$

- The pressure ratio is the discharge t suction pressures $r_P = P_2/P_1$.

$$\eta = 1 - \left(\frac{1}{r_P}\right)^{\frac{\gamma-1}{\gamma}} \qquad (12)$$



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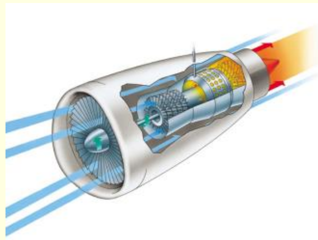
Jet Engines

- In an ICE or a gas-turbine the power becomes available through a rotating shaft.
- An alternate to expand the gases is to use a nozzle that will provide power in the form of kinetic energy.
- The **jet engine** is a **power plant** with **compression**, **combustion** and the **nozzle**.



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Rocket Engines

- Rocket engines differ from jet engines in that the oxidizing agent is carried with the engine
  - Rocket is self contained, does not need an outside source e.g., ambient air.
  - Rocket can operate in vacuum or outer space.
  - Solid and liquid fueled rockets require essentially no compression work.

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Liquid and Solid Fueled Rockets

Rockets

- Liquid Fueled
  - Fuel: combustible material e.g., a petroleum fraction
  - Oxidizing agent: liquid oxygen
- Solid Fueled
  - Fuel: organic polymers
  - Oxidizing agent: May be different than oxygen e.g., perchlorates

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