Lecture 5.44

Combined Cycle and Cogeneration Systems

Agenda

- Introduction to Cogeneration (CHP)
- Thermodynamic Principles of Cogeneration
- Applications and Benefits of Cogeneration
- Introduction to Combined Cycle Power Plants (CCPP)
- The Brayton-Rankine Combined Cycle
- Heat Recovery Steam Generators (HRSG)
- Performance and Efficiency Analysis
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Introduction to Cogeneration (CHP)

- Cogeneration, or Combined Heat and Power (CHP), is the simultaneous production of electricity and useful thermal energy from a single fuel source.
- In conventional power plants, a large portion of thermal energy is rejected to the environment via condensers or cooling towers (typically 50-70% loss).
- CHP systems capture this low-grade reject heat for industrial processes or district heating, increasing overall fuel utilization.
- Can be classified into Topping Cycle (electricity produced first, exhaust heat used) and Bottoming Cycle (high-temp heat used in process first, waste heat generates power).

Thermodynamics of Cogeneration

- Overall Thermal Efficiency (\ensuremath{\eta}_cog) = (W_net + Q_process) / Q_in.
- Utilization Factor (\ensuremath{\epsilon}_u): A more comprehensive metric for CHP, defined as the ratio of useful energy output (electrical + thermal) to the fuel energy input.
- Typical modern CHP systems can achieve Utilization Factors of 80% to 90%, compared to 35-40% for conventional isolated power plants.
- The back-pressure steam turbine is a common prime mover for topping cycles, where exhaust steam is delivered at a pressure suitable for the process heat requirement, rather than expanding to vacuum condenser pressure.

Cogeneration Plant Layout

- Boiler generates high-pressure steam.
- High-pressure steam expands in a turbine to generate electricity (W_out).
- Steam is extracted or exhausted at a specific pressure to satisfy industrial heating demands (Q_process).
- Condensate from the process is returned to the boiler feed pump.

Applications and Benefits of Cogeneration

- Industrial Applications: Chemical plants, paper mills, refineries, and food processing facilities with continuous steam demands.
- District Heating: Providing space heating and hot water to residential and commercial areas in cold climates.
- Economic Benefits: Significant reduction in overall fuel consumption and energy costs for facilities requiring both power and heat.
- Environmental Benefits: Reduced greenhouse gas emissions per unit of useful energy produced due to higher overall efficiency.

Introduction to Combined Cycle Power Plants (CCPP)

- A Combined Cycle Power Plant integrates a high-temperature topping cycle with a lower-temperature bottoming cycle to maximize efficiency.
- Most common configuration: Gas Turbine (Brayton cycle) as the topping cycle and Steam Turbine (Rankine cycle) as the bottoming cycle.
- Gas turbines reject exhaust gases at extremely high temperatures (500\ensuremath{^\circ}C to 600\ensuremath{^\circ}C).
- Instead of venting this heat to the atmosphere, it is routed to a Heat Recovery Steam Generator (HRSG) to produce steam.

The Brayton-Rankine Combined Cycle

- Synergy of cycles: The Brayton cycle operates efficiently at high temperatures but has a high heat rejection temperature. The Rankine cycle operates well at lower temperatures.
- Overall Efficiency (\ensuremath{\eta}_cc) = \ensuremath{\eta}_gas + \ensuremath{\eta}_steam - (\ensuremath{\eta}_gas * \ensuremath{\eta}_steam).
- Modern Brayton-Rankine CCPPs achieve thermal efficiencies exceeding 60% (Lower Heating Value basis).
- Provides fast start-up capability from the gas turbine side, crucial for grid stability and peaking loads, combined with the high efficiency of the steady-state steam cycle.

T-s Diagram of Combined Cycle

- Top loop: Brayton cycle representing compressor, combustion chamber, and gas turbine.
- Bottom loop: Rankine cycle representing pump, HRSG (heat addition), steam turbine, and condenser.
- The critical interface is the heat exchange region where the cooling curve of the gas turbine exhaust matches the heating/boiling curve of the water/steam.

Heat Recovery Steam Generator (HRSG)

- The HRSG is a massive heat exchanger connecting the gas and steam cycles.
- Operates without supplementary firing (typically), relying entirely on gas turbine exhaust heat.
- Consists of three main sections: Economizer (preheats water), Evaporator (boils water to steam), and Superheater (increases steam temperature above saturation).
- Advanced CCPPs use multi-pressure HRSGs (dual or triple pressure) to minimize exergy destruction during heat transfer, better matching the gas cooling curve.

Efficiency and Performance Factors

- Gas Turbine Inlet Temperature (TIT): Higher TIT increases Brayton cycle efficiency and provides hotter exhaust for the Rankine cycle, boosting overall plant efficiency.
- Pinch Point Temperature Difference: A smaller pinch point increases heat recovery (more steam) but requires a exponentially larger, more expensive HRSG.
- Condenser Pressure: Lowering the condenser pressure in the steam cycle increases work output, subject to cooling water availability.
- Supplementary Firing: Sometimes burners are added in the HRSG duct to increase steam production during peak demand, though this generally lowers overall thermal efficiency.

Environmental Benefits and Economics

- Lower CO2 Emissions: Due to high efficiency (¿60%) and the use of natural gas (lower carbon-to-hydrogen ratio than coal), CCPPs emit about 50% less CO2 per MWh than traditional coal plants.
- Reduced Water Usage: Only the steam cycle portion requires cooling water, making CCPPs consume roughly 1/3 the water of a comparable conventional steam plant.
- Capital Cost and Build Time: Lower capital cost per kW and faster construction times compared to nuclear or large coal facilities.
- Flexibility: Highly adaptable to cyclic operation, complementing intermittent renewable energy sources on the modern grid.

Summary

- Cogeneration (CHP) improves fuel utilization (up to 90%) by simultaneously producing electrical power and useful thermal energy for industrial processes.
- Combined Cycle Power Plants (CCPP) integrate a Brayton topping cycle with a Rankine bottoming cycle to achieve electrical efficiencies exceeding 60%.
- The HRSG acts as the vital link in a CCPP, recovering exhaust heat to drive the steam turbine.
- CCPPs offer significant environmental and economic advantages, including lower emissions, reduced water usage, and high operational flexibility.

Next Lecture Preview

- Next time, we will explore the Economic Analysis of Power Plants.
- We will discuss fixed costs, operating costs, and the levelized cost of energy (LCOE).
- Topics will include load curves, diversity factor, and capacity factor.
- Please review the fundamentals of engineering economics.