Content

Lecture 10 - overview

• Steam power plant (Rankine cycle)
  ➢ Superheating and reheating: thermodynamics
  ➢ Cycle with regenerator, supercritical cycle

• Organic Rankine Cycle

• Refrigeration: compression cycle (inverse Rankine)

• Brayton cycle (Gas Turbines)
  • Ideal vs real Brayton air cycle

• Regeneration

• Closed Brayton Cycle
Superheating and reheating

- The steam turbine: high expansion ratio ($\beta_P=1884$) and problem of condensation
- Our example: quality $q_4=0.81$. Max for current turbines $q_4=0.9$
- From Carnot: increase of $P$ is beneficial: thermal energy introduced at higher $T$
- Reheating
Supercritical cycle

- Efficiency: \( \eta_{\text{cycle}} \propto \frac{T_{\text{max}}}{T_{\text{min}}} \)
- Limit: materials
- Best steam power plants: (ultra) supercritical
- 300 bar and 630 °C, \( \eta_{\text{cycle}} = 48 \% \)
Regeneration (1)

- Need for deaeration

- Large inefficiency $\Rightarrow$ liquid preheating with steam spilled from the turbine
Regeneration (2)

- Positive and negative effect
- Ideal: continuous regeneration
  = Carnot (“Arab phoenix”)
- Common to all modern ECS and processes (heat integration)
Example: evaluation of regeneration

- Data as in the superheated cycle

- Steam extraction at 7 bar. It provides heating from 2 to 3

- Need to calculate state 3, 4, and 6
State 3 (dearator)
Organic Rankine Cycle turbogenerator

- Small capacity: from few kW up to 1-2 MW \(_e\) (optimal turbine)
- Renewable energy!
- Good for low-temperature heat sources (geothermal)
- Dry expansion
- Analysis: the same as steam cycle, but different fluid
Refrigeration

Vapor compression cycle

- Objective: cooling, thermal energy transfer (food, home, ..)

- Inverse Rankine cycle (same cycle shape in the T-s and P-h diagrams)

- Thermal power transfer is obtained by means of mechanical power (compression)

- Working fluid: refrigerant to match environment conditions
Vapor comp. cycle analysis: Input data

**INPUT DATA**

- Working fluid: R245fa
- Evaporation temperature: \( T = 268.15 \text{ K} \)
- Condensation temperature \( T = 305.15 \text{ K} \)
- Compressor: \( \eta_{\text{is, compr}} = 0.75 \)
## Properties of Saturated R245fa (Vapor-Liquid) as a Function of Temperature

**Thermodynamic model:** StanMix, R245fa

<table>
<thead>
<tr>
<th>Temp. (°C)</th>
<th>Pressure (bar)</th>
<th>Specific Volume (Liquid m³/kg, Vapor m³/kg)</th>
<th>Internal Energy (Liquid kJ/kg, Vapor kJ/kg)</th>
<th>Enthalpy (Liquid kJ/kg, Vapor kJ/kg)</th>
<th>Entropy (Liquid kJ/kg.K, Vapor kJ/kg.K)</th>
</tr>
</thead>
<tbody>
<tr>
<td>-50</td>
<td>0.031525</td>
<td>0.00005501, 4.381</td>
<td>-281.80, -73.0</td>
<td>-281.80, -59.2</td>
<td>-0.1017, -0.0133</td>
</tr>
<tr>
<td>-40</td>
<td>0.0626</td>
<td>0.00005580, 2.301</td>
<td>-270.75, -66.5</td>
<td>-270.75, -52.1</td>
<td>-0.9623, -0.0243</td>
</tr>
<tr>
<td>-30</td>
<td>0.116347</td>
<td>0.00006666, 1.288</td>
<td>-259.48, -59.7</td>
<td>-259.47, -44.7</td>
<td>-0.9149, -0.0317</td>
</tr>
<tr>
<td>-20</td>
<td>0.204148</td>
<td>0.00007599, 0.761</td>
<td>-247.97, -52.8</td>
<td>-247.96, -37.2</td>
<td>-0.8686, -0.0362</td>
</tr>
<tr>
<td>-10</td>
<td>0.340655</td>
<td>0.00008682, 0.472</td>
<td>-236.23, -45.7</td>
<td>-236.20, -29.6</td>
<td>-0.8231, -0.0381</td>
</tr>
<tr>
<td>-5</td>
<td>0.432692</td>
<td>0.00009171, 0.377</td>
<td>-230.26, -42.1</td>
<td>-230.23, -25.8</td>
<td>-0.8006, -0.0382</td>
</tr>
<tr>
<td>0</td>
<td>0.539665</td>
<td>0.00009875, 0.305</td>
<td>-224.23, -38.5</td>
<td>-224.19, -22.0</td>
<td>-0.7783, -0.0379</td>
</tr>
<tr>
<td>2</td>
<td>0.594483</td>
<td>0.00009999, 0.280</td>
<td>-221.79, -37.1</td>
<td>-221.75, -20.4</td>
<td>-0.7694, -0.0377</td>
</tr>
<tr>
<td>4</td>
<td>0.648715</td>
<td>0.00010274, 0.258</td>
<td>-219.35, -35.6</td>
<td>-219.31, -18.9</td>
<td>-0.7606, -0.0373</td>
</tr>
<tr>
<td>6</td>
<td>0.706857</td>
<td>0.00010749, 0.238</td>
<td>-216.90, -34.2</td>
<td>-216.85, -17.3</td>
<td>-0.7518, -0.0370</td>
</tr>
<tr>
<td>8</td>
<td>0.769109</td>
<td>0.00010774, 0.220</td>
<td>-214.43, -32.7</td>
<td>-214.38, -15.8</td>
<td>-0.7430, -0.0365</td>
</tr>
<tr>
<td>10</td>
<td>0.836777</td>
<td>0.00011020, 0.204</td>
<td>-211.96, -31.2</td>
<td>-211.90, -14.2</td>
<td>-0.7342, -0.0360</td>
</tr>
<tr>
<td>12</td>
<td>0.906772</td>
<td>0.00011277, 0.189</td>
<td>-209.47, -29.8</td>
<td>-209.41, -12.6</td>
<td>-0.7254, -0.0354</td>
</tr>
<tr>
<td>14</td>
<td>0.982612</td>
<td>0.00011548, 0.175</td>
<td>-206.98, -28.3</td>
<td>-206.91, -11.1</td>
<td>-0.7167, -0.0348</td>
</tr>
<tr>
<td>16</td>
<td>1.063417</td>
<td>0.00011811, 0.162</td>
<td>-204.47, -26.8</td>
<td>-204.39, -9.5</td>
<td>-0.7080, -0.0341</td>
</tr>
<tr>
<td>18</td>
<td>1.149416</td>
<td>0.00012100, 0.151</td>
<td>-201.95, -25.3</td>
<td>-201.86, -8.0</td>
<td>-0.6993, -0.0334</td>
</tr>
<tr>
<td>20</td>
<td>1.240841</td>
<td>0.00012390, 0.140</td>
<td>-199.41, -23.8</td>
<td>-199.32, -6.4</td>
<td>-0.6900, -0.0326</td>
</tr>
<tr>
<td>22</td>
<td>1.337929</td>
<td>0.00012686, 0.131</td>
<td>-196.87, -22.4</td>
<td>-196.77, -4.9</td>
<td>-0.6820, -0.0318</td>
</tr>
<tr>
<td>24</td>
<td>1.440924</td>
<td>0.00012999, 0.122</td>
<td>-194.31, -20.9</td>
<td>-194.21, -3.3</td>
<td>-0.6734, -0.0309</td>
</tr>
<tr>
<td>26</td>
<td>1.550073</td>
<td>0.00013330, 0.114</td>
<td>-191.74, -19.4</td>
<td>-191.63, -1.8</td>
<td>-0.6647, -0.0300</td>
</tr>
</tbody>
</table>
Refrigeration cycle: Analysis (1)
Refrigeration cycle:
Analysis (2)
Calculation of the COP
Brayton cycle

- Advantage of a gas cycle (simple, light)
- Why gas turbine came after steam engines
- Working fluid: air (ideal gas)
- Operating principle
- Processes
Brayton cycle calculation: Input data

**INPUT DATA: operating parameters**
- State 1, 293.15K (20 °C), 1.013 bar (atmospheric pressure)
- State 2, 0.4 MPa (4 bar)
- State 3, 798.15 K (525 °C), 0.4 MPa (4 bar)
- State 4, 1.013 bar

**INPUT DATA: components efficiencies**
- Compressor: \( \eta_{is, \text{comp}} = 0.65 \)
- Turbine: \( \eta_{is, \text{turb}} = 0.85 \)

Same as in the Rankine Cycle example
Assumptions

• Kinetic and potential energies negligible at states 1, 2, 3, and 4
• Compressor and turbine adiabatic
• No pressure drop in the heater
• The system is at steady state
• Equilibrium states at 1, 2, 3, and 4
• Air can be modeled as a polytropic ideal gas \((\gamma = 1.4 \ C_p = \text{const} = 1.04 \ \text{kJ/kg\cdot K})\) or as an ideal gas with \(C_p = C_p (T)\) (FluidProp/GasMix)
Compressor work (state 1&2)
Air Heating (state 3)
Turbine work (state 4)
Net power output and efficiency

Comparison with Superheated Rankine cycle for similar compression and expansion efficiencies, but higher TIT.

\[
\eta_{I,\text{Rankine}} = 0.34 \\
\eta_{II,\text{Rankine}} = 0.62
\]
Efficiency of the ideal Brayton cycle

\[ P_v = RT, \quad c_p = \text{const.}, \text{ isentropic compression/expansion} \]

\[ \eta = \frac{w_{\text{net}}}{q_{\text{in}}} = 1 - \frac{q_{\text{out}}}{q_{\text{heater}}} = 1 - \frac{c_p(T_4 - T_1)}{c_p(T_3 - T_2)} = 1 - \frac{T_4/T_1 - 1}{T_3/T_2 - 1} \cdot \frac{T_1}{T_2} \]

\[ \frac{T_4}{T_1} = \frac{T_3}{T_2} \Rightarrow \eta = 1 - \frac{T_1}{T_2}. \]

\[ \frac{T_1}{T_2} = \frac{T_3}{T_4} = \left( \frac{P_2}{P_1} \right)^{\frac{1}{\gamma}} \]

\[ \beta = \frac{P_2}{P_1} = \frac{P_3}{P_4} \]

\[ q = \frac{\gamma - 1}{\gamma} \]

\[ \eta = 1 - \beta^{-q} \quad \text{Depends only on } \beta \text{ and } \gamma \]
Ideal gas cycle

$$W_{\text{net}} \text{ max for } T_4 = T_2$$
Comparison real vs ideal cycle

• The most relevant losses are in the compressor and turbine: limitation of ideal-gas analysis ($\beta$ too high is a problem)

• Limit on TIT (blade cooling)

• Fuel issue
Gas Turbine

Advantages:

- High temperature & low pressure -> high power/weight
- No blade erosion with high-quality fuel
- Fast load-change

Applications:

- Aircraft propulsion (ships, trains)
- Combined Cycle, Peak-shaving
- Cars (for hybrid engines in the future?)
Gas turbine cycle: parameters

Ideal

$T_{IT} = 1400 \, ^\circ C$

$T_{IT} = 800 \, ^\circ C$, $900 \, ^\circ C$, $1000 \, ^\circ C$

$\beta(\eta_{\text{max}}, T_{IT})$
Regeneration

- Reduction of thermal losses
- Note: $T_4$ often in excess of 450 °C
- For given TIT, maximum efficiency at modest $\beta$ (increase $T_4 - T_2$)
- Recuperator: technological problem
Closed Brayton cycle gas turbine
Final remarks

- Importance of assumptions
- Always mass and energy balances
- Thermodynamic cycles: comparison with Carnot cycle
- Courses on gas turbines of the Master in Sustainable Energy Technology:
  - WB4420 Gas Turbines and
  - WB4421 Gas Turbines Simulation/Application