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Efficiency of Gas Turbine Engines

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Cover Page Footnote

Acknowledge research partners Ricky Mitchell and Josh Hunter.

Gas Turbine Engine Cycle Analysis Confirmation

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ABSTRACT

The following paper will confirm Price Induction's test bench data for the DGEN 380 engine. This study will demonstrate how Price Induction's test bench data may be verified by performing a parametric cycle analysis of the individual components of a DGEN 380 engine. The ultimate goal of this research is to determine how to make gas turbine engines more efficient. To achieve this goal, the researchers will confirm that gas turbine engines perform best in colder temperatures and then determine how to make gas turbine engines more efficient based on the collected data.

I. INTRODUCTION

The purpose of this study is to analyze gas turbine engine performance (more specifically turbofan engine performance) with the ultimate goal of improving the efficiency of gas turbine engines. The data collected will be used to confirm that gas turbine engines perform best at colder temperatures. The experimental and theoretical data collected from Price Induction's test bench validates the confirmation. The test bench uses environmental conditions to output data on thrust, efficiency, and pressures/temperatures at specific components in the turbofan engine. The theoretical aspect of this research relies on a combination of equations that compute specific data for different portions of the engine to calculate overall thrust and efficiency. Once both methods confirm that gas turbine engines perform best in colder temperatures, the researchers will have insight into how to improve the efficiency of these engines.

II. LITERATURE REVIEW

The engine analyzed in this study is a gas turbofan DGEN 380 engine. The DGEN 380 engine was designed to provide flight for personal light jets that can seat four to five people. As a result, it is the smallest gas turbofan engine in the world. This engine's flight restrictions are a maximum altitude of 25,000 ft and a maximum takeoff weight of 2,500 kg. Most aircraft are equipped with twin turbofan engines, two on both sides, to compensate for an engine failure. A photo of the DGEN 380 engine, produced by the Price Induction company, can be seen in Fig. 1 below.

FIGURE 1. DGEN 380 Turbofan Price Induction Engine. [2]

To analyze this engine theoretically and experimentally, one must understand the components of a gas turbofan engine and how they work in general. A turbofan engine consists of an inlet fan, compressor, combustion chamber, turbine, and a nozzle [3]. Turbofan engines have a low thrust specific fuel consumption (TSFC) and are economical in their fuel use [5]. Turbofan engines accelerate large masses of air to a lower velocity than other engine types [4], which results in a higher propulsive efficiency [6]. The area of the inlet of the turbofan engine is large, which results in higher amounts of drag. This increased drag reduces efficiency.

The Inlet component of a turbofan engine has a direct correlation with the internal airflow and the freestream flow through the engine. A typical inlet for any gas turbine engine has numerous blades that are large enough to hold two double-decker buses. An inlet sucks in the massive amount of air required by the engine from its freestream conditions to the conditions required at the compressor's entrance with uniform flow. The DGEN 380 has a subsonic inlet design. Subsonic inlets are used when the aircraft speed is under Mach 1, where Mach is the ratio of the speed of the aircraft to the speed of sound. Therefore, Mach 1 is just 1 times the speed of sound, and Mach 2 is 2 times the speed of sound, and so forth [7]. An example of a subsonic inlet can be seen in Fig. 2 below, while the airflow pattern for a subsonic inlet can be seen in Fig. 3.

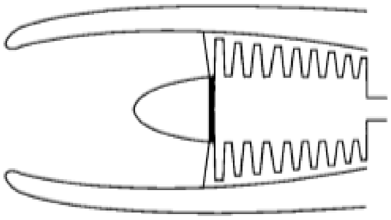

FIGURE 2. Basic Subsonic Inlet Model [1].

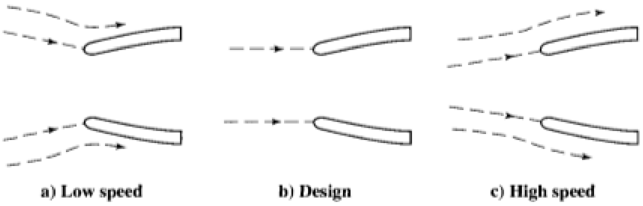

FIGURE 3. Subsonic Inlet Flow Pattern [1].

Supersonic inlets are for applications where the speed exceeds Mach 1. Because these types of inlets surpass Mach 1, supersonic inlets are subject to shock waves. Shock waves are the result of a body moving through a medium (air) above the speed of sound. Since the body is traveling through the air faster than the speed of sound, air molecules explode, causing shock waves. To increase the magnitude of the supersonic inlet, more shock waves would be needed to compress the entering air, which ensures that the engine will be able to perform over a multitude of Mach numbers [7].

Behind the inlet are compressors that increase the pressure of the entering airflow. The compressors will cause the efficiency of the combustion process and power extraction process to increase. The compressor's job is to do exactly what it is named for, which is to compress. The inlet sucks in massive amounts of air, and those air molecules then reach the compressor, where more blades compress the air molecules that were sucked in by the inlet. When these air molecules are compressed, the kinetic energy increases between them. As a result, the pressure increases as well. When there is an increase in the air pressure, the volume of the air will decrease. This decrease in air volume will result in the combustion of the fuel to occur in smaller volumes. There are two types of compressors on a turbofan engine. The first type is the single-stage centrifugal compressor. Centrifugal compressors are made up of an impeller, diffuser, and a manifold. For this design, air enters the compressor near the hub of the impeller. The rotational motion of the impeller causes the air to undergo severe compression. Compression occurs when the velocity of the air increases [9].

The next type of compressor is the axial compressor. This air flows in the axial direction through the rotor blades and stator vanes that are concentric with the axis of rotation. The path of the airflow in an axial compressor decreases in cross-sectional area. As the area decreases, the density of the air increases from each stage of the compressor [10]. The combustor chamber is next behind the compressor blades. Its purpose is to take the compressed fast-moving air molecules and hold them in a can to be injected with fuel (usually methane). Methane is injected into the can of compressed air molecules, causing a chemical reaction. This explosion is what creates the thrust to push an aircraft forward. The combustor also ensures that the temperature of the gases that are produced do not exceed the temperature limit of the structure. A combustion chamber consists of a can and annular [11].

In a turbofan engine, the turbine is designed to extract kinetic energy from the expanding gases that flow from the combustion chamber. The kinetic energy is used to produce energy for the shaft and to drive the compressor. An axial turbine also has multiple stages. There are two types of axial turbines, impulse and reaction turbines. The impulse turbine has the same relative inlet velocity and relative discharge velocity of the rotor [13], while the reaction turbine has a different inlet velocity and a different discharge velocity.

The exhaust nozzle's purpose is to increase the velocity of the exhaust gas before discharging from the nozzle. The nozzle also collects the gas flow from the turbine. The pressure ratio across the nozzle controls the expansion process. Thus, the maximum thrust for a given engine is achieved when the exit pressure equals the ambient pressure. The two types of nozzles are the convergent and the convergent-divergent nozzle. When the pressure ratio is less than 2, a convergent nozzle is used. A convergent-divergent nozzle is used for supersonic applications.

III. METHODS

In this study, the researchers performed a parametric analysis of the DGEN 380 engine's component parts to confirm that gas turbine engines perform best in colder temperatures using Price Induction's test bench results. As this engine is the smallest gas turbine engine in the world, it is more accessible to experimentation than regular-sized engines which are not readily available for study. The test bench is organized into three different modules that: 1) analyze the engine's aerodynamic behavior, 2) analyze the engine's thermodynamic behavior, and 3) evaluate the component parts of the DGEN 380 engine. The parametric cycle analysis is broken into two stages. The first stage analyzes the overall total temperature or stagnation temperature (the temperature reached when a constant flowing fluid is brought to rest). The first stage also analyzes the engine's pressure. The second stage analyzes the different components of the turbofan engine. The following equations are used to perform the parametric analysis for the DGEN 380's engine:

$$T_t = T(1 + \frac{\gamma - 1}{2} M^2) \text{ where,}$$

$$T = Static\ (Thermodynamic)\ Temperature$$

$$\gamma = ratio\ of\ specific\ heats = 1.4$$

$$M = Mach\ Number = \frac{V}{a} = \frac{V}{\sqrt{\gamma g_c R T}}$$

Where

$V = Flow\ Velocity$

$a = speed\ of\ sound = 343\ {}^{m}/_{s}$

$g_c = gravity = 9.81\ m/s$

$R = gas\ constant\ of\ air =$286.9

Equation (1) Total Temperature

Equation (1) is the total temperature equation. To describe further, to determine the Total temperature (Tt) at any point in a gas turbine engine, we have to know the static temperature (T). This static temperature is also known as stagnation temperature because it is the temperature at which velocity (flow of air) equals zero. In the Mach number equation, gamma is the ratio of specific heats, which is 1.4 for air, and T is the temperature of the environment. Together these variables are used to find the total temperature (Tt) at any component of a gas turbine engine.

$$P_t = P(1 + \frac{\gamma - 1}{2} M^2)^{\gamma/(\gamma-1)}$$

Where

$P = Static\ Pressure$

$\gamma = ratio\ of\ specific\ heats = 1.4$

$$M = Mach\ Number = \frac{V}{a} = \frac{V}{\sqrt{\gamma g_c R T}}$$

Equation (2) Total Pressure.

Equation (2) is the total pressure equation. To determine the pressure at any point in a gas turbine engine, this equation must be used. P is the static pressure. Static pressure is the atmospheric pressure, which varies depending on the altitude.

$$F = \left\{\frac{a_o}{g_c}\frac{1}{1+\alpha}\left[\frac{V_9}{a_o} - M_o + \left(\frac{V_{19}}{a_o} - M_o\right)\right]\right\}\dot{m}_o$$

Where

$a_o = speed\ of\ sound = \sqrt{\gamma R g_c T_o}$

$g_c = gravity = 9.81\ m/s$

$\dot{m}_o = initial\ mass\ flow\ rate$

Equation (3) Thrust.

Equation (3) is the Thrust or Force equation, where Force is denoted by F.

$$V_9 = \left[\sqrt{\frac{2}{\gamma - 1}\left\{\tau_\lambda - \tau_r\left[\tau_c - 1 + \alpha\left(\tau_f - 1\right)\right] - \frac{\tau_f}{\tau_r \tau_c}\right\}}\right] a_o$$

Equation (4) Exit Velocity.

Where

$$\tau_\lambda = Temperature\ Ratio\ at\ Burner = \frac{T_{t4}}{T_o}$$

$$\tau_r = Temperature\ Ratio\ of\ Freestream = 1 + \frac{\gamma - 1}{2} M^2$$

$$f = \frac{C_p T_0}{h_{PR}}(\tau_\lambda - \tau_r \tau_c)$$

Equation (5) Fuel/Air Ratio.

Here, “f” is the Fuel or Air ratio. In the below equation, “S” is the specific thrust. The bypass ratio is denoted by “α.” η_T is the thermal efficiency, and η_p is the propulsive efficiency.

$$S = \frac{f}{(1+\alpha)(\frac{F}{\dot{m}_0})}$$

Equation (6) Specific Thrust.

$$\eta_T = 1 - \frac{1}{\tau_r \tau_c}$$

Equation (7) Thermal Efficiency.

$$\eta_P = 2M_0 \frac{V_9/a_0 - M_0 + \alpha({V_{19}}/a_0 - M_0)}{{V_9}^2/{a_0}^2 - {M_0}^2 + \alpha({V_{19}}^2/{a_0}^2 - {M_0}^2)}$$

Equation (8) Propulsive Efficiency.

Below is the net power equation, denoted by W_{out}.

$$W_{out} = \frac{1}{2g_c}[(m_o + m_f)Ve^2 - m_o Vo^2]$$

Equation (9) Net Power.

Here, m_o denotes the mass flow rate of air, and m_f is the mass flow rate of fuel. V_e denotes the velocity exiting the inlet, while V_o is the velocity of air entering the inlet.

IV. RESULTS

For this study, thrust, power, and efficiency were compared with altitude. For the thrust vs. altitude plot, various environmental inputs had to be adjusted to obtain valid results for the thrust vs. altitude graph, which can be seen in the following Fig. 4 below. For instance, the speed is held constant while the temperatures were analyzed at various levels. In each of these environmental input instances, one can see the effects on the thrust-output of the turbofan engine. All of these plots have been combined into one performance curve, which displays the thrust-output for the parametric analysis study of the DGEN 380 engine. There is a hump in the performance curve at 3000 meters. This hump means the aircraft reaches its maximum amount of thrust in a given flight at 3000 meters. Ultimately, Figure 4 shows how a change of temperature can affect the overall thrust, where temperature increases decrease the overall thrust. This graph demonstrates that thrust fluctuates as altitude increases. The fluctuating altitude proves that turbofan engines perform better in colder temperatures because hotter temperatures produce less thrust.

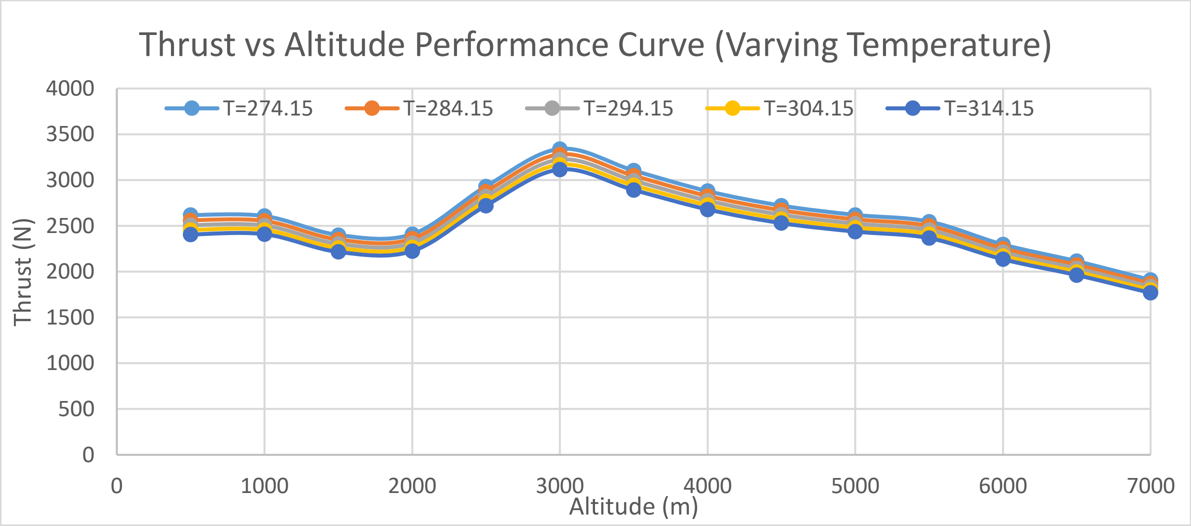

FIGURE 4. Thrust vs Altitude with varying temperature and when the Speed=70m/s

Equation 3 theoretically confirms that DGEN 380 engines perform best at colder temperatures. Eq. (4) is a variable in Eq. (3), so Eq. (4) had to be calculated first. Since thrust vs. altitude was being measured at various temperatures, the chosen temperatures were input for Greek letter Tau(τ). These temperatures were in kelvin and randomly chosen. The theoretical calculations confirmed our experimental results, in that gas turbine engines produce less thrust in hotter temperatures.

The following graph (Fig. 5) shows power vs. altitude. As the temperatures increase, the power decreases. Just like Fig. 4, this graph also has a hump or peak point at 3000 meters. This peak point means when the aircraft reaches 3000 meters in altitude, it is producing the maximum output of power in a given flight, which makes sense because this is also the point where the maximum amount of thrust is produced. Both graphs having similar trends is positive because it confirms our collected data by matching two different parameters (thrust and power). This graph shows that as the temperature increases, the aircraft loses power. Therefore, it will lose thrust as well. This loss of thrust is a negative feature that produces a potentially dangerous situation, because all aircrafts need thrust and power to fly. This negative feature makes sense and proves again turbo fan engines perform better in colder temperatures because hotter temperatures produce less thrust. As for the theoretical results, Eq. (9) was used to calculate the net or total power of the engine. The obtained results matched the Experimental results from the test bench that produced the graph below. So far, the relationship between thrust and temperature, and power and temperature, have been proven true experimentally and theoretically.

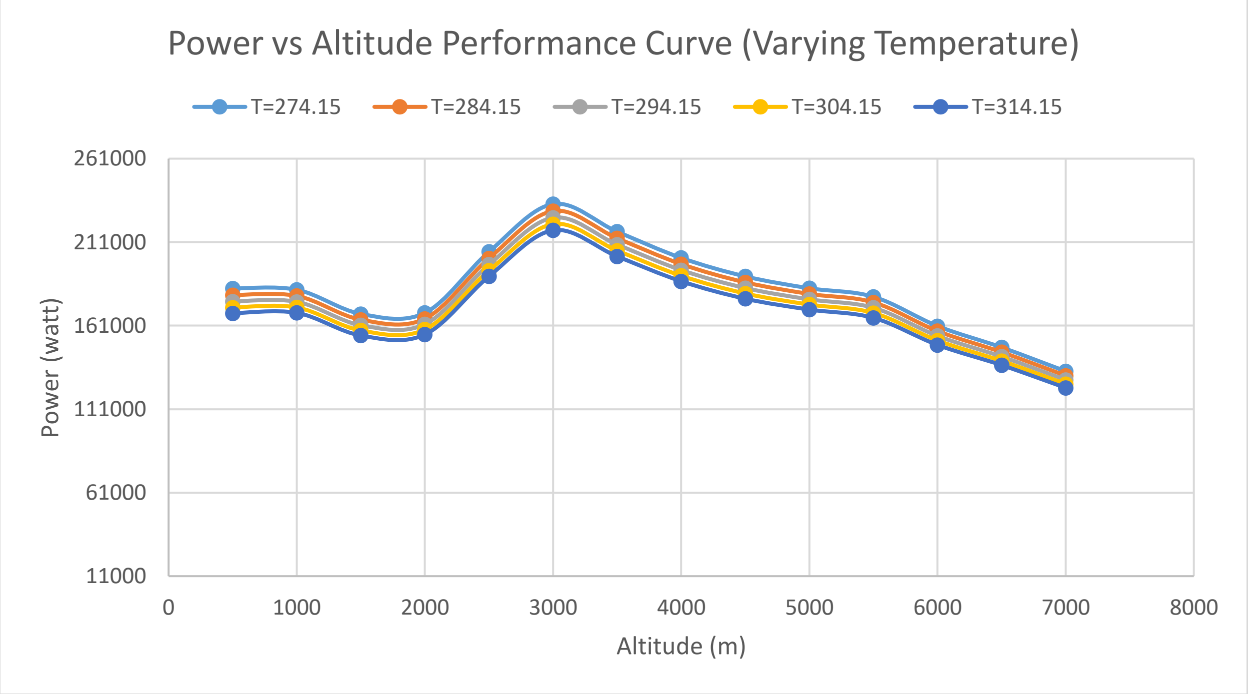

FIGURE 5. Power vs Altitude with varying temperature and when the Speed=70m/s

The last plot is the Efficiency vs. the Altitude plot (Figure 6), whose analysis takes the same approach as that used to analyze thrust vs. altitude. The speed and temperature are constant but are analyzed at different parameters. This method was done to show the effect that the speed and the temperature have on the overall efficiency of the turbofan engine. Figure 6 shows this relationship, where the overall efficiency of the turbofan engine fluctuates. The efficiency increases as the altitude increases and then becomes relatively static with an efficiency of approximately six percent. One can see the same peak at 3000 meters in this graph, as was documented in Fig. 4 and 5. This peak shown in both figures means the aircraft reaches its maximum efficiency at its maximum altitude, which is 3000 meters. However, the trend is reversed in Figure 12. This reversed trend is a problem because as the temperature increases, efficiency increases. This trend should not happen. As the temperature increases, the engine's efficiency should decrease because it is directly related to its performance. Our previous two graphs prove an increase in temperature produces less thrust and power. This decrease in thrust and power means the efficiency, should also decrease as the temperature increases. For some reason, this efficiency graph shows the opposite relation

and indicates these findings are flawed.

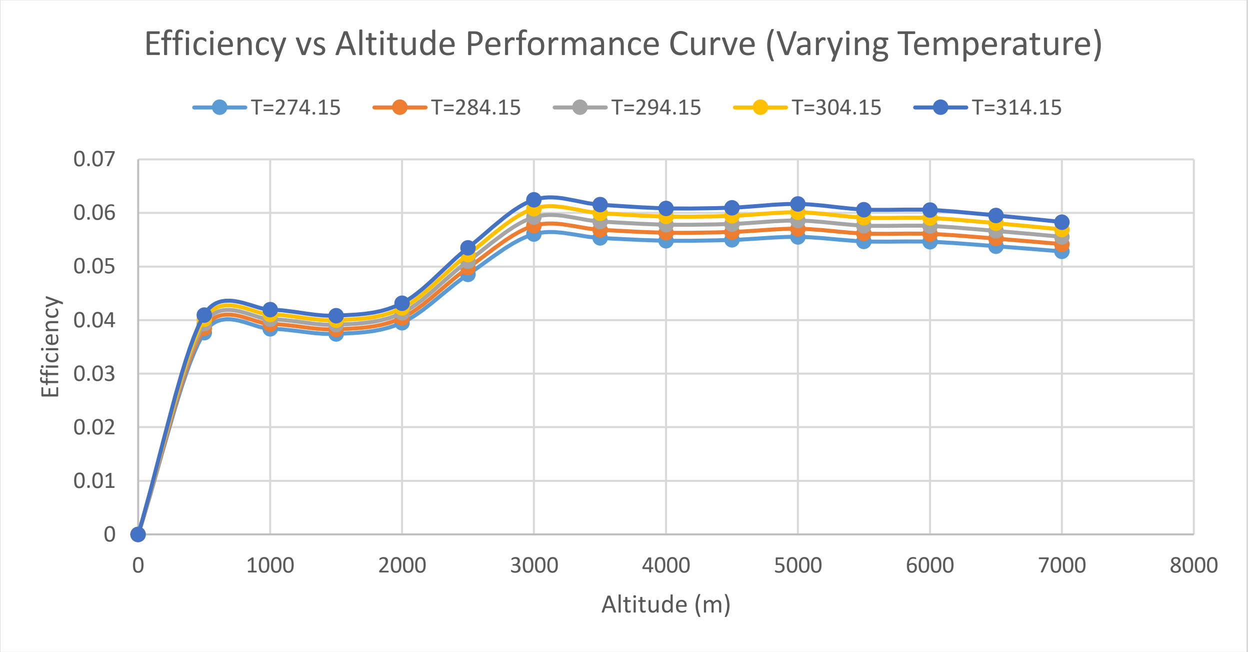

FIGURE 6. Overall Efficiency vs Altitude with varying temperature and when the Speed=70m/s

V. DISCUSSION

The purpose of this research was to prove that gas turbine engines perform best in colder temperatures in two ways: experimentally and theoretically. In order to confirm this, thrust, power, and efficiency had to be analyzed experimentally (test bench) and theoretically (calculations). The data collected from the test bench graphs shows that an increase in temperature decreases the engine's thrust and power. The theoretical calculations also matched this relationship for thrust and power. In Fig. 4 and 5 one can see the same peak at 3000 meters; the engine is producing the maximum amount of thrust and power in a given flight. Both the thrust vs. altitude and power vs. altitude graphs successfully confirm that gas turbine engines perform best in colder temperatures. However, the efficiency graph and data do not match, and this indicates there is a problem with this study's methodology, namely that our variables could not be replicated. This problem stems from a technical malfunction within the test bench apparatus that resulted in a system reboot and wipe that deleted our study data. Since there was no data from the thrust and power parameters, we were unable to replicate the study's exact values for environmental conditions, velocities, mass flow rates, etc. This mishap is likely why the efficiency results are incorrect. This hiccup resulted in a lack of verifiable data from the data pool. Further research should include active data backups as a part of the methodology. Despite these issues, the results that were obtained from the parametric cycle analysis (theoretical portion) and the test bench (experimental portion) match. More importantly, they also prove gas turbine engines perform best in colder temperatures. Gas turbine engines perform best in colder temperatures because warm air is less dense than cold air. This research confirmed this fact both experimentally and theoretically. Both validations are important because analyzing a system under certain conditions can help one figure out how to improve its overall performance. Based on this research, the efficiency of gas turbine engines can be improved by optimizing the inlet blades. The material, curvature, and angle of the inlet blades have a dynamic effect on the air entering the engine. If the perfect combination of material and angle of curvature can be determined, then the temperature of incoming air may be reduced, which will ultimately produce more power and thrust. For the parametric cycle analysis, the maximum thrust was 3200 N, which can be seen in Fig. 4. The DGEN 380 engine has a maximum rated thrust of 2500 N. So, the data collected shows a thrust of 700 more newtons than the published DGEN 380 data. This disparity could be due to the fact that the DGEN 380 engine is the smallest gas turbine engine in the world and isn't meant to fly at the altitude or speed set in this study. In addition, the temperature could have influenced these results because random temperatures were chosen in kelvin ranging from 274.15 to 314.15. All of these temperatures are present at altitudes below the cruising altitude. The cruising altitude for the DGEN 380 is 10,000 feet, and the maximum altitude is 25,000 feet. The altitudes chosen for this research are all below the cruising altitude (10,000). Being below cruising altitude may have something to do with the data producing more thrust than that documented by the manufacturer. The power calculations performed in this research show that speed and temperature played huge roles in the power output. The parametric cycle analysis performance curves are similar to that of the test bench because both have maximum values at 3000 meters. Both graphs (Fig. 4 and 5) have the same trend, and both prove true the relationship between temperature and power/thrust to be true. Temperature and power/thrust are in an inverse relationship where, as the temperature increases, the aircraft's thrust and power decreases. This inverse relationship should be the case for our efficiency data, but the data collected showed an opposite result due to errors in experiment methodology.

CONCLUSION

Despite a lack of data to properly analyze the efficiency parameter, the study was mostly successful. The thrust and power parameters were both confirmed with experimental and theoretical data. In order to analyze the efficiency parameter more accurately, a third data point should be used: simulation. A simulation in SolidWorks could possibly produce accurate efficiency results. Beyond that, one would have to design the DGEN 380 engine and perform a Computational Fluid Dynamics analysis on the engine to get more accurate data. With the data proving that these engines work best in colder temperatures, the next step in this research would be to test the impact of blade optimization on the engine's temperature in warmer climates.

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CITATIONS

FIGURE 1. DGEN 380 Turbofan Price Induction Engine. [2]

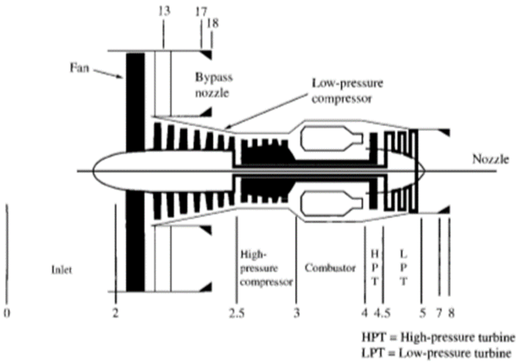

FIGURE 2. Turbofan Engine Schematic. Adapted from Elements of Propulsion Gas Turbines and Rockets.

pg 9. 2006.

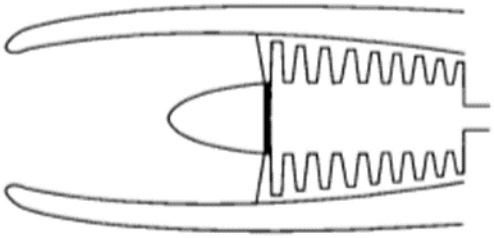

FIGURE 3. Basic Subsonic Inlet Model Adapted from Elements of Propulsion Gas Turbines and Rockets.

pg 244. 2006.