AEROENGINE DESIGN PROJECT

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In the AA 461 Airbreathing Propulsion project, student teams are challenged to design a gas turbine engine core comprising a compressor, combustor, and turbine, focusing on performance, maintaining acceptable numbers, identifying cost-efficient designs, and managing specified mass flow rates under defined inlet conditions. Utilizing tools such as CEARUN to analyze compressor, and TURBN & COMPR to analyze the turbine, and combustion.

INTRODUCTION AND BACKGROUND

The Aeroengine Design Project focuses on designing a gas turbine engine core for efficient and cost-effective airbreathing propulsion systems. This project involves designing a compressor, combustor, and turbine, and addressing challenges such as optimizing core performance and maintaining acceptable turbine inlet temperatures.

This is where gas turbine engine cores serve as the collective combuster, compressor, and turbine. The compressor pressurizes incoming air efficiently, considering factors like rotor angular velocity and swirl distribution. The combustor ignites fuel and compressed air, influencing engine performance, emissions, and material constraints. The turbine extracts energy from combustion to drive the compressor and auxiliary systems, requiring careful choices for efficiency, work output, and mass flow rates. Each decision is justified based on efficiency, design requirements, and anticipated impacts on cost and performance, at the design point. The design point is the optimum operating condition for best performance. Concerning this specific design, the design point was taken to be at a pressure of 101.3 kPa and a temperature of 298 K.

COMPRESSOR

In the compressor design section of this project, the primary objective is to maximize the total compressor ratio while considering exit temperature and total compressor efficiency. We will discuss the efficiencies, total pressure, and temperature plots, as well as all the relevant equations.

Compressor: COMPR Data

In this subsection, we delineate the fundamental parameters guiding the design and operation of the compressor. The compressor is an axial compressor which was analyzed using the COMPR program. The inputs that were fixed in the COMPR program were mass flow rate, rotor angular velocity, inlet total pressure, inlet total temperature, Mach number, diffusion factor, rotor chord/height ratio, stator chord/height ratio, polytropic efficiency, stator loss coefficient, specific heat ratio, gas constant, mass flow rate, and rotor angular velocity.

Mass Flow Rate	60 kg/s
Rotor Angular Velocity	1000 rad/s
Inlet Total Pressure	101.3 kPa
Inlet Total Temperature	298 K
Mach Number	0.5
Diffusion Factor	0.5
Rotor Chord/Height Ratio	0.5
Stator Chord/Height Ratio	0.5
Polytropic Efficiency	0.9
Approx. Stator Loss Coeff.	0.03
Ratio of Specific Heats	1.4
Gas Constant	0.287 kJ/kg-K
Cp	1.0045 kJ/kg-k
Swirl Distribution	-1

TABLE I. Fixed COMPR Program Inputs

The values of these inputs are shown in Table I. The varied variables were the number of stages, α_1, and the solidity. Each of these variables was changed independently of one another to explore the relationship between said variable and total pressure ratio, total temperature ratio, and total efficiency. The number of stages was varied from stage 1 to stage 20, with increments of one stage. The values of α_1 varied from ten to eighty degrees, with increments of five degrees. The solidity was varied from 0.3 to 1.2, with increments of 0.1. The COMPR program outputs each stage's exit temperature, exit pressure, and efficiency.

Compressor: Plots

Here, we will discuss plots illustrating the behavior of the Compressor.

Plot 1 shows the relationship between compressor pressure ratio and solidity. Solidity typically refers to the ratio of blade chord length to the spacing between blades in a compressor. The plot indicates that as the solidity increases, the pressure ratio also increases. Similar to the previous plot, plot 2 shows the relationship between compressor temperature ratio and solidity. As solidity increases, the temperature ratio also increases. This trend might have implications for compressor efficiency and thermal management.

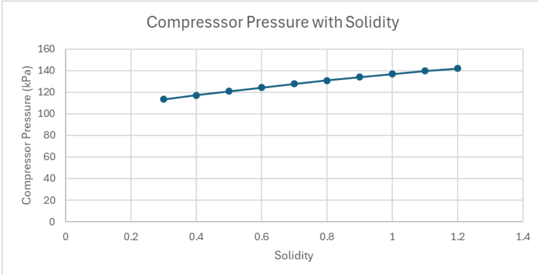

FIG. 1. Compressor Pressure Ratio with solidity

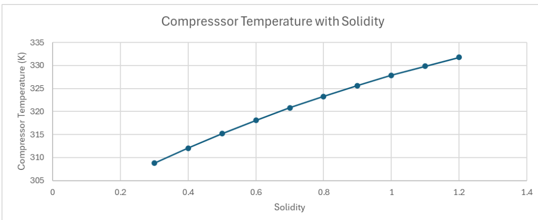

FIG. 2. Compressor Temperature Ratio with solidity

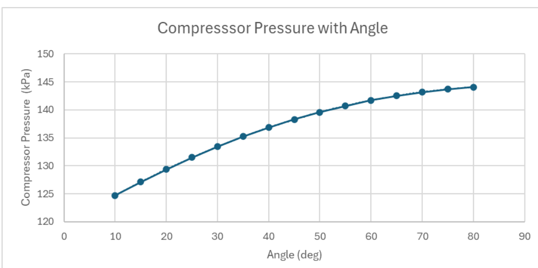

FIG. 3. Compressor Pressure with Angle.

Plot 3 shows how the pressure ratio changes with the inlet angle (alpha one angle) of the compressor. It suggests that as the inlet angle increases, the compressor pressure ratio also increases.

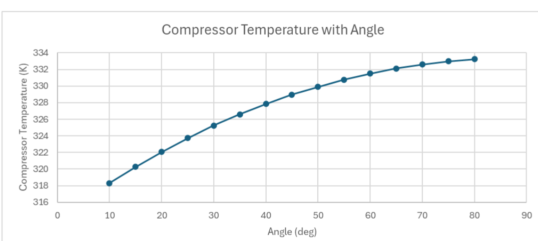

FIG. 4. Compressor Temperature with Angle

Similar to the previous plot 4, this one shows the relationship between the compressor temperature ratio and the inlet angle (alpha one angle). As the inlet angle increases, the temperature ratio also increases.

Plot 5 shows how the pressure ratio changes with the number of compressor stages. It suggests that as the number of stages increases, the pressure ratio also increases. This is generally desirable as it indicates improved compression.

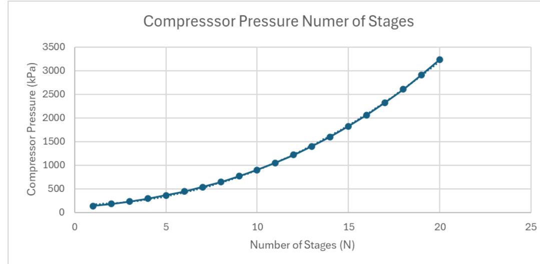

FIG. 5. Compressor Pressure with stages

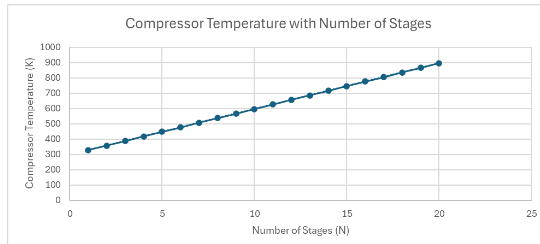

FIG. 6. Compressor Temperature with Number of Stages

Contrary to the previous plot, plot 6 indicates that the temperature ratio increases with the number of compressor stages. While a higher pressure ratio is desirable, an increase in temperature ratio might imply higher thermal loads and potentially reduced efficiency.

Plot 7 indicates that as the number of stages increases, compressor efficiency decreases, which is undesirable. This suggests potential design or operational issues that need further investigation. Improving efficiency may require reassessing design parameters or optimizing operational processes to achieve better performance.

Compressor Considerations

This section goes in-depth in the analysis of the specific considerations influencing the design and performance of

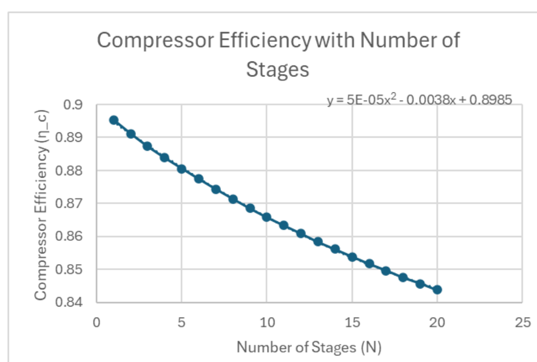

FIG. 7. Caption

the Compressor.

1. Effect of compressor outlet temperature and pressure on combustor and turbine

An analysis was conducted to understand how variations in compressor outlet temperature and pressure affect combustor and turbine efficiency. From Table II, we can observe the obtained compressor outlet temperature and pressure, which were $P_{out} = 2210$ kPa and $T_{out} = 793$ K, respectively. Optimizing this relationship ensures efficient energy transfer and operational integrity across the propulsion system.

2. Maximize compressor pressure ratio (p_{02}/p_{01}), within limitations of system

Now let us discuss maximizing the compressor pressure ratio (p_{02}/p_{01}) while considering system constraints. This involved compression levels with structural and operational limits to enhance system efficiency and reliability. We can see this obtained compressor pressure ratio (p_{02}/p_{01}) for each stage and the trend it shows on plot 5. As the number of stages increases, the pressure ratio also increases. This indicates improved compression efficiency.

3. Work/power required to run compressor

Efficient energy utilization was prioritized, focusing on minimizing the work or power needed to drive the compressor.

4. Compressor efficiency

Compressor efficiency, reflecting its ability to convert input energy into work, was obtained. Utilizing the COMPR program, the goal was to enhance efficiency across all conditions, reducing fuel consumption and environmental impact while improving system performance. Also from in between pressure ratio, temperature ratio, and efficiency, a picked value of the number of stages, alpha 1, and the solidity resulted in a high-pressure ratio, as well as an acceptable temperature ratio and a good efficiency.

Compressor: Analysis Justification

The total temperature ratio, total pressure ratio, and total efficiency were then calculated with equations 1, 2, and 3 respectively. Finally, the compressor-specific work, compressor outlet temperature, and compressor outlet pressure were calculated with equations 4, 5, and 6 respectively. The results are shown in Table II.

$$\tau_c = \tau_{s1} \times \tau_{s2} \times \cdots \times \tau_{s16} \tag{1}$$

$$\pi_c = \pi_{s1} \times \pi_{s2} \times \cdots \times \pi_{s16} \tag{2}$$

Moving to Equation (3), it calculates the total compressor efficiency (η_c), considering changes in pressure and temperature. This efficiency measure is essential for evaluating how well the compressor performs overall and improving its design for better efficiency. In our analysis, detailed in Table II, the efficiency is 85.1%.

Total Compressor Temperature Ratio τ_c	2.66
Total Compressor Pressure Ratio π_c	21.8
Total Compressor Efficiency η_c	85.1%
Total Compressor Specific Work $\dot{W}$	497 kJ/kg
Compressor Outlet Temperature T_{out}	793 K
Compressor Outlet Pressure P_{out}	2210 kPa

TABLE II. Compressor Results

$$\eta_c = \frac{\pi_c^{\frac{\gamma-1}{\gamma}} - 1}{\tau_c - 1} \tag{3}$$

Equation (4) computes the specific work required to run the compressor per unit mass of air, taking into account specific heat capacity, inlet temperature, and compressor efficiency. This equation is essential for evaluating the energy requirements of the compressor.

$$\dot{W} = \frac{Cp * T_{in}}{\eta_c} \times (\pi_c^{\frac{\gamma-1}{\gamma}} - 1) \tag{4}$$

Finally, Equations (5) and (6) calculate the compressor outlet temperature (T_{out}) and pressure (P_{out}) respectively, providing crucial information about the state of the air leaving the compressor. These equations are integral to understanding downstream processes like combustion and turbine operation.

$$T_{out} = T_{in}\tau_c \tag{5}$$

$$P_{out} = P_{in}\pi_c \tag{6}$$

These equations, along with the corresponding plots presented in the earlier sections, collectively contribute to a comprehensive analysis of the compressor system, enabling the evaluation of its thermodynamic performance and design considerations.

Conclusion

In conclusion, the compressor design section of this project emphasizes maximizing the total compressor ratio while considering exit temperature, total compressor efficiency, and relevant auxiliary equations. Analysis of parameters such as solidity, inlet angle, and number of stages provides insights into pressure and temperature behaviors critical for optimizing compressor performance and system efficiency. Additionally, equations derived for total compressor efficiency, specific work, outlet temperature, and pressure were done.

Inputs	Value
Temperature (K)	1706.1
Pressure (kPa)	2213.1
CO (Mole Fraction)	2.4104×10^{-6}
NO (Mole Fraction)	0.0022334
Inlet Total Pressure (kPa)	2213.121624
Oxidizer Temperature (K)	793.2173197
Fuel	Jet-A(L)
Fuel-Air Ratio	0.39

TABLE III. Jet-A(L) CHAMBER

Inputs	Value
Temperature (K)	1494.7
Pressure (kPa)	1212.5
CO (Mole Fraction)	1.9914×10^{-7}
NO (Mole Fraction)	0.00089973
Inlet Total Pressure (kPa)	2213.121624
Oxidizer Temperature (K)	793.2173197
Fuel	Jet-A(L)
Fuel-Air Ratio	0.39

TABLE IV. Jet-A(L) THROAT

COMBUSTOR

The Combustor section of our report delves into the heart of the engine, where the transformation of fuel and air into high-temperature gases occurs. We will discuss reasonable fuel choices with rationale explanations, plots of T_f, CO, and NO, as well as the implementation of T_{04} limits, relevant equations, and lastly, statement combustion strategies such as conventional, LPP, or RFL.

Combustor: CEARUN Data

In this subsection, we delineate the fundamental parameters guiding the design and operation of the combustor. Key considerations include the selection of fuel type, combustion strategy, and equivalence ratio. The choice of each parameter is underscored by its impact on combustion efficiency, temperature distribution, and exhaust emissions.

Moreover, we consider the impact of compressor performance (as analyzed by COMPR) on combustor inlet conditions and subsequent combustion processes. Table II shows us that the compressor outlet temperature and outlet pressure that were used as the combustor inlet temperature and the combustor inlet pressure. The fuel-air ratio varies from 0.1 to 2.0 with increments of 0.1. The fuel-air ratio was then iterated upon and varied from 0.30 to 0.40 with increments of 0.01.

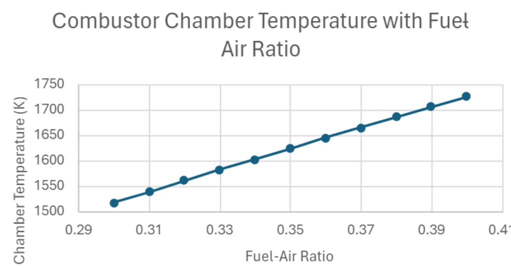

FIG. 8. Combustor Temperature Ratio with Fuel-air Ratio

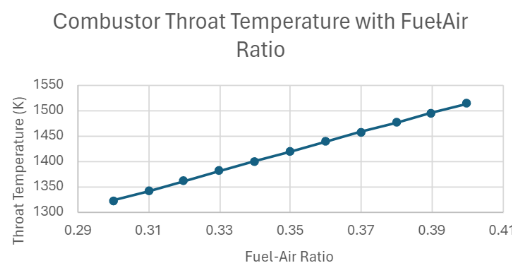

FIG. 9. Combustor Throat Temperature Ratio with Fuel-air Ratio

Combustor: Plots

Here, we will discuss plots illustrating the behavior of the combustor. These plots serve to elucidate trends in temperature profiles, fuel consumption rates, and emissions levels, providing insights into the performance characteristics of the combustor design. Now after wanting to maximize the temperature ratio while staying under a throat temperature of 1500 K, the data showed us that we would likely want to pick a value of the fuel-air ratio in between 0.3 and 0.4.

The first plot (Figure 8) depicts the combustor temperature ratio concerning the fuel-air ratio. It shows a trend where increasing the fuel-air ratio leads to a rise in temperature ratio. Also, we see a constraint in the throat temperature, which should not exceed 1500 K. So, based on this constraint, along with the desire to maximize the temperature ratio, a fuel-air ratio between 0.3 and 0.4 appears good.

Similarly, Figure 9 displays the throat temperature ratio variation with the fuel-air ratio. It further underscores the importance of maintaining the throat temperature within acceptable limits while optimizing the temperature ratio.

Moving on to pressure considerations, Figures 10 and 11 present the chamber and throat pressure ratios against the fuel-air ratio, respectively. These plots provide insights into pressure variations within the combustor under different fuel-air mixtures.

Furthermore, Figures 12 and 13 show the mole fraction of CO and NO in the chamber concerning the fuel-air ra-

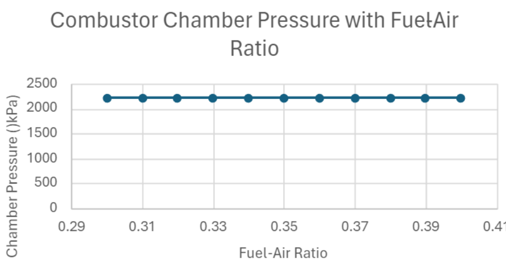

FIG. 10. Combustor Chamber Pressure Ratio with Fuel-air Ratio

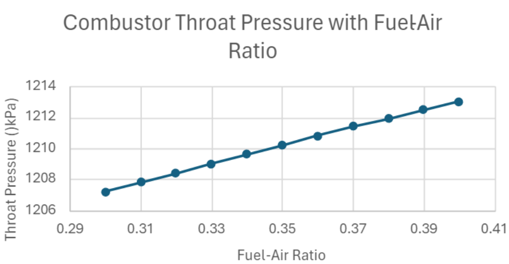

FIG. 11. Combustor Throat Pressure Ratio with Fuel-air Ratio

tio. Also, a lower fuel-air ratio is associated with smaller CO and NO emissions, indicating a preference for ratios closer to 0.3 or 0.4.

Lastly, Figures 14 and 15 show us the compressor cross-section and airfoil design, offering additional insights into the combustion system.

Combustor Considerations

In this part, we dive into the combustion chamber's workings. We look at things like how much fuel it needs, its temperature (which we keep under 1500 K for safety), and what comes out of it. Keeping an eye on these factors helps us make smart choices for our engine. We found the temperature at the exit is 1494 K. The exhaust gives us very little CO and a bit of NO, with numbers being

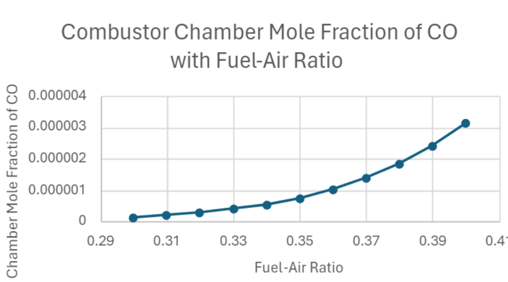

FIG. 12. Combustor Chamber Mole Fraction CO with Fuel-Air Ratio

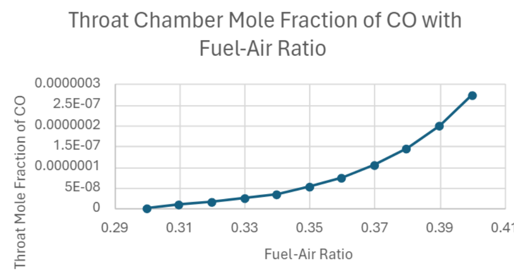

FIG. 13. Combustor Chamber Mole Fraction NO with Fuel-Air Ratio

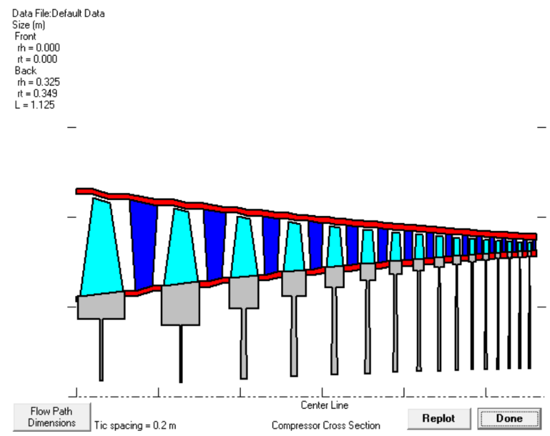

FIG. 14. CEARUN: Compressor Cross Section

2.00×10^{-7} for CO and 9.00×10^{-4} for NO.

1. Amount of fuel required

The amount of fuel you use affects how well the engine burns and how the whole engine works. It is shown that a fuel-air mix between 0.3 and 0.4 gives the best results. This range makes sure there's enough fuel for burning without using too much, which can make the engine work badly and create more emissions.

2. Combustor exit/turbine entrance temperature (a reasonable materials limitation might be

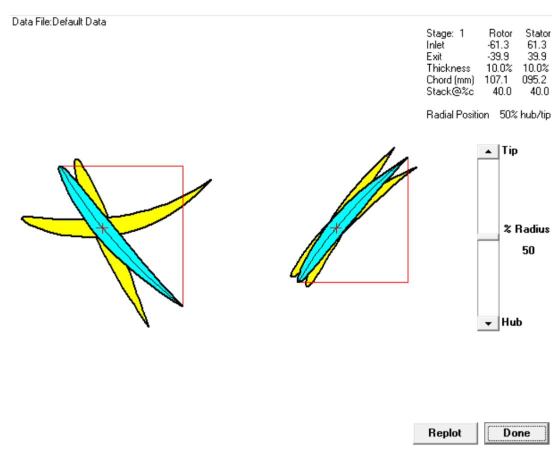

FIG. 15. CEARUN: Sketch

1500 K)

The combustor exit/turbine entrance temperature serves as a crucial parameter governed by material limitations and operational constraints. A reasonable maximum temperature was set at 1500 K to ensure compatibility with available materials. The actual exit temperature was found to be 1494 K, which aligns closely with the designated limit, demonstrating effective temperature management within the combustor.

3. Estimates of exhaust emissions

Estimating exhaust emissions, particularly the mole fractions of CO and NO. The mole fraction of CO was determined to be 2.00×10^{-7}, and NO was 9.00×10^{-4}. Plots these offer valuable insights into the performance characteristics of the combustor under different conditions. The selection of Jet-A(L) fuel, with a fuel-air ratio of 0.39, was rationalized based on its standardization, energy density, and environmental considerations. This choice aligns with the goal of maximizing combustion efficiency while minimizing emissions.

4. Combustor: Analysis Justification

In this segment, we rationalize the choices made during the analysis phase, detailing the reasoning behind the selected fuel type, combustion strategy, and equivalence ratio. The choice of Jet-A(L) fuel for the combustor is based on its availability, energy density, safety, and industry standardization.

By analyzing various fuel-air ratios, we found that a fuel-lean approach, with a ratio of 0.39, maximizes combustion efficiency while minimizing emissions. This strategy ensures complete combustion and reduces the formation of harmful pollutants like CO and NO. Tables III and IV provide detailed data on temperature, pressure, and mole fractions of CO and NO within the combustor chamber and at the throat, supporting our analysis.

Conclusion

In conclusion, the design of the combustor represents a balance between optimizing combustion efficiency, managing thermal loads, and mitigating environmental impact. Through much analysis, we have a combustor that meets the specified design requirements while adhering to practical constraints.

TURBINE

In the turbine section, our aim is to achieve efficient operation, minimize costs, and meet critical requirements such as compressor-turbine matching and airflow considerations. We will discuss plots of total pressure and temperature, efficiencies, check if $P_{05} \geq 1$ atm, and finally relevant equations.

Parameter	Value
Unknown	Tt3
Loss model	Polytropic efficiency
Number of Stages (10 Max)	10
Mass Flow Rate	45.35kg/s
Rotor Angular Velocity	1000 rad/s
Inlet total temperature	298 K
Inlet total pressure	101.3 kPa
C_p	1.24541 kJ/kg K
*Alpha 1 for first stage	0 degrees
Mach 1 for first stage	0.4
Specific heat ratio	1.3
Gas constant	0.287 kJ/kgK
Mean radius	0.25 m
Mean rotor velocity	250 m/s

TABLE V. Turbine Parameters

Turbine: TURBN Data

In this section, we explore insights from the TURBN program to understand how the turbine works and its important features for our project. The values of these inputs are shown in Table V.

The turbine stages consistently show high efficiency, ranging from 90.22% to 90.44%. As we move through the stages, we notice an increase in mass flow, temperature, and pressure. This tells us that the turbine effectively adds energy to the fluid. Adjustments in vane and blade counts help optimize energy conversion, keeping the turbine design well-balanced with a steady velocity ratio of 1.0000.

Turbine: Plots

Here, we will discuss plots showing the behavior of the turbine. We explored key graphs with the data from the TURBN program data and some hand-calculated results, this helped us understand how the turbine behaves at different stages.

Plot 17 shows how the pressure ratio (Pt3/Pt1) changes as the fluid moves through the turbine stages. As expected, the pressure ratio increases gradually as the fluid goes through the turbine.

Similarly plot 16 shows how the temperature ratio (T_{t3}/T_{t1}) changes throughout the turbine stages. Like the pressure ratio, the temperature ratio also increases as the fluid progresses through the stages. Analyzing these temperature dynamics helps assess the turbine's thermal efficiency and operational characteristics.

Next in plot 18 shows us the turbine's efficiency at different stages of operation. It reflects how effectively the turbine converts energy within the system. From the

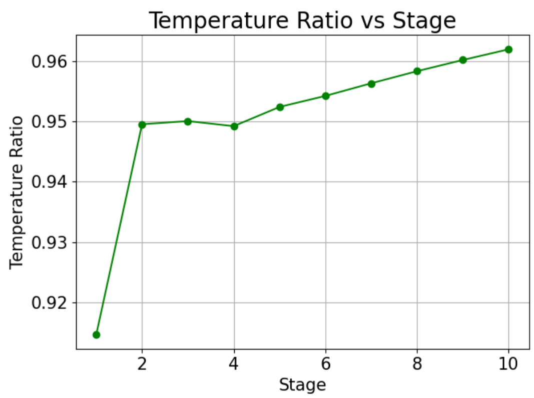

FIG. 16. Temperature Ratio vs Stage

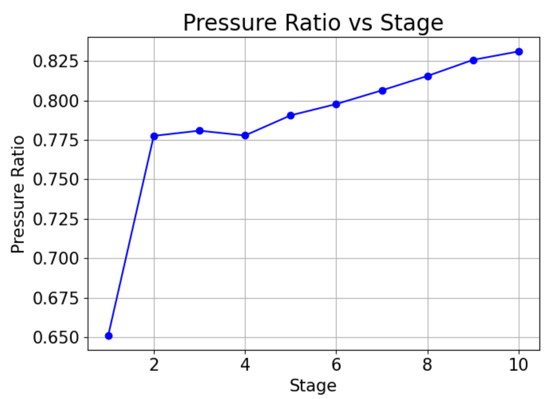

FIG. 17. Pressure Ratio vs Stage

graphs we can see a steady incline in the plot are we go on in the stages. Analyzing these trends helps fine-tune the turbine design for maximum energy conversion efficiency.

Lastly, in plot 19, the yellow line illustrates the work done by the turbine at each stage, indicating the amount of energy extracted from the fluid as it progresses through each stage. As expected, the work output decreases as the fluid moves through the turbine and loses energy. The second purple line represents the mass flow rate through the turbine stages. Interestingly, while the work output decreases, the mass flow rate also decreases. Bleed air was not utilized for this analysis. The calculated mass flow rate for the turbine came out to be 45 kg/s, which is decreasing from 60 kg/s from the compressor. This suggests that the turbine's work is matching the flow rate of the fluid passing through its stages.

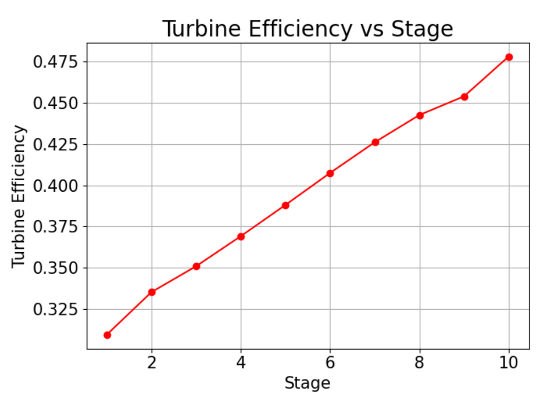

FIG. 18. Turbine Efficiency vs Stage

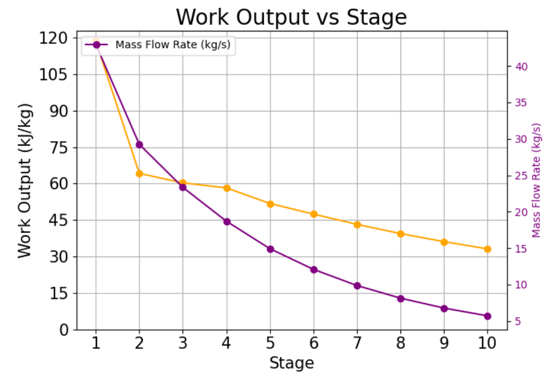

FIG. 19. Work Output vs Stage

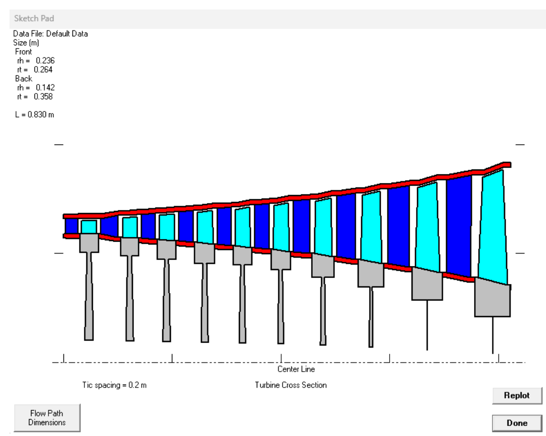

FIG. 20. TURBN: Sketch Pad

Analyzing pressure and temperature changes across stages helps us understand a deeper understanding of the turbine's physical operation. The diagram in Figure 20 helps visualize the turbine's design and operational parameters, aiding in our understanding of its performance.

Turbine: Considerations

This section goes in-depth in the analysis of the specific considerations influencing the design and performance of the turbine.

1. Work output (Compressor-turbine matching)

Based on results from the TURBN program data and plotted results, we analyze the total turbine work output to determine the necessary number of turbine stages required for driving the compressor efficiently. Plot 19 helps us see the relationship between work output and stage progression. This shows us how to precisely determine the requisite number of turbine stages to drive the compressor efficiently while minimizing costs. For instance, with a mass flow rate of 45.35 kg/s and rotor angular velocity of 1000 rad/s. We calculate the total turbine work output using equation 7.

2. Turbine efficiency

Now the efficiency was found using data from the TURBN program and 18. We can see the increasing efficiency trends across different turbine stages. For instance, with efficiencies ranging from 90.22% to 90.44%. We calculate the total turbine efficiency using equation 10.

3. Mass flow rate

Lastly, the mass flow rate through the turbine, as indicated in the TURBN program data and Plot 17, shows a decreasing trend relative to the stages. We observe a reduction from 60 kg/s at the compressor to 45 kg/s at the turbine, suggesting efficient energy conversion. The total turbine mass flow rate is calculated using equation 13.

Turbine: Analysis Justification

The data addresses the considerations in the design. first we will focus on work output, extra work output, turbine efficiency, and then the mass flow rate.

First, in terms of work output, the approach to achieve an optimal compressor-turbine match is crucial. the data table 19 shows the output work for each stage. The work output (W_{out}) of the turbine is determined by the change in enthalpy (Δh) of the working fluid passing through the turbine and it can be calculated using equation 7.

$$W_{out} = C_p \times (T_{t1} - T_{t3}) \tag{7}$$

Now the total temperature and pressure ratios play a pivotal role in understanding the performance of the turbine throughout its operation. The total temperature ratio (T_{tratio}), representing the ratio of outlet to inlet temperature, is calculated as 0.7143, indicating a substantial decrease in temperature across the turbine stages and it can be calculated using equation 8.

$$T_{tratio} = \frac{T_{outlet}}{T_{inlet}} \tag{8}$$

Similarly, the total pressure ratio (P_{tratio}), shows the ratio of outlet to inlet pressure, is found to be 0.1538. This ratio drops in pressure as the working fluid through the turbine stages. Such a pressure reduction is imperative for the extraction of work from the fluid stream, and it can be calculated using equation 9.

$$P_{tratio} = \frac{P_{outlet}}{P_{inlet}} \tag{9}$$

Regarding turbine efficiency, the data from TURBN shows consistent efficiency levels across turbine stages. The turbine efficiency ($\eta_{turbine}$) is defined as the ratio of actual work output to the ideal work output, and it can be calculated using equation 10.

$$\eta_{turbine} = \frac{C_p \times (T_{t1} - T_{t3})}{R \times T_{inlet} \times \left(\frac{P_{t1}}{P_{t3}}\right)} \tag{10}$$

Next the turbine outlet temperature ($T_{toutlet}$) can be calculated using equation 11.

$$T_{t\ \text{outlet}} = T_{t1} - (T_{t1} - T_{t3}) \times \left(\frac{P_{t1}}{P_{t3}}\right)^{\left(\frac{C_p \times (T_{t1} - T_{t3})}{R \times T_{\text{inlet}} \times (P_{t1}/P_{t3})}\right)} \tag{11}$$

Similarly, the turbine outlet pressure ($P_{toutlet}$) can be calculated using the equation 12.

$$P_{toutlet} = P_{03} \times \left(\frac{P_{04}}{P_{03}}\right) \tag{12}$$

With a python code the outlet pressure ($P02$) from the turbine to ensure it meets the critical atmospheric pressure threshold of 1 atm. If $P02$ is 1 atm or higher, it indicates sufficient exhaust pressure for proper system operation. Conversely, if $P02$ falls below 1 atm, adjustments or further analysis may be necessary to maintain optimal turbine performance. This validation step enhances the assessment's reliability by considering a crucial parameter for turbine operation.

$$\dot{m} = M_1 \times \frac{P_{t1}}{R \times T_{t1}} \times \sqrt{C_p \times R \times T_{t1}} \tag{13}$$

Lastly mass flow rate ($\dot{m}$) through the turbine ensures that it operates within its limits and provides the necessary power output. It was found to be around 45 kg/s. The mass flow rate is calculated using Equation 13.

Conclusion

In conclusion, the turbine section of the TURBN program showed us the turbine characteristics, including temperature, pressure, velocity, and efficiency across stages. Plots depicting total pressure, temperature, turbine efficiency, and work output help visualize performance trends and aid in optimizing turbine design.

AEROENGINE DESIGN PROJECT CONCLUSION

In conclusion, the project has provided invaluable insights into designing and analyzing the gas turbine engine core (compressor + combustor + turbine). Our objective was to meet specific design considerations and requirements, including optimizing engine core performance, maintaining acceptable turbine inlet temperatures, identifying the most cost-efficient design, and handling a specified mass flow at specified inlet conditions, at the design point of 101.3 kPa and 298 K.

Leveraging tools such as COMPR, TURBN, and CEARUN, we thoroughly explored key factors like compressor pressure ratios, combustor temperatures, and exhaust emissions to enhance efficiency, performance, and cost-effectiveness. Through careful analysis supported by comprehensive plots and evaluations, we gained a deeper understanding of the core's functionality and identified potential areas for improvement.