The Thermodynamics of a Jet Engine

Ishaan Aggarwal

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1 Introduction

The first and second laws are usually illustrated for closed systems. Thermodynamics textbooks (like Carrington's) discuss the Carnot cycle and other closed cycles (for example, the Rankine, Otto, etc.) and calculate their ideal performance based on the assumption of reversible transformations. Many of the machines used to transfer thermal energy (even those that are examples of closed cycles) contain fluids that exchange energy with their surroundings. Jet engines, which can be viewed as an assemblage of several of these devices, provide an important and interesting application of thermodynamic laws to open stationary systems. However, most introductory thermodynamics textbooks do not discuss such engines from a general perspective.

The purpose of this paper is to analyze a generic jet engine and show the simplicity, power, and the beauty of the laws of thermodynamics. We will find that it is possible to understand the nature of a gas turbine engine (the industry standard), the role of the turbine, the compressor and why increasing the compression ratio and developing turbines able to withstand high temperatures were important in the development of jet engines for commercial aircraft. We will also understand how this development was affected by the constraints imposed by the second law. In this paper, I will introduce the thermal efficiencies of a simple jet engine, which will help us understand and measure the performance of the jet engines. We then analyze the overall efficiency and the thrust, which depend also on the maximum temperature attained. We discuss the consequences of this dependence for finding the best design for a jet engine. We then investigate the effects of irreversibilities in the compressor and turbine on the overall efficiency, in a brief manner.

2 Theory

The simple jet engine operates on the ideal Brayton cycle. The first gas turbine that implemented the Brayton Cycle (not knowingly however, because it was created before the Brayton Cycle was even established) was John Barber's gas turbine patented in 1791. George Brayton was an engineer that designed the first continuous ignition combustion engine which was a two-stroke engine that was sold under the name "Brayton's Ready Motors." The design employed the thermodynamic processes that is now considered "The Brayton Cycle," but is also coined The Joule Cycle. The gas turbine was patented in 1872. The design was a engine connected to a reservoir of pressurized atmospheric air and gas which would only turn on if a valve was turned. This would release the pressurized gas to a combustion vessel, which would turn pistons to create mechanical work and re-compress the gas in the reservoir [1].

The Brayton Cycle can be described quantitatively in the gas turbine engine of a jet by two diagrams, the Temperature/Entropy Diagram and the Pressure/Volume Diagram. Figure 1 shows the T-S diagram of the ideal brayton cycle. In total there are 8 processes to describe the Brayton Cycle:

1) Ambient air in the atmosphere that is currently undisturbed.

1 -> 3) Ambient air comes into contact with the compressor of the gas turbine and the pressure and temperature rises dramatically. The rise in pressure comes from work being done the air by the compressor which packs the air into the mixer/combustion chamber, and the rise in pressure causes a rise in temperature in the gas molecules because volume of the vessel stays constant (PV = nRT). Because this is an ideal process, entropy is believed to stay the same, thus this is an isentropic process (in reality though, entropy does increase due to the flow and movement of the gas molecules).

$3->5$) The atmospheric air has been compacted into the combustion chamber where gaseous fuel is mixed with the air. Once this mixture has been ignited, we a see a steep rise in the temperature and entropy (not the pressure, because the curves represent a specific value of pressure, so this is an isobaric process) due to the combustion reaction of the fuel and air. The energy from the chemical bonds in the fuel are broken due to ignition and a highly exothermic reaction occurs which raises entropy because of the breaking down of hydrocarbon chains to water and air (more molecules) and raises the temperature due to increased ambient energy from the exothermic reaction.

$5->8$) At point 5, the pressurized fuel and air leave the combustion chamber to the expansion chamber, where we see a quick drop in pressure due to a larger volume and exposure to the surroundings. The energy from the combustion chamber is used two for two purposes: spinning a turbine that is connected to the compressor (which keeps the Brayton Cycle running continuously) and as thrust. These two purposes represent point 6 and ideally is an isentropic process. The quick drop in pressure shows how the energy from the air in the combustion energy is used mechanically to turn a turbine that will run the compressor process because the energy it takes to compress the atmospheric energy is lesser than the energy produced from the ignition of the fuel. The energy left over from spinning the turbine is the used as thrust to do work (such as flight in a jet). The expelled air then becomes ambient air that is of a higher energy level than the air from point 1, but will eventually lose energy to the surroundings (isobaric process) and become the initial ambient air.

The same processes are also shown in a P-V diagram (Fig 2), however the points are not the same as the time progression is different.

3 Description

Figure 3 illustrates the simplest model of a jet engine. The outside air is at temperature T_i, and its speed relative to the aircraft, the inlet velocity, is v_i. The air enters the engine through a diffuser, which lowers its speed and increases its pressure. The air then goes into the combustion chamber, and each unit mass of air absorbs energy q, increasing its internal energy. Finally, the air is exhausted through a nozzle, which accelerates the air until it attains the exit velocity v_e at temperature T_e.

To analyze this engine, we will apply the same equation to the diffuser, the combustion chamber, and the nozzle. The relation,

$$q - w = \delta h + \delta e \tag{1}$$

expresses conservation of energy for open stationary systems with a constant mass flow rate [2]. Here, w is the work per unit mass performed by the air inside the open system of interest (w= 0 for the diffuser, the combustion chamber, and the nozzle in which there are no movable parts), δh is the difference between the exit and inlet specific enthalpies, and δe_c is the difference between the exit and inlet kinetic energies per unit mass. This means that if the exit temperature is the same as the initial external temperature, all the thermal energy that is given to the system in the combustion chamber will be used to increase the kinetic energy of the air, leading to maximum thrust.

However, the second law of thermodynamics implies that the complete conversion of thermal energy into work (or into kinetic energy of the air) is impossible and that the most favorable situation (maximum production of work) is realized if all the processes are reversible. Because the transformations undergone by air in the compressor and the turbine are also assumed to be adiabatic and reversible, we have,

$$T_2 = T_1 \left(\frac{P_2}{P_1} \right)^{(1-\gamma)/\gamma} \tag{2}$$

The compression ratio $r = P_2/P_1$ depends on the characteristics of the compressor. The thermal efficiency of the jet engine can now be written as,

$$\eta_{th} = \frac{\delta e_c}{q} = 1 - \frac{a}{1+\epsilon} \tag{3}$$

where $0 < a = r^{(1-\gamma)/\gamma} \leq 1$, because both the compression ratio r and the adiabatic coefficient γ are greater than one. The results for the thermal efficiency indicate the qualitative behavior of jet engines. In particular, the thermal efficiency is a simple function of the speed of the aircraft and the compression ratio of the compressor only—no dependence on the absorbed energy was found. The thermal efficiency is the same whether we use a small or a large amount of thermal energy; the kinetic energy of the aircraft varies proportionally. According to these idealized results, if we need to travel faster, we should just use more fuel (to increase the thermal energy). However, the temperature inside the jet engine will rise with the travel speed, and we risk melting the compressor or the turbine.

The Thermal efficiency as a function of pressure ratio is plotted in Figure 4. This graph shows a logarithmic increase in efficiency with a linear increase in pressure ratios. As described above there are limits to the turbine blades which in turn limit the efficiency of the engine.

4 Discussion

This analysis shows why the invention of turbojet engines is regarded as a technological revolution in aircraft engine manufacturing. Optimization of performances is difficult and depends, among other things, on the maximum velocity we require the aircraft to achieve. I did not discuss other major technological achievements of jet engines. One example is the afterburner, which is placed between the turbine and the nozzle and in which fuel is again injected, thereby creating a new combustion chamber and increasing aircraft thrust. Because they consume more fuel, afterburners are not efficient and for that reason are commonly used only in military aircraft. Another technological advance is turbofan engines [0]. Here, a large fan driven by the turbine forces a considerable amount of air through a duct surrounding the engine. The detailed analysis of jet engines is complex and ranges from the description of engines to the aerodynamical or structural problems associated with aircraft (see [0] for example. Our numerical analysis can be extended to other interesting problems as well.

5 Summary

I discussed the thermodynamics of the simple jet engine with a compressor, combustion and a turbine outlet. I used the brayton cycle and thermal efficiencies of it to showcase the current limitations of our technology.

6 Figures

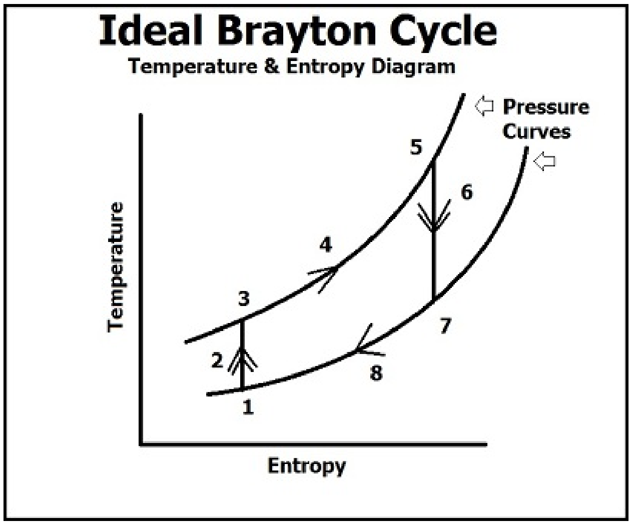

Figure 1: This is the T-S curve of the Ideal Brayton Cycle. We can see that there are 8 processes to describe the Brayton cycle in terms of temperature, entropy, and pressure.

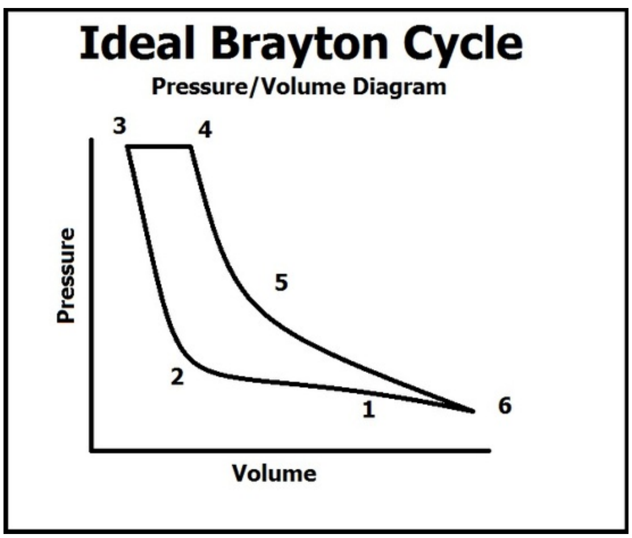

Figure 2: This is the P-V curve of the Ideal Brayton Cycle. In this diagram, there are six processes that describe the pressure and volume of the gas. A common mistake is by thinking the volume relates to the vessel of the reaction, when in fact it is the volume of the gas.

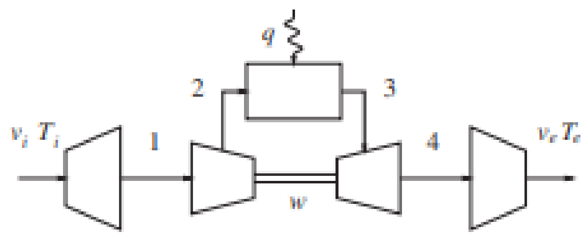

Figure 3: A simple model of a jet engine. The air enters the engine through a diffuser,travels through the compressor, goes to the combustion chamber, expands through the turbine and is exhausted through a nozzle.

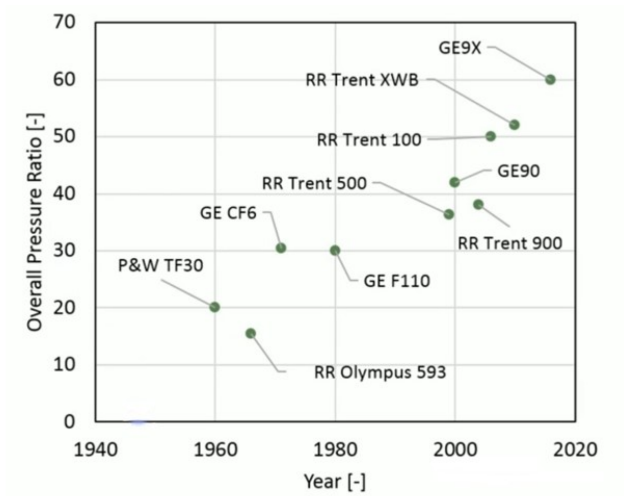

Figure 4: This is the plot of the thermal efficiency vs pressure ratio of a jet engine. We see a log plot with diminishing returns in the efficiency with linear increase in pressure ratios.

7 References

References

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