02-Power Plants

Text: 1.2 – 1.5

ECEGR 451
Power Systems

Overview

- Generation Statistics
- Thermodynamic Cycles

Generation

- Total number of generators in U.S.: 16,924
  - Natural Gas: 5,470
  - Hydro: 3,988
  - Petroleum: 3,744
  - Coal: 1,493
  - Renewables: 1,823
  - Nuclear: 104
- Total nameplate capacity: 1,075,000 MW

Exercise

Power plants do not supply full (rated) power continuously.

How much electrical energy would be generated if all power plants in the U.S. supplied rated power continuously over the course of one year?

How does this compare to the annual electrical energy consumption in the U.S.?

[hint: total electrical consumption in the U.S. was 3,726 TWh in 2011]

Exercise

How much electrical energy would be generated if all power plants in the U.S. supplied rated power continuously over the course of one year?

1,075,000 x 8760 = 9,417,000,000 MW = 9,417 TWh

How does this compare to the annual electrical energy consumption in the U.S.?

Capacity Factor = 3,726/9,417 = 39.5%

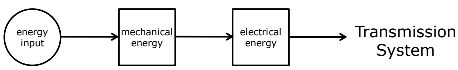
Why do you think the utilization is this low?

Generator Characteristics

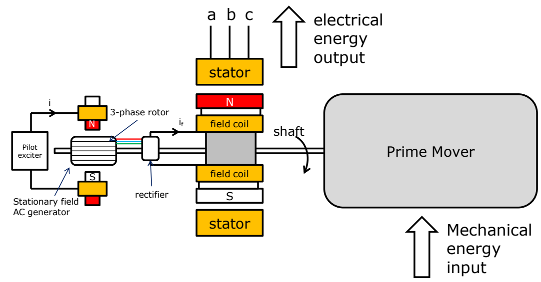
- Technical specifications rely largely on:
  - fuel source
  - thermodynamic cycle
  - generator (electrical)

Thermodynamic Cycles

- Common thermodynamic cycles:
  - Rankine
  - Brayton
- A working knowledge of each will suffice



Brushless Excitation



Thermodynamic Cycles

- Efficiency of the energy conversion process is never 100%

$$\eta = 100 \times \frac{P_o}{P_{in}}$$

- Where
  - P_o: output power (W)
  - P_{in}: input power (W)

Thermodynamic Cycles

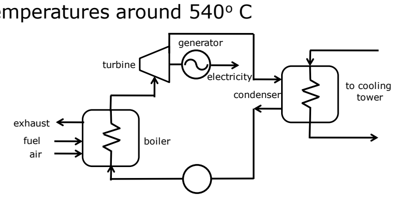
- Carnot Efficiency: upper limit of the efficiency of a thermodynamic process

$$\eta_c = 1 - \frac{T_C}{T_H}$$

- Where
  - T_c: temperature of cold reservoir (K)
  - T_h: temperature of hot reservoir (K)

Rankine Cycle

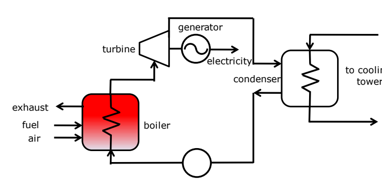
- Used in coal/nuclear power plants
- Steam is the working fluid
- Temperatures around 540° C



Rankine Cycle

Fuel is combusted in the boiler

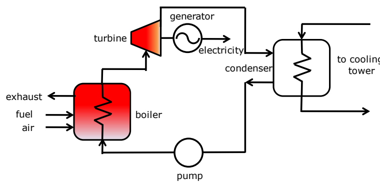
- Energy is transferred to the water, which vaporizes into steam



Rankine Cycle

Steam expands through the turbine

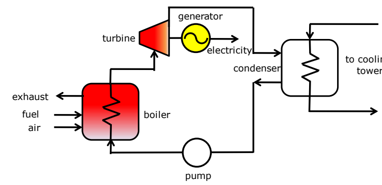
- Pressure is reduced
- Turbine shaft spins



Rankine Cycle

Synchronous generator produces electricity

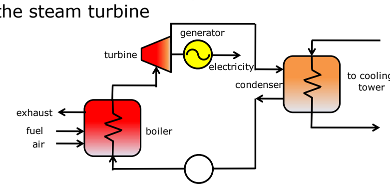
- Provides a counter torque to the shaft



Rankine Cycle

Steam is cooled in the condenser

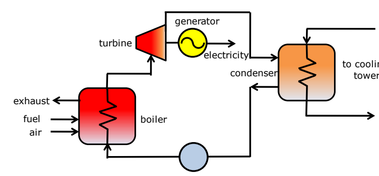
- Steam condenses into water
- Cooling of the working fluid helps suck the steam through the steam turbine



Rankine Cycle

Condensed water is pumped back into the boiler

- Work is required to operate the pump



Rankine Cycle Summary

- Heat is input into the boiler
- Work is input into the pump (small amount)
- Work is output by the turbine
- Heat is output by the condenser

Rankine Cycle

- Steam temperature is around 540°C
  - Thermal stress limitations
- Condensed water is around 30°C
- What is the upper (Carnot) efficiency of this operation?

Rankine Cycle

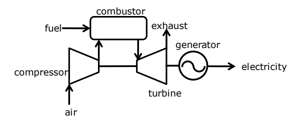
- Carnot efficiency is:

$$\eta_c = 1 - \frac{T_C}{T_H} = 1 - \frac{30 + 273.15}{540 + 273.15} = 62.7\%$$

- In reality, this is much closer to 40%
- Many modifications exist
  - Reheating
  - Use of turbine stages

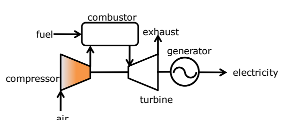
Brayton Cycle

- Used in natural gas power plants (Combustion Turbine (CT))
- Same cycle as jet engines
- Temperatures around 1400° C



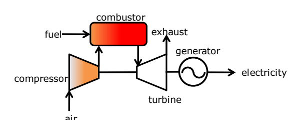
Brayton Cycle

- Air is compressed
  - Compression ratios up to 30:1
  - Compressor is mechanically driven by the turbine shaft



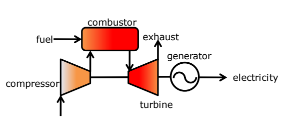
Brayton Cycle

- Compressed air is mixed with fuel (natural gas) and combusted
  - Very high temperature, up to 1400 °C



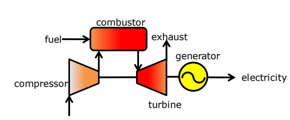
Brayton Cycle

- Gases expand in the turbine
  - Coupled with generator and compressor



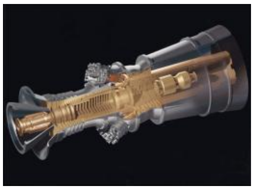
Brayton Cycle

- Synchronous generator produces electricity
  - Provides a counter torque to the shaft



Brayton Cycle

- High operating temperatures increase efficiency, but work required to compress decreases the efficiency
- Typically in the range of 25-35%



Generators

- There are many variations on the cycles described to increase efficiency
  - Combined cycle use the exhaust heat from a CT to generate steam
    - Efficiencies up to 60%
- If steam is used directly for another process, then efficiencies up to 85% can be realized

Generator Characteristics

- Approximately 90% of electrical energy generated use Rankine or Brayton cycles
- Large variation within these generator types

Generator Characteristics

- Capacity: maximum amount of real power that can be produced by an energy source, also known as nameplate capacity

- Capacity Factor: expressed as the percentage (energy produced)/(capacity x time under consideration), includes expected and unexpected outages

Generator Characteristics

- Real Power Limitations (max and min): minimum is usually dictated by stable combustion limitations, maximum is determined from equipment ratings

- Reactive Power Limitations (max and min): usually dictated by the generator exciter (limited by the field winding rating)

Generator Characteristics

- Regulation: the ability of a generator to vary its real power output up and down on time scales less than five minutes in accordance with a control signal.

- Start-up time: the amount of time it takes for a generator to safely be brought from an off state to its minimum generation amount.

- Shut-down time: time it takes for a generator to transfer from its minimum output to grid disconnection.

Comparison

Characteristic	Coal	Nuclear	Natural Gas
Thermodynamic Cycle	Rankine	Rankine	Brayton
Efficiency	35-45%	35-45?%	25-35%
P_{max} (includes plants with multiple generators)	0.5-3.2 GW	1-3.8 GW	<1GW
P_{min}	15-25% of P_{max}	???	Near 0
Capacity Factor	high	high	low
Start-up/Shut-down time	hours	hours to days+	Minutes
Ramp Rate	Slow (1%/min)	Very slow (hours)	Very fast (5%/min)
Regulation Range	±3-4%	None	±10%

Generator Types

- Steam Turbines and Combustion Turbines:
  - 2-pole (3600 rpm) round-rotor synchronous 4-pole (1800 rpm) round-rotor synchronous
- Hydro-Turbine
  - 50-pole (144 rpm) salient-pole synchronous
  - 24-pole (300 rpm) salient pole synchronous
  - Various other multi-pole designs
- Wind Turbine
  - Single/Doubly-fed induction generator with gear box