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Energy and Exergy Analysis of Combined Cycle Power Plant of Abadan

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Extended Abstract

1. Introduction

Combined cycle power plants are recognized as efficient, cost-effective, and environmentally friendly solutions for electricity generation. The core principle involves enhancing the simple Brayton cycle efficiency by recovering waste heat from gas turbine exhaust gases to produce steam and generate additional power in a steam turbine cycle. Over time, the performance of power plants degrades due to equipment wear and suboptimal operation of components such as ejectors, condensers, and heaters. Identifying critical points of energy and exergy loss through simulation and comparison with design conditions is essential for planning effective maintenance and optimization strategies. This study employs Thermoflow software, a robust tool for power plant design and simulation, to perform a detailed thermodynamic analysis of the Abadan CCPP, focusing on the impact of two different fuels. The research builds upon previous works that have utilized energy and exergy analyses to diagnose inefficiencies in various thermal and combined cycle plants, consistently identifying boilers/HRSGs and condensers as major sites of loss.

2. Methodology: Thermodynamic Analysis Framework

The thermodynamic assessment consists of two main parts: energy (First Law) analysis and exergy (Second Law) analysis.

2.1. Energy Analysis

The First Law of thermodynamics (energy balance) for a steady-flow control volume is applied to each component of the combined cycle. Key governing equations for the gas cycle (compressor, combustion chamber, gas turbine) and the steam cycle (dual-pressure HRSG, steam turbine, condenser) are derived. The overall thermal efficiency (η_{th}) of the combined cycle is defined as the net power output divided by the total fuel energy input. Component-specific equations calculate work inputs/outputs, heat transfer rates, and enthalpies at various state points.

2.2. Exergy Analysis

Exergy is defined as the maximum useful work obtainable when a system is brought into equilibrium with its environment. Exergy analysis quantifies the location, magnitude, and causes of thermodynamic irreversibilities (exergy destruction) within the cycle. The exergy destruction rate ($\dot{E}x_d$) and the Second Law (exergetic) efficiency (η_{II}) are calculated for each major component, including the air compressor, combustion chamber, gas turbine, duct burner, HRSG, steam turbine, and condenser. This analysis reveals the true thermodynamic value of energy degradation and pinpoints components with the highest improvement potential.

3. Case Study: Simulation of the Abadan Combined Cycle Power Plant

The Abadan CCPP model consists of four GE9171E gas turbine units (124.3 MW each) and two Siemens steam turbine units (160 MW each), paired with dual-pressure HRSGs. The simulation was developed in Thermoflow's GT Pro module using design data for ambient conditions, pressure ratios, turbine inlet temperatures, and steam cycle parameters. The analysis was conducted for two fuel scenarios:

1. **Natural Gas:** The primary fuel, with a Lower Heating Value (LHV) of 46,328 kJ/kg.
2. **Diesel Fuel:** An alternative, with an LHV of 31,325 kJ/kg.

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The simulation validated the model against plant design data, showing good agreement for parameters like gas turbine exhaust temperature (~556°C) and mass flow rate (~408.7 kg/s).

4. Results and Discussion

4.1. Energy Analysis Results

The overall energy (First Law) efficiency of the plant was calculated as **40.17% for natural gas** and **34.17% for diesel fuel**. The Sankey diagram of energy flows (Figure 4) shows that approximately 95.5% of the total input energy comes from fuel. However, only about 40.16% is converted to net electrical power. The largest energy loss occurs in the condenser (rejecting heat to the environment), accounting for roughly 35.5% of the total input energy, followed by stack losses at 21.84%.

4.2. Exergy Analysis Results

The exergy (Second Law) efficiency was found to be **46.28% for natural gas** and **40.36% for diesel fuel**, confirming the superior thermodynamic performance of natural gas. The exergy destruction breakdown (Figure 6) identifies the **gas turbine combustion chamber as the most significant source of irreversibility**, responsible for **27.66%** of the total exergy destruction. This is due to the high-temperature combustion process and the large temperature difference between the flame and the working fluid. The **HRSG is the second-largest contributor**, causing **8.89%** of exergy destruction. Component-level exergetic efficiencies were also determined, with the steam turbine showing the highest efficiency (~89.41%) and the condenser the lowest (~35.15%).

4.3. Comparative Fuel Performance

A direct comparison demonstrates that using natural gas improves both the energy and exergy efficiencies of the plant by approximately **6 percentage points** compared to diesel (Figure 9). The total exergy destruction rate is also lower for natural gas (51.4%) than for diesel fuel (57.11%). This establishes natural gas as the thermodynamically preferred fuel for this plant configuration, leading to more efficient resource utilization and lower irreversibilities.

5. Conclusion

This study presented a detailed energy and exergy analysis of the dual-pressure, duct-fired Abadan combined cycle power plant for two fuel types. The key conclusions are:

1. The **combustion chamber** is the paramount site of exergy destruction (27.66%), highlighting a key area for advanced research, though practical limits exist due to material constraints and NOx formation.
2. The **Heat Recovery Steam Generator (HRSG)** is the second major contributor to inefficiencies (8.89%), suggesting potential for optimization in heat exchange design.
3. The **condenser** is responsible for the largest energy loss, representing a significant heat rejection to the environment.
4. **Natural gas** proves to be a significantly more efficient fuel than diesel for this plant, yielding roughly **6% higher energy and exergy efficiencies** and resulting in lower overall exergy destruction.

The results provide a clear diagnostic map for prioritizing operational improvements and confirm the thermodynamic benefits of using natural gas in combined cycle power generation.

Keywords: Exergy analysis, Combined cycle, Heat recovery steam generator,exergy efficiency.
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