HIGH PERFORMANCE JET PROPULSION SYSTEMS FOR AEROSPACE INDUSTRY

Robert Scammon, Ian Connor, David Luby

Nedyalkov & Students LLC (Group 32)

ABSTRACT

In this report, we will be looking into the Brayton cycle, with a focus on the jet engine application. We will study the parameters of the cycle and what can happen when those parameters are changed. The efficiency will be calculated to figure out how useful the cycle is. And using that efficiency, a general range can be calculated. A specific Jet fuel will be recommended after a study on different types is performed. Following, an optimal altitude will be recommended as well as studying ramjet efficiency against mach number analysis.

1. INTRODUCTION

The Brayton Cycle is named after George Brayton, an American engineer even though it was originally patented by an Englishman named John Barber in 1791. The cycle is a heat cycle that originally contained a piston compressor and expander. But, in modern applications, like in a jet engine, a gas turbine engine is used that follows the process of the original Brayton cycle. In our study, we look at the jet engine application and look into how to optimize the cycle. First we studied the effects of changing the efficiency in the compressor, turbine, and nozzle. Following that, we studied the effects of changing the pressure ratio and the maximum temperature. Using our efficiency we solved for, the range as a function of cruising speed could then be found. And that study made it possible to compare different jet fuels and their respective ranges as well as their emissions to decide which fuel should be recommended. From there, cruising altitude was studied to see what altitude our aircraft should fly at to be the most efficient. Finally, thrust was studied as a function of the mach speed in a RamJet application.

2. MATERIALS AND METHODS

The materials used were the coding program Matlab, and the internet. Matlab was used to code our tasks to come up with our answers. The internet was used to find reasonable values for a realistic cycle and base our aircraft off of successful aircraft.

2.1 Investigate the Effects of the Efficiency of the Compressor, Turbine, and Nozzle

The subscript "ac" will refer to the actual cycle values, the subscript "s" will refer to the idealized value.

ηC , the efficiency of the compressor

ηT , the efficiency of the turbine

ηN, the efficiency of the nozzle

$$h2ac=h1+((h2s-h1)/\eta C) \tag{1}$$

$$h4s=h3ac+((h4ac-h3ac)/\eta T) \tag{2}$$

$$h5ac=(\eta N*(h5s-h4ac))+h4ac \tag{3}$$

$$\eta = (h4ac-h5ac)/(h3ac-h2ac) \tag{4}$$

$$2.60 \geq \eta C + \eta T + \eta N \tag{5}$$

Using efficiencies in the range from 0.72 to 0.90 for the compressor and turbine, we create a matrix of nozzle efficiencies so that Equation 5 is always met. Then using those efficiencies run them through a script that solves for the efficiencies of the brayton cycle. We can then easily find the maximum cycle efficiency and what component efficiencies led to that result.

2.2 Study the Effects of Pressure Ratio and Maximum Temperature on the Actual Cycle

The effect of the pressure ratio (PR) and maximum temperature (T_{MAX}) on the actual cycle were performed using the optimal compressor, turbine and nozzle efficiencies found in analysis 2.1 (n_c = 74.94%, n_t = 87.06%, n_n = 98.00%). Analysis of the effect of PR was performed in MATLAB by solving for the actual cycle efficiency (n_{AC}) and increase in kinetic energy (ΔKE) for a range of PR from 10 to 80. Analysis of the effect of T_{MAX} on the actual cycle was performed in MATLAB by solving for n_{AC} and ΔKE for a range of T_{MAX} from 1300 K to 1800 K.

2.3 Estimate the Range of the Vehicle as a Function of its Speed

For estimating the range as a function of speed, the first step was to find the coefficient of lift and coefficient of drag for the NACA 0015 airfoil design. As well as estimating the coefficient of drag of the fuselage of the airplane. After estimating the area of the wings and the range of speed of our aircraft, the lift forces and drag forces were calculated based on our values.

$$L = \frac{1}{2} \cdot C_L \cdot \rho \cdot A \cdot V \tag{6}$$

$$D = \frac{1}{2} \cdot C_D \cdot \rho \cdot A \cdot V \tag{7}$$

Using the efficiency from the actual cycle, the heat was solved for using the heating value of average jet fuel.

$$Q = Heating\, Value \cdot M_{Fuel} \quad (8)$$

And with this value, the work was solved for giving enough values to solve for the capable range of our aircraft as a function of the chosen speeds.

$$W = Q \cdot Efficiency \quad (9)$$

$$R = W \cdot D \quad (10)$$

2.4 Recommend a Fuel and Evaluate Range and CO2 Emissions

For the fuel choice for our aircraft, three jet fuels were studied to decide which fuel we would use. Those jet fuels were Jet A-1, Jet B, and TS-1. To evaluate the range effects of these fuels, the heating value was acquired from the internet to solve for the ranges depending on cruise speed. Afterwards, the CO2 emissions were solved for as a function of cruising speed by looking at the chemical makeup of the fuel and using stoichiometry to solve for the weight of CO2 that is being disposed of into the atmosphere. Based on these values, a recommendation was made on which jet fuel to use.

2.5 Investigate the Performance and Efficiency of the Vehicle at Different Cruising Altitudes

Using temperature and pressure values from Reference 1, we were able to run a script that found the cycles efficiency, using the maximum component efficiencies, at different altitudes.

Then using equation 6, and the fact that lift is also equal to the mass of the aircraft multiplied by gravity, we were able to solve for the Cl. Then using Reference 2, we were able to correlate the Cl values with Cd values. Then using equation 7, we were able to calculate the drag of the aircraft. We were also able to use equation 8 to find the work of the airfoil. Dividing the work by the drag got us the range the aircraft could fly varying altitudes.

2.6 Overall Ramjet Cycle Efficiency as a Function of Mach Number

The overall efficiency for a ramjet cycle as a function of the flight mach number was calculated using design parameters: max temperature (T_{MAX}), aircraft velocity (V_A), and inlet pressure (P_i) and temperature (T_i) with kerosene as the combustible fluid ($Q_c = 43\ MJ/kg$).

The mach numbers were calculated using equation 11, and the overall efficiency was calculated using equation 12.

Equation 11: $M_{Flight} = \frac{V_A}{\sqrt{\gamma R T_i}}$

Equation 12: $\eta_{OVR} = \frac{ST V_A}{f Q_c}$

Where γ is the ambient specific heat ratio, and R is the universal gas constant for air in Equation 1 and ST is the specific thrust and f is the fuel to air ratio in Equation 2.

3. RESULTS AND DISCUSSION

2.1 Investigate the Effects of the Efficiency of the Compressor, Turbine, and Nozzle

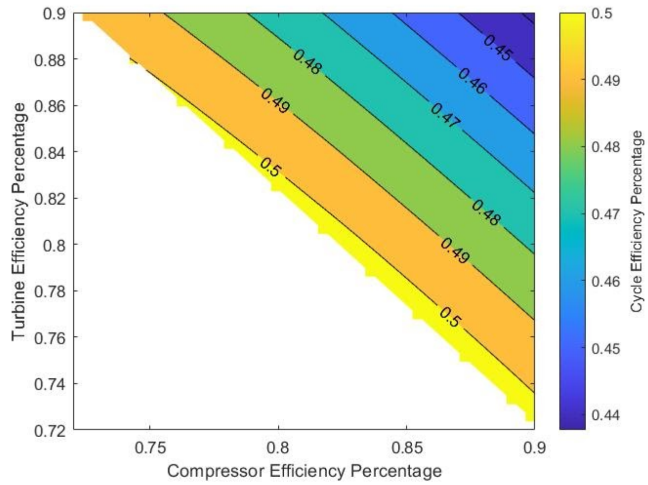

Figure 1 (Cycle Efficiency as a function of Turbine, Compressor and Nozzle Efficiency)

The maximum cycle efficiency is 0.5048, when the nozzle efficiency is 98%, the compressor efficiency is 74.94% and the turbine efficiency is 87.06%. Together these efficiencies add up to 260%, the maximum allowed efficiencies. It makes sense that the cycle efficiency is at its highest when the nozzle efficiency is at its highest because the cycle efficiency is determined by the kinetic energy in the nozzle divided by the heat added in the combustor. The higher the efficiency of the nozzle, the faster the fluid leaves the nozzle, the greater the KE. It also makes sense that the turbine has a higher efficiency than the compressor because the actual work of the turbine is equal to the amount of work the combustor does. If the work of the turbine is lower, then the work of the combustor is lower. If the work is low in the combustor, then the heat added is also low, and the efficiency grows bigger because of it.

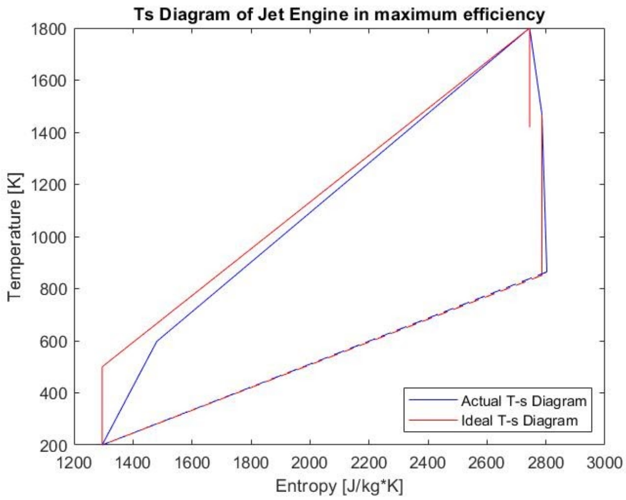

Figure 2 (Representation of the T-s diagram for the max cycle efficiency)

Figure 2 shows the T-s diagram for the cycle working at .5048 efficiency, which means the nozzle is working at 98% efficiency, the compressor is working at 74.94% efficiency, and the turbine is working at 87.06 efficiency.The cycle starts at an inlet temperature of 200 Kelvin, and pressure of 30 kPa. The first step in the process is compression. As shown in Figure 2, this process is idealized as isentropic, meaning no entropy is created. We can also see that with a compressor working at 74.94% that entropy is indeed created causing Temperature to increase more than ideally. The next process is isobaric combustion, that mixes fuel with the air in the engine and ignites bringing the temperature to a max of 1800 Kelvin. The next process in the cycle is running the high temperature air/fuel mixture through the turbine.Ideally, this process isentropic like before, however because the turbine is not 100% efficient, entropy is still generated. Likewise is true for the nozzle. The air is then expelled into the atmosphere, but is shown in Figure 2 as isobaric heat rejection as a dashed line.

2.2 Study the Effects of Pressure Ratio and Maximum Temperature on the Actual Cycle

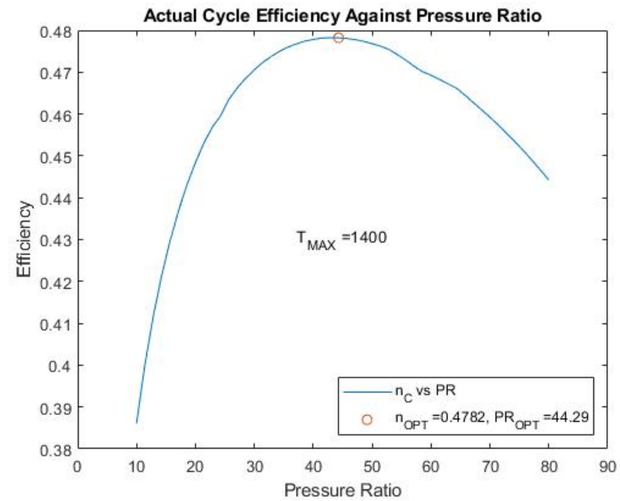

Figure 3 (Actual cycle efficiency as a function of pressure ratio)

Figure 3 shows that increasing *PR* increases n_c for ratios of about 10 to 44 and decreases n_c for *PR's* of about 44 and greater. The max temperature used for the calculations was 1400 K. The optimal pressure ratio was about 44 ($PR_{OPT} = 44.29$) for the actual cycle accounting for component efficiencies in section 2.1 and is indicated in Figure 3 at the location of the orange circle ($N_{OPT} = 47.82\%$).

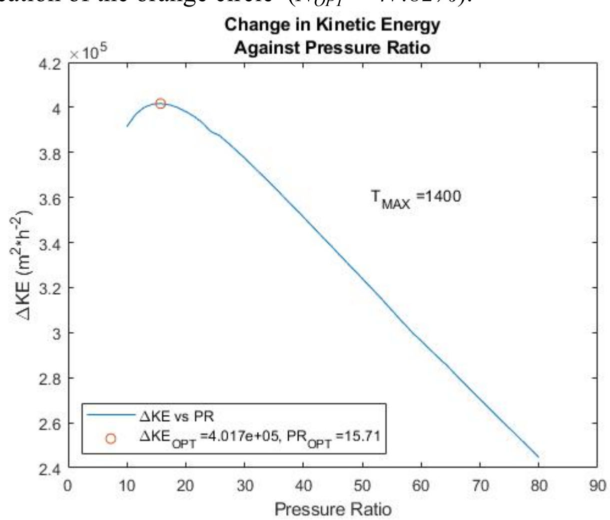

Figure 4 (Change in kinetic energy against pressure ratio for actual cycle)

Figure 4 shows that increasing *PR* increases ΔKE for ratios of about 10 to 16 and decreases ΔKE for *PR's* of about 16 and greater. The max temperature used for the calculations was 1400 K. The optimal pressure ratio was about 16 ($PR_{OPT} = 15.71$) for the actual cycle accounting for component efficiencies in section 2.1 and is indicated in Figure 4 at the location of the orange circle ($\Delta KE = 4.02E+5\ m^2 * s^{-2}$).

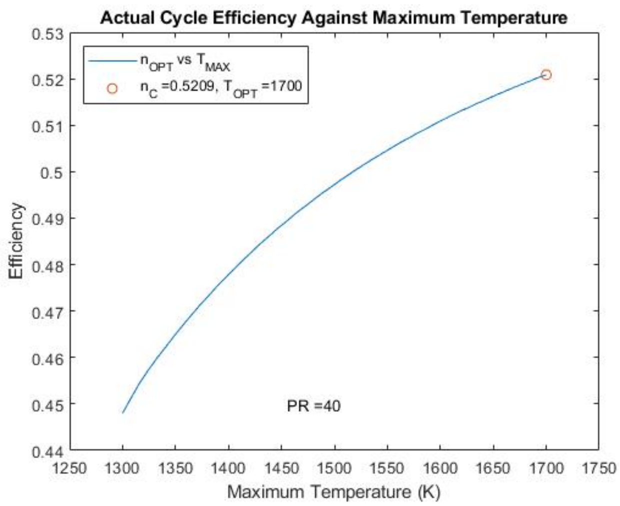

Figure 5 (Actual cycle efficiency against maximum temperature)

Figure 5 shows that increasing T_{MAX} increases n_c consistently for any temperature. The pressure ratio used for the calculations was 40. The optimal max temperature of the temperature range was 1700 K ($T_{OPT} = 1700\ K$) for the actual cycle accounting for component efficiencies in section 2.1 and is indicated in Figure 5 at the location of the orange circle ($N_{OPT} = 52.09\ \%$).

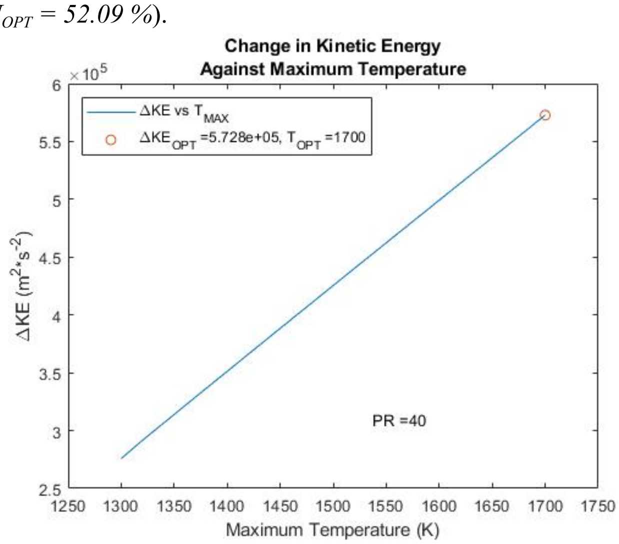

Figure 6 (Change in kinetic energy against maximum temperature for actual cycle)

Figure 6 shows that increasing T_{MAX} increases ΔKE consistently for any temperature. The pressure ratio used for the calculations was 40. The optimal max temperature for the temperature range was 1700 K ($T_{OPT} = 1700\ K$) for the actual cycle accounting for component efficiencies in section 2.1 and is indicated in Figure 6 at the location of the orange circle ($\Delta KE = 5.73E+5\ m^2 * s^{-2}$).

2.3 Estimate the Range of the Vehicle as a Function of its Speed

It was found that the coefficient of lift for the NACA 0015 airfoil came out to be 0.75 and the coefficient of drag came out to be 0.07. The wing area was estimated to be $25m^2$ and the area of the fuselage was estimated to be about $11m^2$. Using a speed range of 140-250 m/s, the following figure could be created.

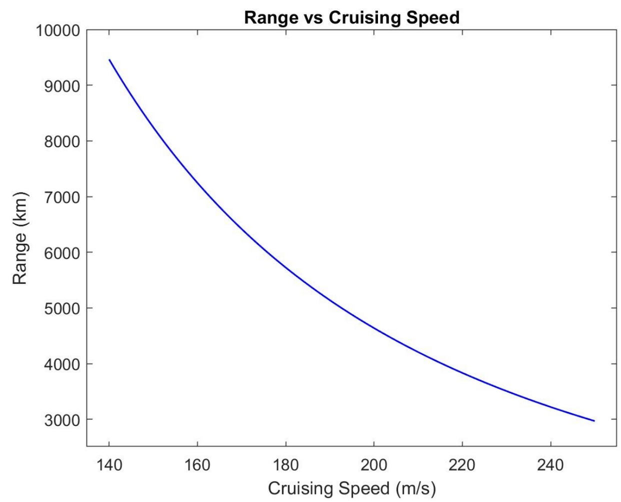

Figure 7 (Range as a Function of the Cruising Speed)

From the figure above, you can see that the trend is when the speed increases, the range of the aircraft will decrease. This trend is steep at the lower speeds and gets shallower as the speed increases. The minimum range required was set to 3000 km which the aircraft meets at a speed of 250 m/s or 900 km/h.

2.4 Recommend a Fuel and Evaluate Range and CO2 Emissions

Three fuels were evaluated in this test, and those fuels were Jet A-1, Jet B, and TS-1. When studying the heating values of these fuels, they were extremely similar which is due to the tight restrictions in jet fuels. The Jet A-1 and Jet B fuels both had a value of 42.8 MJ/kg while the TS-1 had a value of 42.9 MJ/kg. Resulting in the following figure.

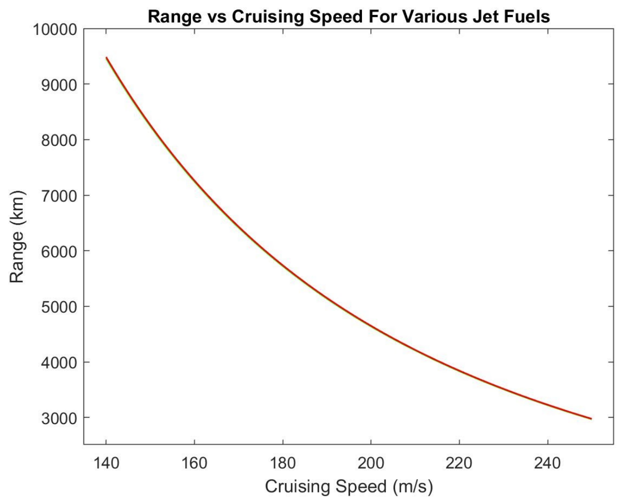

Figure 8 (Range as a Function of Cruising Speed for Multiple Jet Fuels)

The lines are so close in this graph due to the similarity in heating value in these fuels. Next, the CO2 emissions were calculated based on the chemical compound of jet fuel as a function of cruising speed.

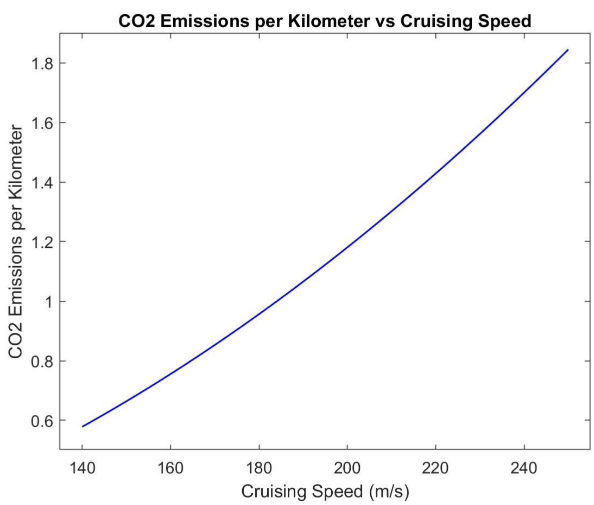

Figure 9 (CO2 Emissions as a Function of Cruising Speed)

In this figure, you can see that as the speed increases, the emissions of the aircraft will also increase. The slope starts out shallow and gets steeper as the speed increases. Based on the results, the recommended fuel was TS-1 due to its increased heating value. And using TS-1, a final figure was made showing it's final data.

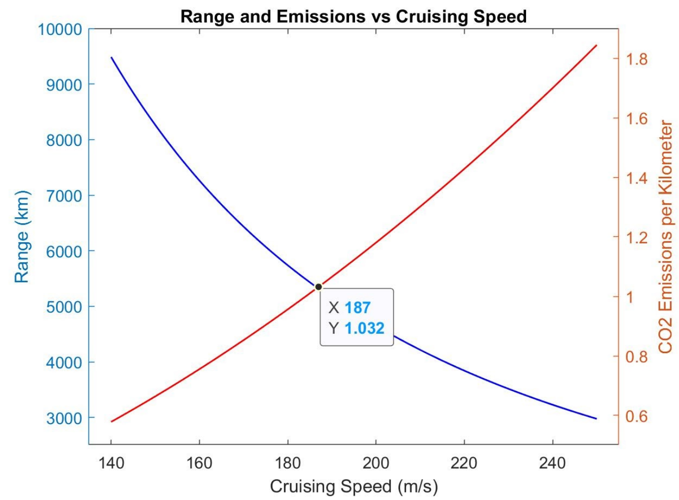

Figure 10 (Range and Emissions as a Function of Cruising Speed)

After combining the last two figures into one figure for the jet fuel TS-1, one can see that to maximize the speed traveling while also wanting to maximize range and minimize CO2 emissions, traveling at a speed of 187 m/s or 673 km/h would be the best option.

2.5 Investigate the Performance and Efficiency of the Vehicle at Different Cruising Altitudes

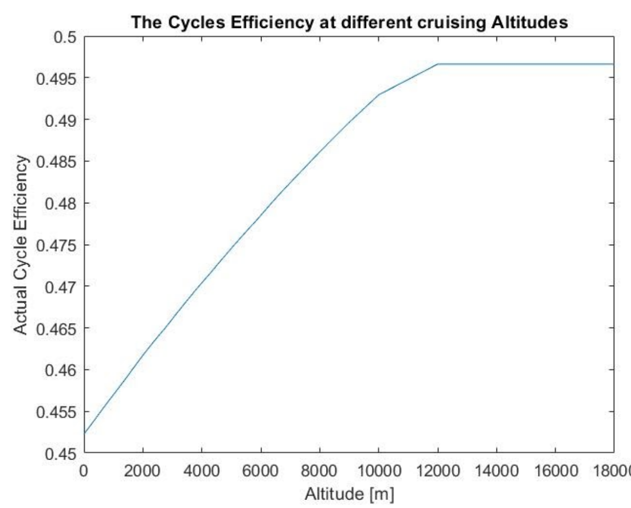

Figure 11 (The Cycle Efficiency in terms of Altitude)

The Brayton cycle in jet application efficiency increases as the aircraft gains altitude. This is because the air at high altitude is colder and the cold air increases the ratio between the inlet air and the heated air in the combustor. This temperature ratio is directly related to the density ratio of the air in the engine. Because the combustor is isobaric, and is in a constant sized container, the larger the temperature ratio gets, the lower the density will get. The low density air means that the air is traveling faster, so the cycle efficiency improves. The cycle efficiency levels off at 12,000 meters, and therefore there is no benefit for flying above the threshold.

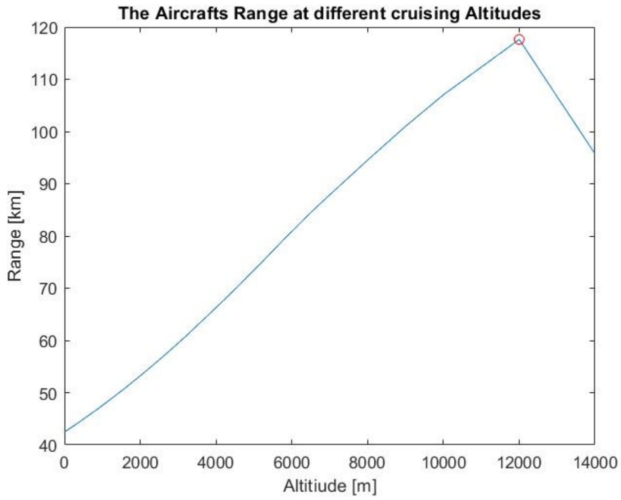

Figure 12 (The Range of the Trip in terms of Altitude)

The range increases as the altitude increases. As shown in Figure 11, the cycle efficiency increases until 12,000 m where it levels off. In Figure 12, it makes sense that the range is increasing with altitude, because the efficiency is increasing and is at its maximum at 12,000 m. After 12,000 m the range starts to decrease when climbing higher. At this height air is less dense, so airfoils compensate by flying with a larger angle of attack. However, a larger angle of attack creates more drag. For this airfoil, there is too much drag past 12000m.

In conclusion, the information in Figure 11, and Figure 12 informs us that the optimum altitude for flying is 12,000 meters.

2.6 Ramjet Cycle Efficiency as a Function of Mach Number

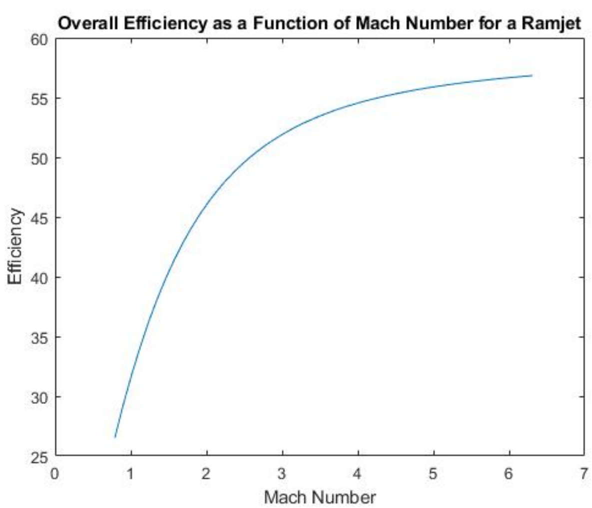

Figure 13 (Overall ramjet cycle efficiency as a function of mach number)

Figure 13 shows the efficiency of a ramjet cycle as a function of the flight mach number. As mach number increases, so does the efficiency of the ramjet cycle. T_{MAX} for the cycle was 2500 K, P_i was 50 kPa, and T_i was 250 K. The velocity of the aircraft ranged from 250 m/s to 2000 m/s and the altitude was 30,000 ft.

4. CONCLUSION

We found that the maximum cycle efficiency is about 51%. The optimal pressure ratio was 44 and maximum temperature was 1700 K. The jet fuel TS-1 was recommended for use as well as a cruising speed of 187 meters per second. And the optimal altitude is 12,000 meters. The ramjet cycle calculations provide that the overall cycle efficiency increases as mach number increases.

REFERENCES

[1] air_data_v2.xls

[2] http://airfoiltools.com/airfoil/details?airfoil=naca0015-il