Thermodynamic Modeling of Power Cycles (Rankine & Brayton)

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1. Introduction

This report summarizes the numerical modeling of two distinct power generation cycles: a **Rankine Cycle** (steam power plant) and a **Brayton Cycle** (gas turbine). Using MATLAB, we simulated these systems to evaluate how design choices such as boiler pressure in steam plants or pressure ratios in jet engines affect performance. The models move beyond ideal textbook cases by incorporating component inefficiencies and variable fluid properties, utilizing principles from *Thermodynamics: An Engineering Approach* (Cengel & Boles).

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2. Task 1: The Rankine Cycle (Steam Power)

We modeled a steam power plant operating between a condenser pressure of 10 kPa and varying boiler pressures (5–15 MPa), with a fixed turbine inlet temperature of 500°C.

Modeling Assumptions:

- **Fluid:** Water/Steam (using standard steam table data).
- **Ideal vs. Real:** We compared the ideal cycle to a real cycle by applying isentropic efficiencies to the pump (eta_p = 0.85) and turbine (eta_t = 0.90).
- **Process:** We assumed isobaric (constant pressure) heat addition in the boiler and rejection in the condenser, which is standard per Cengel & Boles (Chapter 10).

Key Results & Engineering Interpretation:

- **Efficiency vs. Pressure:** Our parametric sweep showed that thermal efficiency increases as boiler pressure rises. However, the gains start to diminish at higher pressures. Pushing pressure too high (>15MPa) yields diminishing returns while drastically increasing the cost and safety risk of the piping.
- **The Back-Work Ratio (BWR):** A critical finding was the extremely low Back-Work Ratio (< 1%). Because water is a liquid (incompressible), the pump requires very little energy to raise the pressure.
    - *Significance:* This makes the Rankine cycle incredibly stable. Even if the pump becomes inefficient, it won't kill the system's net power output. This contrasts sharply with the gas turbine.

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3. Task 2: The Brayton Cycle (Gas Turbine)

We modeled a compact gas turbine for high-altitude use, focusing on how air density and pressure ratios impact design limits.

Modeling Assumptions:

- **Fluid:** Air (treated initially as Ideal Gas, then with variable specific heats).
- **Variable Physics:** We implemented a temperature-dependent specific heat C_p(T) model. As air heats up in the combustor (1300 K), it becomes "stiffer" (higher C_p), which our model showed leads to slightly

lower predicted efficiencies than the "Cold Air Standard" assumption usually taught in intro classes.

Key Results & Engineering Interpretation:

- **The "Sweet Spot" Trade-off:** The MATLAB sweep revealed a conflict:
  - **Max Efficiency** occurs at high pressure ratios (r_p > 20).
  - **Max Net Work** occurs at moderate ratios (r_p \approx 12).
  - *Decision:* For an aerospace startup, weight is critical. We recommend designing for **Max Work (r_p=12)** rather than max efficiency. A smaller engine producing more power per kg is better for flight than a heavy, hyper-efficient one.
- **The "Thin Air" Problem (Altitude):**
  - Efficiency stays roughly constant with altitude because it depends on temperature *ratios*, not absolute pressure.
  - However, **Net Power** drops drastically. At high altitude, low air density reduces the mass flow rate. Since Power = m*w_net,, the engine produces significantly less thrust at 30,000 ft than at sea level.

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4. Comparison & Conclusion

Comparing the two analyses highlights a fundamental thermodynamic difference:

Metric	**Rankine Cycle (Steam)**	**Brayton Cycle (Gas)**
Working Fluid	Phase-change (Liquid/Vapor)	Single Phase (Gas)
Compression	Pump (Liquid) = **Low Energy Cost**	Compressor (Gas) = **High Energy Cost**
Back-Work Ratio	Very Low (< 1%)	Very High (~40-50%)
Sensitivity	Stable. Pump inefficiency is negligible.	Sensitive. If the compressor fouls, the engine stalls.

References:

- Cengel, Y. A., & Boles, M. A. *Thermodynamics: An Engineering Approach*. McGraw-Hill Education. (Chapters 9 & 10).