Operational Reactor Safety
22.091/22.903

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Professor of the Practice

Lecture 8
Power Cycles for Nuclear Plants
Rankine and Brayton
Topics to be Covered

• Review of Rankine Cycle
  – Basic
  – Superheat
  – Multi-fluid cycles

• Brayton cycle
  • Pressure Ratios
Important Terms and Concepts

- Enthaply - \( h = \text{Btu/lbm} \) (heat content)
- Entropy - \( \text{Btu/}^0\text{R} \)
- Specific Heat - \( C_p \text{ Btu/lbm }^0\text{R} \) at constant pressure
- Mass Flow Rate = \( \dot{m} \) - lbm/hr
- Pressure Ratio - \( P_2/P_1 \) (For gas systems)
- Power – Watts - Btu/hr
- Work - Btu
- Efficiency - \( \frac{W_f - W_p}{Q_{in}} \) (Heat Added)
Governing Equations

• Heat Transfer
  – Mass flow, specific heat, temperature
  – Mass flow, specific enthalpy
  – Efficiency factors – heat loss

• Use of Steam Tables

• Quality
Rankine Cycle

FIG. 2-5. Schematic of two-loop nuclear power plant.

FIG. 2-4. Internally reversible Rankine cycle with saturated vapor.

Thermal Efficiency = Heat Added - Heat Rejected

Heat Added

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Important Equations

\[ Q_{\text{in}} = \dot{m} (h_1 - h_B) \]
\[ W_t = \dot{m} (h_1 - h_2) \]
\[ W_p = \dot{m} (h_B - h_3) \]
\[ Q_{\text{in}} = C_p \dot{m} (T_{\text{in}} - T_{\text{ou}}) \]

FIG. 2-4. Internally reversible Rankine cycle with saturated vapor.
Rankine Cycle with Feedwater Heaters

FIG. 2-9. Schematic of Rankine cycle with two closed-type feedwater heaters.
REFINED RANKINE CYCLE USING SUPERHEATING AND REGENERATIVE HEATING

Thermal Efficiency = \( \frac{(\text{Heat Added} - \text{Heat Rejected})}{\text{Heat Added}} \) \( \cong 0.42_{\text{max}} \)
Power Cycles

FIG. 2-12. Internally reversible Rankine cycle with superheat and a variable-temperature heat source.

FIG. 2-13. Ts diagram of internally reversible supercritical and reheat cycles.
Binary Cycle Plants

FIG. 2-16. Schematic of a mercury-steam binary-vapor power plant.
Gas Reactor Cycles

- Brayton Cycle
- Brayton-Rankine Dual Cycle
- Real Example – Pebble Bed
- Choices for Efficiency and Cost
  - Materials
  - Costs
  - Efficiency Trade-offs
Brayton Gas Cycle - Open

FIG. 7-1. The direct open cycle. (a) Cycle diagram; (b) $T_s$ diagram.
# Perfect Gas Relationships

<table>
<thead>
<tr>
<th>Process</th>
<th>$p, v, T$ relationships</th>
<th>$u_2 - u_1$</th>
<th>$h_2 - h_1$</th>
<th>$s_2 - s_1$</th>
<th>$W$ (nonflow)</th>
<th>$Q$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Isothermal</td>
<td>$T = \text{const}$</td>
<td>0</td>
<td>0</td>
<td>($R/J$) $\ln (v_2/v_1)$</td>
<td>($p_1v_1/J$) $\ln (v_2/v_1)$</td>
<td>($p_1v_1/J$) $\ln (v_2/v_1)$</td>
</tr>
<tr>
<td>Constant pressure</td>
<td>$p = \text{const}$</td>
<td>$c_v(T_2 - T_1)$</td>
<td>$c_p(T_2 - T_1)$</td>
<td>$c_v \ln (T_2/T_1)$</td>
<td>$p(v_2 - v_1)/J$</td>
<td>$c_p(T_2 - T_1)$</td>
</tr>
<tr>
<td>Constant volume</td>
<td>$v = \text{const}$</td>
<td>$c_v(T_2 - T_1)$</td>
<td>$c_p(T_2 - T_1)$</td>
<td>$c_v \ln (T_2/T_1)$</td>
<td>0</td>
<td>$c_v(T_2 - T_1)$</td>
</tr>
<tr>
<td>Isentropic (adiabatic reversible)</td>
<td>$s = \text{const}$</td>
<td>$c_v(T_2 - T_1)$</td>
<td>$c_p(T_2 - T_1)$</td>
<td>0</td>
<td>$p_2v_2 - p_1v_1$</td>
<td>$J(1 - \gamma)$</td>
</tr>
<tr>
<td>Throttling</td>
<td>$h = \text{const}$</td>
<td>0</td>
<td>0</td>
<td>($R/J$) $\ln (v_2/v_1)$</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Polytropic</td>
<td>$p, v^n = p_1v_1^n$</td>
<td>$c_v(T_2 - T_1)$</td>
<td>$c_p(T_2 - T_1)$</td>
<td>$c_v \ln (p_2/p_1)$</td>
<td>$p_2v_2 - p_1v_1$</td>
<td>$c_v \left(\frac{\gamma - n}{1 - n}\right) (T_2 - T_1)$</td>
</tr>
</tbody>
</table>

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Indirect Brayton Open Cycle

**FIG. 7-2.** The indirect open cycle.
Brayton Cycle – Direct Closed

FIG. 7-3. The direct closed cycle.
Indirect Closed Cycle – Gas to Gas
Indirect Gas to Steam Generator

FIG. 7-5. The indirect closed cycle, gas to water.
Specific Heats of Gases

![Graph showing the variation of molar specific heat at constant pressure for various gases: CO₂, Air, H₂, He.](image)

**FIG. 7-6.** Variation of molar $c_p$ with temperature for various gases.
Ideal Brayton Cycle

FIG. 7-7. An ideal Brayton cycle.
Non-Ideal Brayton Cycle

**FIG. 7-12.** Closed nonideal Brayton cycle with regeneration.
BRAYTON CYCLE WITH REGENERATIVE HEATING

Temperature

Entropy

B

Heat Added

Heat Rejected

P₁

P₂

A

D

E

F

C

Heat Sink

Cooling Water

Compressor

Regenerative Heat Exchanger

Heat Source

Turbine

B

A
Gas-Steam Reactor Power Plant

FIG. 8-1. Schematic of a simple-cycle gas-steam-reactor power plant.

FIG. 8-2. Temperature-enthalpy diagram of a gas-steam heat exchanger in simple cycle.
COMBINED CYCLE BRAYTON (Topping), RANKINE (Bottoming)
VARIOUS VAPOR POWER CYCLES OPERATING BETWEEN THE SAME TEMPERATURE LIMITS
BRAYTON CYCLE WITH REGENERATIVE HEATING

Temperature

Entropy

Heat Added

Heat Rejected

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Reading and Homework Assignment

1. Outside Reading El Wakil Chapters 7, 8
   1. Handout Problem
Handout Problem

Power Cycles and Heat Removal

1. An indirect closed cycle, gas to water reactor power plant generates $2 \times 10^{-6}$ lbm/hr of steam at 1,000 psia and 800 F from feedwater at 200 F. Helium coolant at 200 psia leaves the reactor at 840 F and the boiler at 540 F, is pumped with a polytropic exponent $n=1.50$, and undergoes a 60 psi pressure drop throughout the primary loop. (assume that 2/3 of the pressure drop occurs in the reactor vessel). Assuming no heat losses:

a. Draw the T-S diagram for this cycle including the helium loop.
b. Calculate the mass flow rate of the helium coolant
c. Calculate the reactor power output in Mw thermal
d. Calculate the thermal efficiency of the cycle