Analysis of Turbine Based Combined Cycle Aircraft

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Introduction and Objectives

The task of making airbreathing supersonic and hypersonic aircraft is still relatively difficult for even the most advanced aerospace companies. Most aircraft that travel at these speeds utilize ramjets or scramjets as their propulsion method. Ramjets and scramjets use the ram effect to compress the air before it enters the combustor. The ram effect requires high-velocity airflow from the forward motion of the aircraft to increase the pressure in the combustion chamber. Since these types of engines require high-velocity airflow to start, they cannot be the only source of propulsion for aircraft starting from a stationary position. One method to overcome this limitation is to couple the ramjet with another form of propulsion. The first propulsion device is responsible for initiating takeoff and getting the aircraft up to speed where the ramjet or scramjet can startup and run efficiently. One of the most popular designs utilizes a turbojet as this first stage of propulsion which then transitions to a ramjet or scramjet. This form of propulsion is referred to as a Turbine Based Combined Cycle (TBCC). The most famous example of an aircraft that uses a TBCC engine is the SR-71 Blackbird. The Blackbird could fly at speeds upwards of Mach 3 and at an altitude of 85,000 feet.

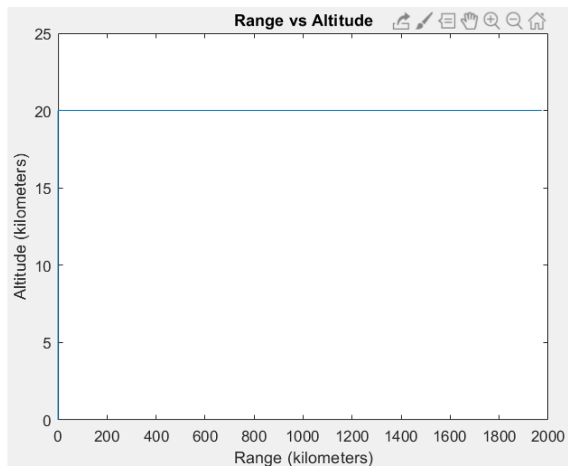
Turbojets are a form of airbreathing engine that consists of an inlet, compressor, combustion chamber, turbine, and nozzle. Air flows through the inlet into the compressor, where the pressure of the air is increased before it enters the combustion chamber. After the compressed air enters the combustion chamber, it is mixed with fuel and ignited. This fuel-air mixture then expands through the turbine and accelerates to a high speed as it exits the nozzle. Some turbojets are equipped with afterburners, which is an added combustion chamber that reheats the turbine exhaust gases. Afterburners are mostly used on supersonic aircraft, with a majority of those being military aircraft, due to the fuel consumption being almost four times greater than that of the main engine (For simplicity of the analysis, it is assumed that the fuel consumption is the same as the main engine). Turbojets are efficient up to a velocity of Mach 2.2. Due to this, turbojets are a great choice for the first engine of a TBCC aircraft.

Ramjets are one of the most popular propulsion devices for aircraft and other systems that travel at supersonic. As was stated earlier, the ramjet does not have a compressor and instead relies on the high velocity of the incoming air to compress the air before it enters the combustion chamber. As billionaire and founder of SpaceX, Elon Musk says, “The best part is no part”. This is ideal for engineers of supersonic aircraft as they do not have to worry about designing a complex compressor that would have to function at supersonic speeds. Ramjets require a velocity of Mach 0.5 to even startup, but at this speed, they are highly inefficient and produce little thrust. The efficiency rises with the velocity of the ramjet until it reaches its most efficient point at around Mach 3.0. Increasing the velocity further results in a drop in efficiency because the incoming air temperature increases with compression. The increased inlet air temperature is closer to the exhaust temperature, which means there is less thermal energy to be extracted from the gas. Even with the decreasing efficiency, ramjets can operate up to speeds of Mach 6.0.

This report assesses the performance of an aircraft powered by a TBCC engine as it starts from takeoff and accelerates to its cruise velocity of over Mach 4 at an altitude of twenty 20 kilometers. The engine is broken up into three distinct phases: turbojet, turbojet with afterburner, and ramjet. The performance of each phase of the engine will be based on several parameters including thrust specific fuel consumption (TSFC), thermal and propulsive efficiencies, and the work done in the compressor and turbine. Using the performance parameters, the maximum range that the aircraft can reach for the determined fuel consumption rate and fuel mass can be determined. For the purpose of the analysis, the aircraft is considered to be similar to a cruise missile, in regards that it does not have any aerodynamic surfaces that produce lift or drag and that the range stops when the aircraft runs out of fuel. The Brayton cycles for both the turbojet and ramjet are assumed to be ideal with no heat loss throughout the cycle.

Results and Discussion

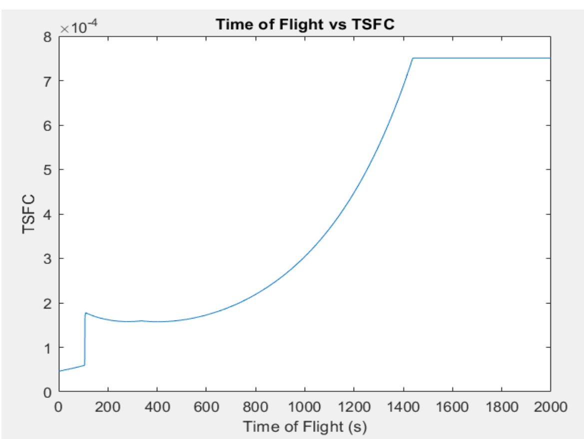
The turbojet of the TBCC was based on the GE J79 turbojet engine, which was used on the SSM-N-9 Regulus II supersonic cruise missile, and the ramjet was based on the Wright XRJ47, which was designed for the SM-64 Navaho supersonic ICMB. The TBCC has a total dry weight of 2,199 kilograms. The combustor exit temperature for the turbojet is 1,210 K, and the ramjet combustor exit temperature is 900 K. The combustor exit temperature gives the turbojet a maximum thrust of 10,805 Newtons and the ramjet temperature gives the TBCC a cruising velocity between Mach 4 and Mach 5 at an altitude of 20 kilometers. Since both engines are based on actual flight proven engines, the inlet area for each one is realistic. The turbojet has an inlet area of 0.773 meters squared, and the ramjet has an inlet area of 1.131 meters squared. For all of the results discussed in this section, a value of 0.5 kilograms per second was used for the fuel mass flow rate and the aircraft started with 1,000 kilograms of fuel. The aircraft starts at sea level and accelerates straight up to the cruise altitude of 20 kilometers, where it will then start going downrange. This assumption simplifies the analysis of the TBCC engine. This flight profile can be seen modeled in **Figure 1** (Range vs Altitude).

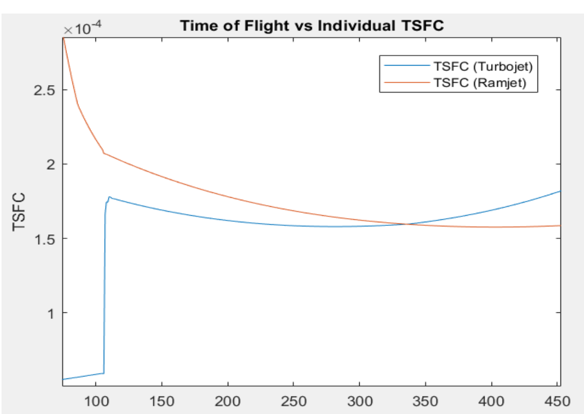


Both engines involved in the TBCC are designed to run on Jet-A fuel, which has a chemical composition of $C_{10}H_{22}$. The stoichiometric air to fuel ratio for the TBCC was found using Equation 2.34, which was a value of 15.0667. It was assumed that the TBCC runs at the stoichiometric ratio as the analysis is looking for the maximum performance of the engine. Using the air to fuel ratio, the specific heat ratio (γ) and isobaric specific heat constant (C_P) were found using Equations 2.16 and 2.15, respectively. The mass flow rate of air into the engine was then found using the fuel mass flow rate and air to fuel ratio. For the purpose of the analysis, it is assumed that the fuel mass flow rate remains constant throughout the entire duration of the flight, no matter which engine it is in. This assumption also means that the air mass flow rate is constant throughout the flight. The fuel to air ratio (f) is equal to the inverse of the air to fuel ratio.

The turbojet runs the entire duration that the aircraft is at subsonic speeds. The exhaust velocity of the turbojet was determined using Equation 5.24 and the combustor exit temperature, and iterating until it reached a constant value. This constant exhaust velocity is based on the assumption that the aircraft does not take off until it reaches full throttle. Since the thrust of an engine is the change in momentum of the flow, defined in Equation 5.23, this means the maximum thrust of the turbojet occurs at takeoff and decreases as the aircraft's velocity increases. The afterburner portion of the flight starts when the aircraft passes through the sound barrier and goes supersonic. The exhaust velocity after the afterburner is determined using Equation 5.24, but uses the temperature in the afterburner instead of the combustor exit temperature. Since the vehicle is inflight when it transitions to its afterburner, it does not produce its maximum thrust when it starts up. The exhaust velocity of the afterburner increases as the aircraft continues to climb towards its cruise altitude. The ramjet portion of the TBCC starts when the ramjet is already at an altitude of 20 kilometers. Since the ramjet requires high-velcoity airflow in order to compress the gas, the exhaust velocity increases with the aircraft's velocity. With a combustor exit temperature of 900 K, the ramjet propels the aircraft to a cruise velocity of Mach 4.75 at its cruise altitude.

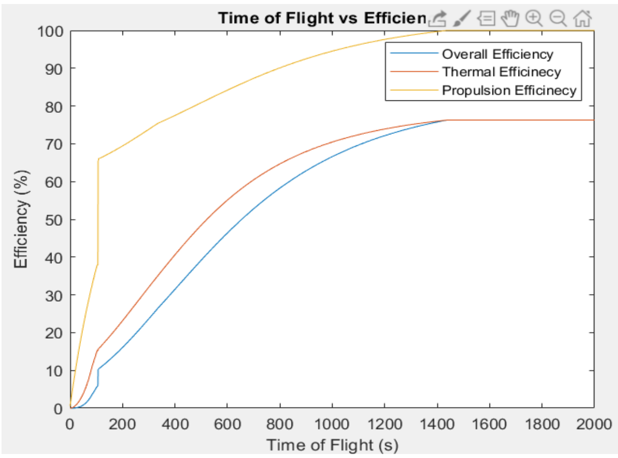
The most difficult part of the analysis is determining when to switch engines in the flight profile. The parameter used to determine when to change from the turbojet (with the afterburner) to the ramjet is the thrust specific fuel consumption. The TSFC is a measure of engine efficiency that measures how much fuel is burned over a given period of at a certain thrust level. The units used from the analysis for TSFC are kilograms per second per Newton of thrust. Since the equation is divided by thrust, a lower TSFC means the engine is more efficient while a higher TSFC means the engine is less efficient. For the analysis of the TBCC, it is already assumed that the fuel flow rate does not change so the only changing variable in the equation is thrust. The TSFC is calculated using Equation 5.28. As was stated earlier, the turbojet transitions to its afterburner when the aircraft starts going supersonic. This switch occurs 92 seconds into flight, and can be seen by a large increase in TSFC in **Figure 2** (Time of Flight vs TSFC). The transition from turbojet with afterburner to ramjet occurs 336 seconds into flight and is represented





in **Figure 2** by a small peak in TSFC followed by a decrease. The transition is also shown in **Figure 3** (Time of Flight vs Individual TSFC) where the ramjet TSFC crosses below the turbojet TSFC curve.

Another benefit that having multiple engines that preform better at different flight conditions is having maximized thermal and propulsive efficiencies throughout the entire flight duration (**Figure 4**). The propuslive efficiency relates the inlet velocity of the air and the exhaust velocity (Equation 5.9). The closer the inlet velocity is to the exhaust velocity, the more propulsively efficient it is. The aircraft has a large increase in propuslive efficiency when it switches to the afterburner, 92 seconds into flight. This is because the turbojet has a high exhaust velocity and combustor exit temperature, which is could not reach without the afterburner. The aircraft reaches 100% propulsive efficiency when it switches to the ramjet cruise portion of flight.This is because the inlet and exhaust velocities are the same, and the aircraft is no longer accelerating. This was able to occur because the ramjet has a lower combustor exit temperature compared to the turbojet (900 K vs 1210 K). The thermal efficiency represents a relation between the inlet and combustor exit temperatures (Equation 5.10). The thermal efficiency reaches a maximum value of 76.27% when the ramjet enters it cruise phase. This is because the engine cannot extract any heat from the gas and convert it to thrust. This is due to the combustor inlet temperature equaling the combustor exit temperature of the ramjet (900 K).



The flight profile of the TBCC aircraft is broken up into six different points in order to get a thorough analysis. This six points are: takeoff, subsonic turbojet acceleration, supersonic turbojet with afterburner acceleration, ramjet startup, ramjet acceleration, and ramjet cruise. The analysis for each point will include the duration that the vehicle is in that point, start and end altitude, start and end range, fuel consumed, fuel remaining, and final weight. These points are analyized using a fuel flow rate of 0.5 kilograms per second and 1000 kilograms of fuel.

1. **Takeoff**

Altitude: 0 kilometers
Range: 0 kilometers
Intial Mass: 3199 kilograms
Fuel Consumed: 0.5 kilograms
Fuel Remaining: 999.5 kilograms
Final Mass: 3198.5 kilograms

2. **Turbojet Acceleration**

Start Time: 1 seconds
End Time: 92 seconds
Final Altitude: 13.248 kilometers
Range: 0 kilometers
Intial Mass: 3198.5 kilograms
Fuel Consumed: 45 kilograms
Fuel Remaining: 954.5 kilograms
Final Mass: 3153.5 kilograms
Average TSFC: 0.000005164 $\frac{kg}{s \bullet N}$

3. **Turbojet with Afterburner**

Start Time: 93 seconds
End Time: 336 seconds
Final Altitude: 20.003 kilometers
Range: 96.003 kilometers
Intial Mass: 3153.5 kilograms
Fuel Consumed: 122 kilograms
Fuel Remaining: 832.5 kilograms
Final Mass: 3031.5 kilograms
Average TSFC: 0.0001566 $\frac{kg}{s \bullet N}$

4. **Ramjet Startup**

Start Time: 337 seconds
End Time: 585 seconds
Altitude: 20.003 kilometers
Range: 364.453 kilometers
Intial Mass: 3031.5 kilograms
Fuel Consumed: 124.5 kilograms
Fuel Remaining: 708 kilograms
Final Mass: 2907 kilograms
Average TSFC: 0.0001609 $\frac{kg}{s \bullet N}$

5. **Ramjet Acceleration**

Start Time: 586 seconds
End Time: 1435 seconds
Final Altitude: 20.003 kilometers
Range: 1219.68 kilometers
Intial Mass: 2907 kilograms
Fuel Consumed: 425 kilograms
Fuel Remaining: 283 kilograms
Final Mass: 2482 kilograms
Average TSFC: 0.0003567 $\frac{kg}{s \bullet N}$

6. **Ramjet Cruise**

Start Time: 1436 seconds
End Time: 2000 seconds
Final Altitude: 20.003 kilometers
Range: 1974.95 kilometers
Intial Mass: 2482 kilograms
Fuel Consumed: 283 kilograms
Fuel Remaining: 0 kilograms

Final Mass: 2199 kilograms

TSFC: 0.0007506 $\frac{kg}{s \bullet N}$

The aircraft flies for a total of 2000 seconds with a fuel flow rate of 0.5 kilograms per second and 1000 kilograms of fuel. The aircraft achieves a total range of 1,974.95 kilometers under these operating parameters (Equation 5.19).

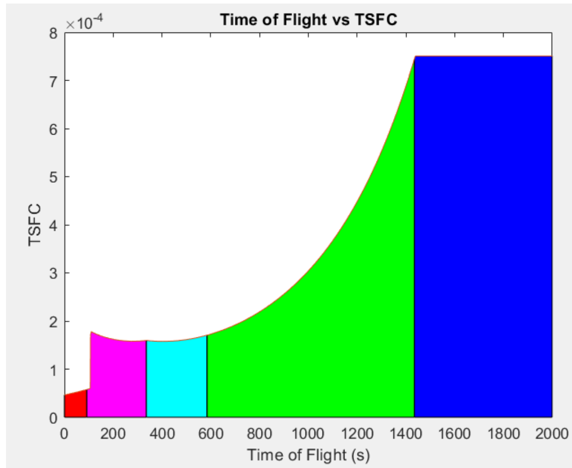
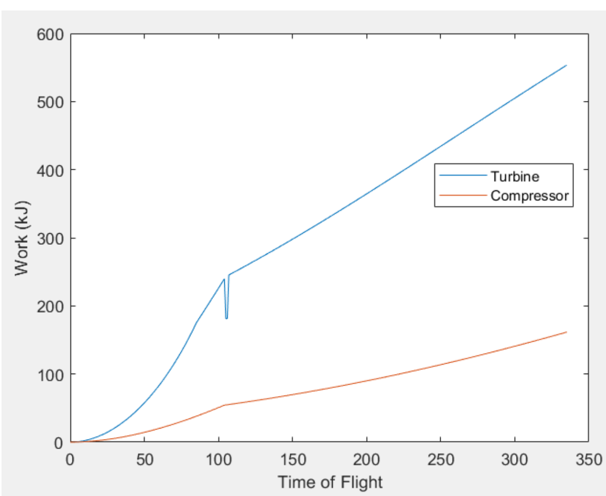


Figure 5 shows the TSFC as a function of time with each operating condition broken into their own time frame. This is done on the "Time of Flight vs TSFC" graph instead of the "Altitude vs Range" graph because the aircraft does not start going downrange until it reaches 20 kilometers in altitude, so the graph would not feature the first two operating conditions. The aircraft spends most of its time in ramjet acceleration, which was a total of 849 seconds, followed by ramjet cruise, which lasted 564 seconds. This means the vehicle spends most of its time using the ramjet, which is partly due to the flight profile climbing straight up before going downrange. At the higher altitude and velocity, the ramjet is more efficient than the turbojet with afterburner, and propels the aircraft to higher speeds.

The turbojet accelerates from being stationary up to flight velocities where the ramjet can start. As it was stated in the introduction, this means the turbojet requires a compressor to increase the pressure of the incoming air to the combustor pressure. This compressor is powered by a turbine, which is located after the combustor and before the nozzle. The turbine is powered by the high velocity gases flowing towards the nozzle. There is work done in both of these mechanisms, and they can be calculated by using Equation 2 and Equation 1, respectively. Work is done to the gas in order to compress it in the compressor, and there is work done by the gas in the turbine, which is was causes it to spin. **Figure 6** shows the values for both the compressor and turbine throughout the entire duration of the turbojet portion of the flight profile. There are two distincts parts of each curve. The first part represents the work done as the aircraft is climbing



towards it cruise altitude. This section has an exponential increase, which is caused by the ambient temperature and pressure decreasing as the altitude increases. The second portion if the curves have a more linear slope for the rest of the turbojet flight. The only changing variable in this part of flight is the increase in the inlet temperature, as it has a positive correlation with the aircraft's velocity. The turbine work is alway greater than that of the compressor, as it must drive the compressor. There is also some of the work lost and it is not all translated to the compressor.

Conclusion

A popular propulsive engine is a Turbine Based Combined Cycle (TBCC), which consists of a turbojet and ramjet. The turbojet propels the vehicle from rest through subsonic flight, where the afterburner starts up. The afterburner portion of the flight accelerates the aircraft supersonically until the ramjet starts up and has a lower thrust specific fuel consumption. The vehicle follows a flight profile where it climbs to its cruise altitude of 20 kilometers before it starts going downrange. Both of the engines use $C_{10}H_{22}$, also known as Jet-A, as the fuel. The turbojet and ramjet are both considered ideal for this analysis of their performance.

Using a fuel consumption of 0.5 kilograms per second and 1000 kilgrams in fuel, the aircraft powered by the TBCC engine is able to achieve a range of 1,974.95 kilometers before running out of fuel. The turbojet burns for a total of 92 seconds before it reaches supersonic speeds and transitions to its afterburner. The turbojet climbs 13.248 kilometers, which is more than half of the altitude required. The afterburner burns for 249 seconds and climbs the rest of the way to 20 kilometers cruise altitude. It also propels the aircraft 96 kilometers downrange. The afterburner switches to the ramjet 337 seconds into flight at a speed of Mach 1.95. This is the point where the ramjet TSFC crosses below the turbojet with afterburner TSFC curve. The aircraft remains using the ramjet for the remaining 1,663 seconds of flight. With a combustor exit temperature of 900 degrees Kelvin, the ramjet accelerates the aircraft to a velocity of Mach 4.75. The ramjet portion of the flight covers 1878.26 kilometers of range and burns 832 kilograms of fuel.

The performance of the engines and the flight profile changes with the fuel consumption rate and the amount of fuel the aircraft has a take off. With a higher fuel consumption rate, the time of flight is decreased and the engine transitions occur earlier in flight. Since the flight duration is reduced, this also means the range is decreased. A lower fuel consumption does the opposite, increasing the range and flight duration and causing the transitions to occur later in flight. Increasing the aircraft's fuel has a similar effect as decreasing the fuel consumption, but only increases the transition times a little bit. The greatest effect the higher fuel load has is the ramjet cruise duration is increased, which allows the vehicle to have a greater range. A decreased takeoff fuel load again has the opposite effect. It slightly decreases the time into flight that the transitions occur. It also decreases the amount of time that the ramjet operates, and can prevent the ramjet from reaching its cruise velocity before it runs out of fuel, depending on how much the fuel load is reduced.

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Appendix

Equation 1: $W_{Turbine} = C_{p(mixture)}(T_3 - T_4)$

Equation 2: $W_{Compressor} = C_{p(air)}(T_2 - T_1)$

Equation 3: $SFC = ((1 + f) * u_e) - v_1$

Equation 4: $Thrust = SFC * m_a$

Equation 5: Acceleration = Thrust / Mass