Power Cycles (Intercooling and Recuperation)

Submitted by:

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1 Introduction

This assignment consists of the analysis of different kinds of Thermodynamic Power Cycles in terms of their specific work and thermodynamic efficiency. In this sense, a simple Brayton cycle for an ideal gas consists mainly of 3 stages – compression, heat addition and expansion –, however, by adding other complex steps to a given cycle, either the power output or the thermodynamic efficiency can be increased. For this assignment, the studied cycle is characterized by the addition of intercooling and recuperation to the simple Brayton cycle, which are defined, respectively, by: the addition of another compression stage for the working fluid, by implementing an intercooler between these stages, in order to reduce the specific work required to reach a higher pressure; and the recuperation of heat from the outlet of the expansion stage, in order to assist the heat injection stage so that less heat needs to be added, thus increasing the thermodynamic efficiency. In sum, for the purpose of this analysis, after modelling the Thermodynamic Power Cycles using a Python code, 5 questions will be answered, which are:

1) How do the compressor and turbine efficiencies affect the overall cycle performance (efficiency and specific work)?
2) Which turbomachinery losses have a larger impact on the performance?
3) How does your cycle compare to the basic Brayton cycle in terms of efficiency and specific work?
4) What is the effect of changing the pressure ratio and/or temperature ratio on the cycle performance?
5) What are the advantages and disadvantages of the new configuration (note: a lower overall pressure ratio requires fewer stages; fewer stages equals lower cost)?

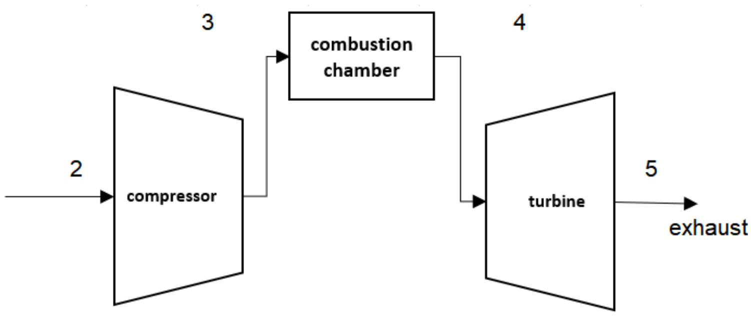

Figure 1: Simple Brayton cycle for an ideal gas

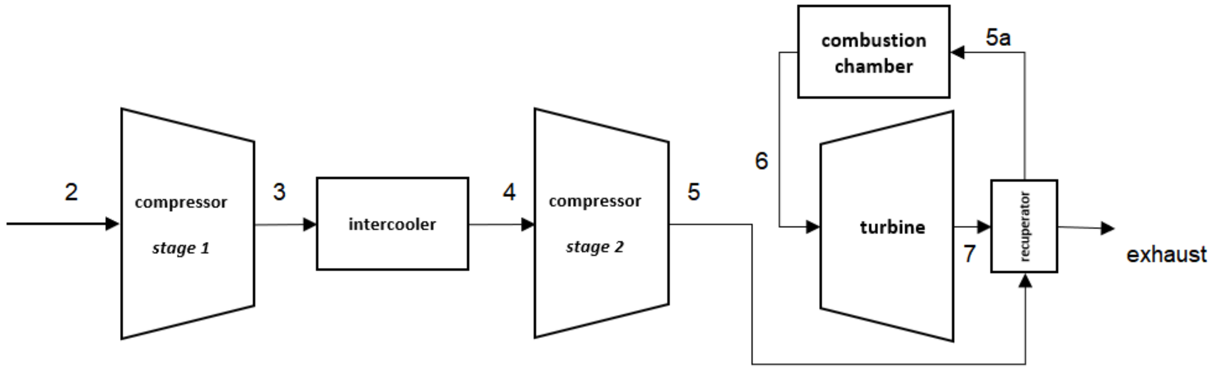

Figure 2: Intercooled+Recuperated Brayton cycle for and ideal gas

1.1. Overall cycle performance (efficiency and specific work)

For this analysis, both the basic Brayton cycle (BC) and the intercooled+recuperated Brayton cycle (I+RC) will be evaluated in terms of the overall performance variation induced by the changes in both the compressor and the turbine polytropic efficiencies. Correlated to that, the following assumptions were made for this assignment:

- For the intercooled or reheat cycle assume:
  - that the two stages have equal pressure ratios;
  - when splitting the compression or expansion, use $PR_1 = PR_2 = sqrt(PR)$
  - that the temperature before the second stage is the same as before the first stage.
- No pressure losses in combustion chamber: $PR_{cc} = 1.0$;
- For all compressors use a polytropic efficiency of $\eta_{p,comp} = 0.85$;
- For all turbines use polytropic efficiency $\eta_{p,turb} = 0.92$;
- For the calculations with ideal gas, assume that the isentropic exponent is constant.

Firstly, the T-s diagram, the Specific Work (SW) x Pressure Ratio (PR) and the Thermal Efficiency (TE) x PR for both cycles with 100% efficiency for compressor and turbine are shown in the following figures (note: the entropy for the I+RC is negative in 2 points, which is explained by the fact that – in all cycles – the entropy defined for the points is derived using the inlet of the first compressor stage as the reference point with zero entropy).

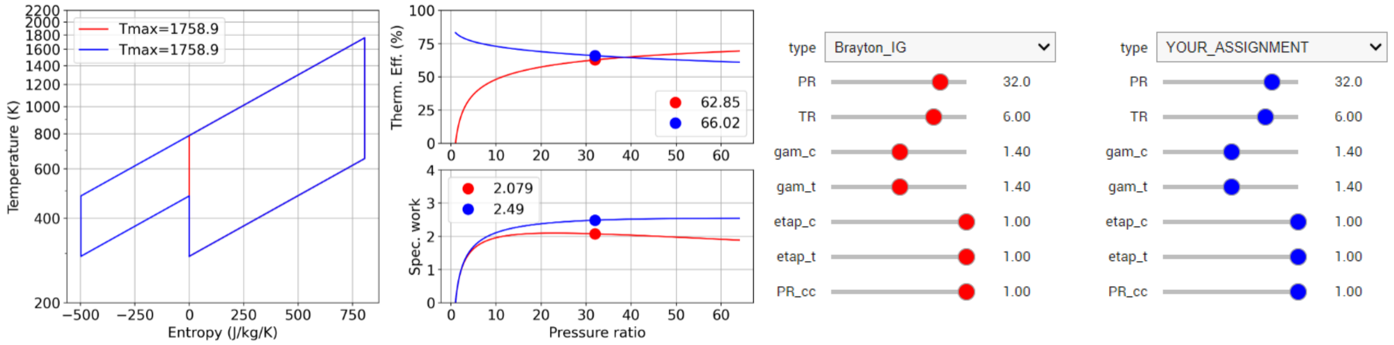

Figure 3: Diagrams for BC and I+RC

From direct observation of the given diagrams, one can conclude that the both the SW and the TE are higher for the I+RC for a PR = 32, however, after the threshold value of $PR_{threshold} \approx 38.5$, the SW is smaller for the I+RC. In this perspective, this can be explained by the fact that the recuperation increases the overall TE of a cycle and that, although the total compressor work is higher for the I+RC than for the BC, the SW is higher due to the increase in the total work output of the I+RC when compared to the BC. On the other hand, if the PR continues to increase, total compressor work will increase at a faster rate than that of the increase of power output, which explains the lower SW for the I+RC. The same holds true when the efficiencies of turbine and compressor(s) are changed to the values defined previously, but the threshold value for SW is now different ($PR_{threshold} \approx 60$).

In order to analyse further, the polytropic efficiencies for turbine ($\eta_{p,turb}$) and compressor(s) ($\eta_{p,comp}$) were decreased in separate tests – all carried out with PR = 32 – by 10% of their maximum value (100%).

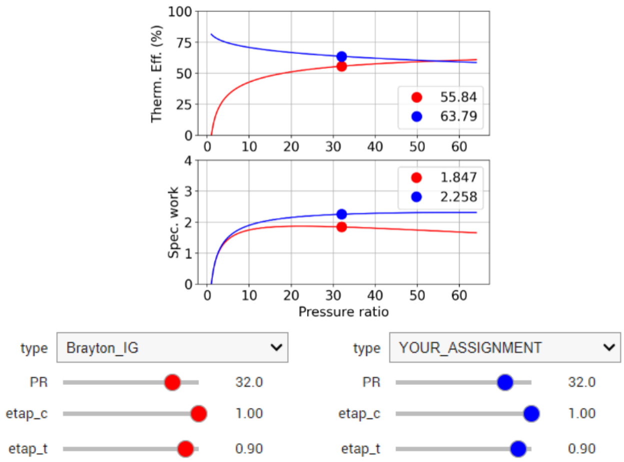

Figure 5: SW and TE for 90% $\eta_{p,turb}$ BC and I+RC at PR = 32

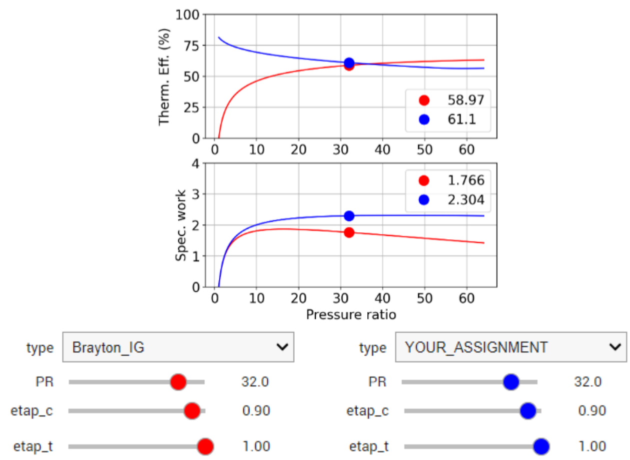

Figure 4: SW and TE for 90% $\eta_{p,comp}$ BC and I+RC at PR = 32

By studying the graphs, one can conclude that the SW is heavily influenced by $\eta_{p,comp}$ in the BC, since the 10% decrease in $\eta_{p,comp}$ caused a ~15.1% decrease in SW in comparison to the ~11.2% decrease caused by the 10% decrease in $\eta_{p,turb}$. Conversely, SW is heavily influenced by $\eta_{p,turb}$ in the I+RC, because the decrease in $\eta_{p,turb}$ caused a ~9.3% decrease in SW in comparison to the ~7.5% decrease caused by $\eta_{p,comp}$. TE varies in the opposite way: in the BC it is more influenced by $\eta_{p,turb}$, with a ~11.2% decrease compared to ~6.2% caused by $\eta_{p,comp}$, and in the I+RC it is more influenced by $\eta_{p,comp}$, with a ~7.5% decrease compared to ~3.4% caused by $\eta_{p,turb}$. Finally, the relative drops in SW and TE are smaller for I+RC than for BC due to the benefits introduced by intercooling and recuperation.

1.2. Turbomachinery losses

The losses in turbomachinery systems that affect its overall performance are diverse and some include frictional, aerodynamic and heat transfer losses, From the previous analysis, it was already noted that for the 2 cycles of interest, losses in the different turbomachinery decrease both SW and TE, but at different amounts depending on the type of turbomachine, that is, whether it is a compressor or a turbine. In this sense, for the BC an inneficient compressor affects the cycle in a greater proportion than an inneficient turbine, that is a bad compressor will reduce SW more than a bad turbine would. On the other hand, for the I+RC an inneficient turbine affects the cycle to a greater extent than an inneficient compressor, that is a bad turbine will reduce SW more than a bad compressor would.

1.3. Comparison between intercooled+recuperated Brayton cycle (I+RC) and basic Brayton cycle (BC)

PR	**BC (TR = 6)**		**I+RC (TR = 6)**		**BC (TR = 7)**		**I+RC (TR = 7)**	
	SW	TE	SW	TE	SW	TE	SW	TE
8	1.515	37.98	1.690	66.88	1.936	38.81	2.111	71.61
12	1.572	42.56	1.841	63.97	2.052	43.71	2.321	69.12
16	1.566	45.24	1.918	61.77	2.083	46.70	2.435	67.23
20	1.533	46.98	1.961	59.97	2.078	48.74	2.506	65.69
24	1.487	48.14	1.986	58.45	2.054	50.22	2.552	64.38
28	1.436	48.93	2.000	57.11	2.020	51.32	2.583	63.24
32	1.381	49.44	2.006	55.93	1.979	52.17	2.604	62.22
36	1.326	49.74	2.008	54.86	1.936	52.82	2.618	61.31

Table 1: SW and TE values plotted for 92% $\eta_{p,turb}$ and 85% $\eta_{p,comp}$ BC and I+RC with varying PR and Temperature Ratio (TR) values

The provided table offers a comparison between the intercooled+recuperated Brayton cycle and the basic Brayton cycle. In this perspective, it contrasts specific work and thermal efficiency values across various pressure and temperature ratios. Based on the table above, it can be concluded that:

- SW and TE are always higher for I+RC across the selected intervals of PR and TR;
- SW increases with PR for both occasions in I+RC, but the same doesn't hold true for BC;
- TE decreases for I+RC until it reaches a critical point where recuperation is not possible anymore, after which BC will have a higher TE;
- For BC TE values are similar across different TR because TE is not dependent on TR, but the values aren't the exact same due to non-ideal efficiencies.

1.4. Effects of varying pressure and/or temperature ratios on cycle performance

By analysing the table presented above and with the aid of the previous graphs, it can be inferred that for BC, if the efficiencies are assumed to be ideal, changing TR has no effect on TE, but it is always directly proportional to SW. Besides that, changing PR has an effect on both TE and SW, however, while PR and TE are always directly proportional, SW increases with PR until it reaches a maximum value and then it starts to decrease. This is due to the fact that, after this threshold value for SW, the increase in work required by the compressor is greater than the increase in power output.

On the other hand, for I+RC changing TR varies both TE and SW, and both TE and SW are directly proportional to TR. Correlated to that, changing PR has an effect on both TE and SW, but the variations depend on the defined value of TR. That is, for higher values of TR, TE is inversely proportional to PR, however, after a certain threshold value, this relation stops being valid. In this view, after TE reaches a minimum value, it starts increasing with PR, and, for even lower values of TR, TE will increase until a maximum value and then continue to decrease with PR. This happens because of the intricacies of the relationship between power output and total compressor work with PR at lower TR values in I+RC. Conversely, SW and PR for I+RC are related in the same way as for the BC, with the threshold values taking place at much higher PR for the same TR values.

1.5. Advantages and disadvantages of intercooled+recuperated Brayton cycle (I+RC) compared to basic Brayton cycle (BC)

To conclude the comparison between BC and I+RC, it is wise to list some of the advantages and disadvantages of this complex cycle compared to a basic cycle. In this sense, the advantages of I+RC include:

- **Increased efficiency compared to BC**;
  - Intercooling reduces the work of compression and recuperation utilizes waste heat from the exhaust, improving the overall thermodynamic efficiency.
- **Increased specific work compared to BC**;
  - Intercooling reduces the work of compression, effectively increasing the net work output;
  - Recuperation utilizes waste heat from the exhaust, preheating the air before it enters the combustion chamber, which increases the work output of the cycle.
- **Lower peak temperatures**.
  - Intercooling helps reduce peak temperatures in the cycle for the same work output, which can be benefitial for the components life, due to the lower thermal stress.

Conversely, the disadvantages of this complex cycle include:

- **Complexity and high costs**;
  - Implementing intercooling and recuperation to a system adds complexity, requiring additional components that increase manufacturing and maintenance costs.
- **Weight and size**;
  - The addition of new components can increase overall size and weight, which can prove disadvantageous in some applications.
- **Limited performance gains**.
  - The benefits of I+RC are noticeable at higher pressure ratios, if, for the desired application, a lower pressure ratio is needed the gains are not significant and the added complexity and costs may not be justified.

Figure 6: Cross-sectional view of LMS100 turbine developed by General Electric. Image sourced from ITP Aero.