Assignment 3
Technical Note

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1 Q1 The Steam That Refused to Go to Waste (Rankine Cycle)

1.1 Modeling Assumptions

In this question, the following assumptions are made:

Ideal Rankine Cycle

1. Steady-state and steady-flow operation.
2. Water/steam is the working fluid.
3. Boiler and condenser operate at constant pressure.
4. Turbine and pump processes are isentropic.
5. Kinetic and potential energy changes are negligible.
6. No pressure losses in piping or heat exchangers.

Real Rankine Cycle

1. Turbine and pump have finite isentropic efficiencies.
2. Irreversibilities affect entropy and enthalpy at: State 2 (after pump) and State 4 (after turbine)
   Other assumptions are the same as the ideal cycle.

Note: I have evaluated the thermodynamic properties of water and steam using the XSteam MATLAB function. XSteam is used only for the purpose of property evaluation and not for cycle simulation

1.2 Thermodynamics related to the Rankine Cycle

The Rankine cycle consists of four states:
State 1: Saturated liquid at condenser pressure
State 2: Compressed liquid at boiler pressure
State 3: Superheated steam at boiler pressure

State 4: Superheated steam at condenser pressure

Key Equations

- Pump Work : $W_p = h_2 - h_1$
- Turbine Work : $W_t = h_3 - h_4$
- Heat added in the boiler : $Q_{in} = h_3 - h_2$
- Net Work : $W_{net} = W_t - W_p$
- Thermal efficiency : $\eta_{th} = \frac{W_{net}}{Q_{in}}$
- Back work ratio : BWR $= \frac{W_p}{W_t}$

1.3 Key Results

The values obtained from the MATLAB code are as follows :

$$\text{Turbine Work} = 1177.389 \text{ kJ/kg}$$
$$\text{Pump Work} = 20.192 \text{ kJ/kg}$$
$$\text{Net Work output} = 1157.197 \text{ kJ/kg}$$
$$\text{Heat added in the boiler} = 3238.470 \text{ kJ/kg}$$
$$\text{Thermal Efficiency} = 0.357$$
$$\text{Back Work Ratio} = 0.0171$$

1.4 Engineering Interpretation

Physical significance of Back-Work Ratio ?
Back-work ratio is the ratio of pump work and the total turbine work. It tells us how much turbine work is consumed by the pump. In Rankine cycles, BWR is usually small which indicates efficient power production.

Why Thermal Efficiency Increases with Boiler Pressure ?
As boiler pressure increases, thermal efficiency increases due to a rise in the average temperature of heat addition and an increase in turbine work output. However, at higher pressures, the rate of increase in efficiency diminishes because pump work increases and the incremental rise in mean heat addition temperature becomes smaller. This results in a gradually flattening efficiency curve.

2 Q2 Chasing Power in the Thin Air (Brayton Cycle)

2.1 Modeling Assumptions

In this question, the following assumptions are made:

General Assumptions

1. Air is treated as an ideal gas.
2. Steady-state, steady-flow operation.
3. Kinetic and potential energy changes are neglected.
4. No pressure losses in the combustor or heat exchangers.
5. Compression and expansion occur between fixed pressure levels.

Ideal Brayton Cycle

1. Compressor and turbine operate isentropically.
2. Specific heats are assumed constant.
3. Heat addition and rejection occur at constant pressure

Real Brayton Cycle

1. Compressor and turbine have finite isentropic efficiencies.
2. Pressure ratios remain fixed; irreversibility affects only temperature and entropy.
3. Two models are considered: Constant specific heat model & Variable specific heat

2.2 Thermodynamics related to the Brayton Cycle

The Brayton cycle consists of four states:
State 1: Compressor inlet (ambient conditions)
State 2: Compressor outlet
State 3: Turbine inlet (after heat addition)
State 4: Turbine outlet

Key Equations

- Compressor Work : $W_c = c_p(T_2 - T_1)$
- Turbine Work : $W_t = c_p(T_3 - T_4)$
- Net Work : $W_{net} = W_t - W_c$
- Heat Added : $Q_{in} = c_p(T_3 - T_2)$

- Thermal Efficiency : $\eta_{th} = \frac{W_{net}}{Q_{in}}$

  For the variable specific heat case, work and heat terms are evaluated using numerical integration of $c_p(T)$.

2.3 Key Results

The values obtained from the MATLAB code are as follows :

VARIABLE C_p MODEL RESULTS :
Compressor Work (variable cp) = 337.678 kJ/kg
Turbine Work (variable cp) = 671.214 kJ/kg
Net Work Output (variable cp) = 333.536 kJ/kg
Heat Added (variable cp) = 860.809 kJ/kg
Thermal Efficiency (variable cp) = 0.387

CONSTANT C_p MODEL RESULTS :
Compressor Work = 330.124 kJ/kg
Turbine Work = 596.858 kJ/kg
Net Work Output = 266.734 kJ/kg
Heat Added = 775.376 kJ/kg
Thermal Efficiency = 0.344
Work Ratio = 0.447
Maximum net work occurs at pressure ratio $r_p = 9.08$

2.4 Engineering Interpretation

Relevance of work ratio in gas turbine operation ?
Work ratio is the ratio of net work and turbine work. It indicates the fraction of turbine work available as useful output after driving the compressor.

How does altitude influence Brayton cycle performance ?
Reduction in inlet pressure due to altitude lowers ambient air density which lowers mass flow rate. This also reduces pressure ratio effectiveness because when P1 decreases, to maintain the same rp, the compressor must produce very low exit pressures. These leads to reducing both net work output and thermal efficiency of the Brayton cycle.