Multi-Parametric Optimization and Gas Path Analysis of a civil Turbofan Aero-engine Incorporating Hydrogen Fuel

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Session 2019-2021

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A Thesis Submitted to the US Pakistan Centre for Advanced Studies in Energy in partial fulfillment of the requirements of the degree of

MASTER of SCIENCE in

THERMAL ENERGY ENGINEERING

US-Pakistan Centre for Advance Studies in Energy (USPCAS-E)

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H-12, Islamabad 44000, Pakistan

February 2022

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Abstract

With growing environmental concerns, hydrogen is being promoted as a clean fuel of the future for sustainable aircraft application. In this context, a multi-parametric optimization and gas path analysis of a civil turbofan aeroengine operating on hydrogen fuel has been presented in this thesis. Key design parameters including the bypass ratio, fan and compressor pressure ratios, turbine inlet temperature, and mass flow rate of the air have been evaluated in GasTurb software to obtain an optimal performance and gas path design of the aeroengine. A comparative analysis has been performed between the baseline hydrogen fueled turbofan (based on the General Electric GE90 high-bypass turbofan) and the optimized hydrogen fueled turbofan aero-engines at cruise condition as design point. As a result, the optimized hydrogen fuel-based turbofan aero-engine delivered a 4.88% decrease in thrust-specific fuel consumption and an increase in thermal efficiency by 5.53%. Furthermore, an optimized gas path for an aeroengine operating on hydrogen fuel exhibits a 6.35% smaller core area and a shorter engine length by 10.84% compared to the baseline. A theoretical and engineering platform for design and evaluation of hydrogen fueled civil turbofans is thus established

Keywords: Civil turbofan aero-engine, sustainable aircraft, hydrogen fuel, gas path design, multi-parametric optimization, modeling, and simulation

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List of Nomenclature

Symbol

M_{air}	Mach Number, [-]
A	Area, [m^2]
π_{intake}	Intake Pressure Ratio, [-]
$\pi_{inner\ fan}$	Inner Fan Pressure Ratio, [-]
$\pi_{outer\ fan}$	Outer Fan Pressure Ratio, [-]
$\pi_{Ip\ compressor}$	IP Compressor Pressure Ratio, [-]
$\pi_{hp\ compressor}$	HP Compressor Pressure Ratio, [-]
$\pi_{bypass\ duct}$	Bypass Duct Pressure Ratio, [-]
β	Design Bypass Ratio, [-]
η_{burner}	Burner Design Efficiency, [%]
Q_R	Fuel Heating Value, [MJ/kg]
π_{burner}	Burner pressure Ratio, [-]
N_{LPT}	Number of LPT Turbine Stages, [-]
NH_{PT}	Number of HPT Turbine Stages, [-]
m_{air}	Mass flow rate of air, [Kgs^{-1}]
F_s	Specific Thrust, [ms^{-1}]
F_N	Net Thrust, [KN]
T-SFC	Thrust Specific fuel Consumption, [$g*(kN*s)^{-1}$]
$\eta_{polytroopic\ inner\ fan}$	Polytrophic Inner fan efficiency, [%]

$\eta_{polytroopic\ outer\ fan}$	Polytrophic Outer fan efficiency, [%]
η_{lpc}	Polytrophic LPC efficiency, [%]
η_{hpc}	Polytrophic HPC efficiency, [%]
η_{lpt}	Polytrophic LPT efficiency, [%]
η_{hpt}	Polytrophic HPT efficiency, [%]
$\theta_{core\ nozzle}$	Design core nozzle angle, [%]
$\theta_{bypass\ nozzle}$	Design bypass nozzle angle, [%]
N_{LPC}	Number of LPC Stages, (-)
N_{HPC}	Number of HPC stages, (-)

Abbreviation

OPR	Overall Pressure Ratio
FPR	Fan Pressure Ratio
A/F	Air to Fuel Ratio
ST	Specific Thrust
NT	Net Thrust
BPR	Bypass Ratio
HPC	High Pressure Compressor
LPC	Low Pressure Compressor
HPT	High Pressure Turbine
LPT	Low Pressure Turbine

SFC	Specific Fuel Consumption

Subscripts

a	Fan Inlet
b	LPC Inlet
c	LPC Outlet
d	HPC inlet
e	HPC Outlet
f	Combustor Outlet
g	HPT outlet
h	LPT inlet
i	LPT outlet
j	Nozzle Inlet
k	Nozzle Outlet
l	Bypass Outlet

List of Publications

1. Multi-Parametric Optimization and Gas Path Analysis of a civil Turbofan Aero-engine Incorporating Hydrogen Fuel for Sustainable Aircraft Applications

International Journal of Hydrogen Energy (Under Review)

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Chapter 1

Introduction

1.1 Background

Worldwide, flights produced 915 million tons of CO_2 in 2019. These emissions have devastating effects on the climate. European Commission adopted a series of legislative proposals setting it how to achieve the target of a net reduction of 55% in greenhouse gas emissions by 2030. Various technologies are used to reduce the overall fuel consumption in modern commercial aircraft[1]. One such technology is the use of hydrogen fuelled gas turbine for civil aircrafts. These aircraft have the potential to theoretically and practically reduce the overall thrust-specific fuel consumption by 5%. Aside from thrust-specific fuel consumption, noise is becoming increasingly important in the commercial engine industry as regulations tighten[2]. Increased noise pollution can lead to airport curfews, which raises overall operational costs due to reduced airport capacity in each time. When it comes to engine design, factors such as thrust-specific fuel consumption, thermal efficiency, emissions, noise, size and weight of engine all play a significant role in overall aircraft performance[3].

Because of the high energy density of hydrogen fuel, the thrust-specific fuel consumption decreases to produce an identical amount of thrust in comparison to the generic fuel. Hydrogen fuel carries 118.9MJ/kg of energy in it, while generic fuel carries 43MJ/kg of energy. The hydrogen's amount of energy is three times higher than kerosene. The density of generic fuel lies between 776 kg/m^3 and 841 kg/m^3 at standard temperature of 15^oC. Upon the combustion of 1 kg of generic fuel (kerosene) and 3.41 kg of oxygen substituted from air, the production of emissions contains 1.26kg of H_2O vapours, 3.151 kg of CO_2, NOx about 15g, SOx about 2g, carbon monoxide about 3.6g and unburned hydrocarbons and soot about 1.4g and 0.05g respectively. While on the other hand, hydrogen has density of 70.81 kg/m^3 and produces the 9kg of H_2O vapours and 4.21g of NOx as emissions while combustion process takes place, depending on the type of engine. The mass of kerosene is 3 times more than that of liquid hydrogen, but it occupies four times greater volume while stored in cryogenic coolers where the temperature of storage tank is about -253.15ºC to be available in liquid hydrogen state. Such low temperature of -253.15ºC requires high thermal insulation to maintain that specific temperature and requires special components for fuel system which could bear such thermal conditions[4].

The thermal efficiency of hydrogen fuelled aero engine is greater than the generic fuel because to achieve the specific turbine inlet temperature (TIT), the amount of fuel consumed by aero engine will be less because of higher energy density of hydrogen.

Figure 1. 1: Side View of commercial aircraft engine GE-90

The General Electric GE-90 engine is a two-spool unmixed flow turbofan engine. The GE-90 engine comprises of a single stage turbofan and a 3 stage low pressure compressor and 10 stages high pressure compressor, a combustor and two stage high pressure turbine and 7 stage low pressure turbine and a nozzle[5].

1.2 Research gaps

The General Electric GE-90 engine has total of seven components as mentioned in the above section, but most of the research is carried out on the combustor dynamics that how combustors will change while hydrogen fuel will be incorporated by replacing with the generic fuel. Combustor may suffer a backlash with the combustion of hydrogen. To avoid the backlash, number of fuel injectors will be increased so that fuel will be distributed across the combustor and compressor may not suffer stall due to air backlash.

There are very few works on the gas path analysis of the aero engines by incorporating different fuels. Because changing the fuel just only affects the combustor dynamics but also changes the gas path of flue gasses through high pressure turbine and low-pressure turbine. The change of fuel from generic to hydrogen will also change the expansion ratio of turbine and compression ratio of compressors because compressor takes power from turbine.

Another research gap, while incorporating the hydrogen fuel is that life cycle assessment of aero engine because fatigue and creep plays important role in the life cycle of engine. Materials of turbomachinery and combustor suffers high pressure and temperature stresses and violating the specific limits will lead to shorter life of engine.

1.3 Aims and Objectives

Most of the research has been done on thermodynamic, exergy, cost, life cycle assessment, and landing and take-off cycle (LTO) analysis of hydrogen-fuelled turbofan engines. Previous studies for hydrogen-fuelled turbofan engines do not provide proper insights into the aerodynamic design for the engines. This paper presents the gas path assessment and multi-parametric optimization of hydrogen-fuelled turbofan engines. This gives us a detailed aerodynamic design of the HP compressor, LP compressor, and the turbine section.

The main objectives of this study are

- thermodynamic analysis of turbofan engine GE90 using hydrogen fuel
- aerodynamic analysis of turbofan engine GE90 using hydrogen fuel
- multi-parametric optimization for hydrogen-fuelled turbofan engine
- reduce the thrust specific fuel consumption (T-SFC) at the required net thrust
- to assess the gas path of baseline and optimized turbofan engine

- a thermodynamic and aerodynamic comparative study between baseline case and optimized case.

1.4 Present Work

The chapters to follow are briefly described below:

Chapter 2 would cover the literature review of most relevant research on gas turbines and hydrogen fuel applications in aviation. Basically, there are three types of hydrogen fueled civil aircrafts. First one is usage of hydrogen fueled gas turbines and, in this technology, kerosene is replaced by liquid hydrogen and its application is in long range aircrafts and mid-range aircrafts. Hydrogen can also be utilized in fuel cell powered civil aircrafts but only for short range applications. For mid-range and short-range applications in civil aircrafts, hydrogen fuel is used for electric propulsion.

In chapter 3, different numerical modeling methods are discussed for the simulations of gas turbine to perform the optimization and to assess the gas path through compressor and turbine.

In chapter 4, methodology of model validation and then performing multi-parametric optimization and gas path assessment is discussed that how to set an appropriate model for obtaining the baseline case for hydrogen fuel and then setting up model for the optimization and assessing its gas path.

Chapter 5 would present the results from the numerical simulations of both the baseline engine and the optimized engine for hydrogen fuel. The results would be compared with those from numerical modeling of baseline engine and optimized engine keeping in view different thermodynamics aspects and turbomachinery of the aero-engine gas turbine. This would bring us to the conclusion of this research and hence a summary of major findings and further possibilities of research will be discussed.

Summary

This chapter describes the background of this thesis work. The hydrogen fueled aircrafts offer the potential to reduce emissions by improving thrust specific fuel consumption and thermal efficiency of aero engine gas turbine. The design of hydrogen fueled aircraft helps to cut the excess fuel required to produce the same thrust to propel the aircraft in comparison to the hydrocarbon fuel. The major drawback of hydrogen fueled gas turbine is the high price of hydrogen and availability of hydrogen. Because till now, hydrogen is not available in abundance and the methods to form hydrogen are mostly non-conventional by steam and dry reforming of methane which gives carbon dioxide as by product. Currently a lot of work is being carried out to produce hydrogen through renewable resources by utilizing wind and solar potential through electrolysis.

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Chapter 2

Literature Review

2.1 Types of hydrogen fueled propulsion system

There are majorly three types of hydrogen fueled propulsion systems. They are categorized as follows.

- Hydrogen fueled aero engine gas turbines
- Fuel cell powered aircrafts
- Distributed electric propulsion system

2.1.1 Hydrogen fueled aero-engine gas turbines

Commercially, the use of hydrogen fuel for the gas turbine is getting matured in aviation industry. The difference between generic fuel and gas turbine was handling of hydrogen fuel due to its menacing nature of explosion and its properties but over the period, scientists have overcome this issue by progress in making the cryogenic coolers to store the liquid hydrogen at -253^{o}C. Hydrogen fueled combustors have different shape than the conventional hydrocarbon fuel combustors because of high energy density of hydrogen[1].

Figure 2. 1: Hydrogen Fueled aero engine gas turbine

GE has gradually experienced running the entire fleet of its gas turbines on hydrogen partially with blends of other fuels and now transforming their gas turbines to 100 % hydrogen fuel. The scope of using the hydrogen as fuel in gas turbine depends on the initial configuration of gas turbines and modifications required to run the existing aero engine gas turbines[2].

2.1.2 Fuel cell powered aircrafts

Fuel cell is the power source for the next generation short-range aircrafts. Fuel cell uses hydrogen and oxygen in an efficient reaction that produces electricity for the electric propulsion and as by product they give heat and water. To decarbonize the aviation industry, fuel cells are most suitable alternative for the future aircrafts. The point of concern is the heavy weight of fuel cell that means you cannot just pick a fuel cell and drop it into the existing aircraft. This will lead to heavier weight of aircraft and more thrust would be required for takeoff and cruise conditions. Hydrogen itself requires huge storage and all these technical problems would require a solution.

Figure 2. 2: Fuel cell based future aircrafts

In this type of aircrafts, fuel cell will get hydrogen and oxygen in it and will produce electricity and this electricity will then be stored in batteries and then transmitted to the fans and these electric fans will produce thrust. This is the most complex configuration of hydrogen powered aircrafts and would require a lot of effort to make it possible soon. However, these aircrafts can be used for mid and short-range of operation[3].

2.1.3 Distributed electric propulsion system

In this type of hydrogen fueled aircrafts, the gas turbine and fuel cell both are configured on the aircraft, but the purpose of gas turbine is not to produce the thrust for the aircraft but to produce the electricity and then this electricity is provided to the electric fans to produce the thrust. There are different configurations for this type of aircrafts and one of them is Blended wing body. Several aircraft with propulsions mounted on the front, aft, and within the wing have been flown. Although the number of propulsions required to classify the propulsion system as DPS is not clearly defined. YB-49 is an example with four turbojet engines installed on either side of the wing with rectangular inlets and circular nozzles. A new hybrid wing body (HWB) also called blended wing body (BWB) aircraft is proposed to achieve high cruise efficiency, lower noise signature, and large internal volume to integrate the propulsions. The propulsion system is based on 12 small conventional engines to enable short take-off and landing (STOL) installed on the upper body of the aircraft near the trailing edge[4].

Figure 2. 3: Blended wing body aircrafts

2.2 Thermodynamic analysis of aero engine gas turbine

Yildiz et al. [5] performed an analysis on the performance, fuel cost, and emissions study of a 50MW simple cycle gas turbine with a recuperator using natural gas and hydrogen as fuel. The analysis shows that despite the higher cost of hydrogen, hydrogen is more efficient in terms of performance and environmental concerns. The cost of fuel for hydrogen was calculated as 0.345$/kWh and the cost of natural gas is 0.075$/kWh for a simple gas turbine cycle at 20 bars, while the price for hydrogen is 0.322$/kWh and for natural gas, it is 0.071$/kWh at 4 bars.

Halil Yalcin Akdeniz et al. [6] have performed a thermodynamic analysis on the PW4056 high bypass turbofan engine used in the commercial fleet. They have performed energy, exergy, and sustainability analysis on the above-said engine. They have varied the engine fuel from hydrocarbon to hydrogen and found out that almost 3 times less fuel is consumed in the case of hydrogen as compared to kerosene. The combustion chamber has the least exergetic efficiency among all components. The sustainability factor is improved for hydrogen and the combustion chamber's exergetic efficiency is improved.

Ozgur Balli et al. [7] have performed a thermodynamic comparison of the TF33 Turbofan engine for both hydrogen and kerosene. They found out that the fuel flow and Specific fuel consumption reduces by 63.83% and 60.61% respectively for hydrogen. Although the fuel cost for hydrogen increased by 300%. The reduced environmental and sustainability factors show that hydrogen is a more environmentally friendly fuel than kerosene. Ozgur Balli et al. [7] have performed a thermodynamic comparison of the TF33 Turbofan engine for both hydrogen and kerosene. They found out that the fuel flow and Specific fuel consumption reduces by 63.83% and 60.61% respectively for hydrogen. Although the fuel cost for hydrogen increased by 300%. The reduced environmental and sustainability factors show that hydrogen is a more environmentally friendly fuel than kerosene. Onal et al. [8] have performed a performance analysis on turbofan engine (JT9D). The thrust force produced by the engine was 206KN and the thrust to weight ratio is 5.4. Different performance parameters like Specific fuel consumption (SFC), propulsive, thermal, and overall efficiency were analyzed.

Yuntao Zhou et al. [9] have studied the climate change effects on the take-off performance of turbofan engines. They studied the increasing temperature of 30 major international airports. In summers, a 0.95% to 6.5% increase in average take-off distance is observed. 0.68% to 3.4% climb rate is increased in summers. Selcuk et al. [10] have done a thermo-ecological performance study for A321-200. The exergetic efficiency of each component is calculated using two different approaches and exergetic improvement potential is shown in the study. ECOP (ecological coefficient of performance) function is calculated and comparatively assessed in different specified flight phases and tenures in terms of environment and sustainability impacts. Nafiz Kahraman et al. [11] have performed a numerical based analysis of the combustor using hydrogen as a fuel and compared it with jet A fuel. The analysis was performed on Rolls Royce Nene turbojet engine and excess air ratios for thermal values have been used. Increasing the EAR value causes an increase in combustion efficiency and pressure drop.

Masakazu nose et al. [12] analyzed the combined cycle for power generation. They successfully developed a gas turbine using natural gas and hydrogen co-fired and hydrogen-fired large gas turbines at Mitsubishi Heavy Industries group. The addition of hydrogen in the mixture was tested with 30% volume in a co-firing test. The proposed combustor for hydrogen combustion is a diffusion combustor because fuel is injected into the air, mitigating the likelihood of a flashback. Steam and water are injected into the combustor to reduce NOx emissions.

2.3 Optimization of aero engine gas turbine

Parisa et al. [13] have done a thermodynamically simulated comparative case study on hydrogen fuel and hydrocarbon fuel and observed that net thrust is increased by 16.27% and SFC is reduced by 65.90% and thermal efficiency of the engine is also improved by 2.65%. The study is based on GE 90 engine with both hydrocarbon and hydrogen fuel. The hydrogen-fueled engine was optimized with different parameters aimed to minimize the SFC. They formulated a MATLAB Simulation code to compute all the calculations. Syed Muhammad Hassan Rizvi et al. [14] designed a high bypass ratio turbofan engine with the cruise as a design point. The objective of the study was to minimize the SFC and to maximize the range of the aircraft with a highly iterative design procedure. The design constraints of the study were fan diameter and overall length. The turbine inlet temperature (TIT) was 1700K and the bypass ratio of 8.5 with an OPR of 38.2 aimed 47.71kN thrust at cruise and 266.2kN thrust during takeoff.

Therkelsen et al. [15] studied low emission gas turbines based on hydrogen fuel. They have successfully operated Micro Gas Turbine (MGT) on hydrogen with fewer environmental hazards and observed a stable operation. Modifications in conventional injectors were also made allowing the engine to operate on pure hydrogen. It was found out that NOx emissions are affected by the ambient temperature condition as well. Natalia Marszałek et al. [16] have studied the performance of the turbofan engine using different fuels. The introduction of an additional combustor configured between high-pressure and low-pressure turbine improves performance and is known as inter turbine burner (ITB). As a result, the specific fuel consumption (SFC) is significantly reduced, and the range of aircraft is increased.

Verstraete et al. [17] have studied the potential use of hydrogen-powered aircraft for long-range applications. They found out that, by using hydrogen as a fuel, the fan diameter can be reduced by 76 to 80% and the takeoff weight can be reduced by 25 to 30%. The fuel weight on aircraft was reduced by 30%. Although the price of hydrogen is 3 to 6 times higher than hydrocarbons, it will be reduced by more commercialization of hydrogen. Balli et al. [18] have studied on JT15D turbofan engine that produces a specific thrust of 315.9N s/kg and its SFC is 15.8g/KN.s. The estimated exergetic efficiency was 21.15% and the actual efficiency was 19.919%. they also studied the environmental and ecological effects of turbofan engines computed as 4.020 and 5.020 respectively. They reported the exergy efficiency Improvement from 19.919% to 24.718%. Sustainable efficiency factor found as 1.249. The least efficient component of the system is found as a Combustion chamber with the most energy destruction and least energetic efficiency.

Bhupendra Khandelwal et al. [19] have investigated the hydrogen properties and traits for future applications for environmental concerns. Various strategies were applied in concern of cryogenically cooled hydrogen so it could be stored at -253^{o}C temperature. Hydrogen production, its storage, engine configuration, and aircraft design and configuration were studied. Sugista et al. [20] have studied steam generated by hydrogen combustion from internal combustion in a close loop cycle for better cycle efficiency and reduction in environmental pollution effects. The efficiency of cycle was improved by 2.7% and environmental hazards were reduced. In the combined cycle study, the topping cycle was considered as best performing with respect to cycle thermal efficiency and feasibility of manufacturing.

Gao Jian-hua et al. [21] have performed a modeling and simulation-based study on a micro turbojet Jetcat-P80. The analysis was performed using GasTurb and the results were compared with the actual model. A reasonable difference was found between the results of simulations and the actual parameters of a gas turbine. Mathew Thomas et al. [22] has studied hydrogen applications for Lamber- St. Louis International Airport. Airports are facing challenges regarding pollution and energy efficiency. Hydrogen combustion and fuel cell technologies proved to be promising to eliminate pollution and become an energy-efficient and reliable resource of energy in the 21st century. The hydrogen applications at the airport include a backup and auxiliary power system, airport light-duty vehicles, and a fueling station.

Summary

This chapter represents the literature review on the aero engine gas turbines performed to carry out the study. Different configurations of hydrogen fueled aero engine are studied. The most feasible option was hydrogen fueled gas turbine due to its mature nature and an ease to convert the existing hydrocarbon engine into hydrogen fueled engine. Thermodynamic modeling was analyzed through different approaches in which different software's were used to study the thermodynamic modeling of aero engine gas turbine. Moreover, different techniques for the optimization were studied which consists of multi parametric optimization and single parameter optimization. MATLAB, gas turbine simulation program and GasTurb were the most frequent software's that were used for the optimization of aero engine gas turbine.

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Chapter 3

Aero-engine gas turbine modelling methods

3.1 Analytical and numerical methods

Based on the findings from the experimental data and simulation data of aero engine gas turbine, the modeling method of all the components like compressor, fan, turbine, combustor, and nozzle are different in each of the software. The basic equations are same for all the methods but the user interface changes from one software to another and different approaches can be used for modeling of gas turbine.

There are several different numerical methods for the development of aero engine gas turbine to study its performance.

3.1.1 MATLAB simulation method

MATLAB is a simulation software tool in which input values are given in the form of equations and then different formulas are formulated in the command window and output performance parameters are obtained in the form of results. Iterations could be performed on MATLAB by giving the command of for loop and different parameters can be compared and best optimal performance parameters could be choosing from the iterative process. There is an existing library model in MATLAB Simulink, in which all the components of gas turbine like compressor, combustor, turbine and nozzle are already formulated and user needs to just input the values to get the results[1].

Parisa et al. [2] have done a thermodynamically simulated comparative case study on MATLAB on hydrogen fuel and hydrocarbon fuel and observed that net thrust is increased by 16.27% and SFC is reduced by 65.90% and thermal efficiency of the engine is also improved by 2.65%. The study is based on GE 90 engine with both hydrocarbon and hydrogen fuel. The hydrogen-fueled engine was optimized with different parameters aimed to minimize the SFC. They formulated a MATLAB Simulation code to compute all the calculations.

3.1.2 GasTurb simulation method

Gas turb is a GUI based gas turbine simulation program in which desired configuration of aero engine is selected at first and then an input page comes up and all the desired input values are given in that section and then the analyse option is selected to assess the performance of the aero engine gas turbine. In gas turb 13, the gas path can also be assessed by using the geometry tool of the software. The optimization can be done by defining the different ranges of the parameters and then there are two options that are systematic iterations and random iterations. By selecting systematic iteration method, the figure of merit is defined that which parameter is going to be optimized and then keeping the output constant best possible performance can be achieved. In gas turb 13, the on design (cruise) and off design (take-off) both simulations can be done by deifying the parameters of altitude and atmospheric temperature.

Gao Jian-Hua et al. [3] have performed a modeling and simulation-based study on a micro turbojet Jetcat-P80. The analysis was performed using GasTurb and the results were compared with the actual model. A reasonable difference was found between the results of simulations and the actual parameters of a gas turbine.

3.1.3 CFD tool for performance assessment

CFD tool is used for assessment of performance of gas turbine using the Ansys software. In CFD, the combustion analysis of combustor is done and seen that how the combustion will take place. Then, these results of combustor dynamics can be implemented on the actual engine. The compressor and turbine blades can be made in Ansys by using blade gen tool and then CFD setup can be implemented to see the aero foil of the blades. The performance of blades and turbofan can also be assessed through CFD.

3.1.4 Gas turbine simulation program

Gas turbine simulation program is a modelling software on components basis environment. The primary tool in this software is used for gas turbine engine performance analysis. This tool presents the steady state and transient simulations for the gas turbines engine with multiple configurations. The core purpose of the software is to analyse the thermodynamic performance. GSP is suitable for the performance and sensitivity analysis of gas turbine engine. The first ever effort to design the software was made at Delft Technical University in 1986 and its name was DYNGEN and further having available for the windows in 1996. Components distortion, malfunctioning of components and altitude sensitivity all are the key parameters to be analysed in this software[4].

Summary

In this chapter, introduction to different methods for the performance analysis of aero engine gas turbine were studied. There are four different software's through which gas turbine performance can be analysed but our aim was to find the gas path of hydrogen fuelled aero engine and except Gas turb 13, all the other tools are just for performance analysis. The only tool which helps in thermodynamic analysis and gas path assessment is gas turb 13. It gives insights of geometry of engine and a brief analysis for the comparative study.

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Chapter 4

Methodology

4.1 Engine Specification

GE90 is a two-shaft unmixed flow turbofan engine built by General Electric and SNECMA of France. GE90 is known as powerful commercial aircraft with around 380kN of thrust during take-off. Its first application was in the Boeing 777s fleet used in the British airways. The seating capacity for Boeing 777 is around 375 persons equivalent to the weight of 230 tones. The engine is the most fuel-efficient for its fuel type (Kerosene) and it is derivative of the Energy Efficient Engine (E^3) Program. The engine Noise is optimized for its fuel type and the engine falls in the category of environment-friendly engines in comparison to other competitors. It provides almost 33% fewer NOx emissions than today's high bypass ratio engines.

Engine design is encompassing different individual components and parameters. While designing an engine, it is not possible to consider each component and parameter practically. Therefore, it has been designed as a preliminary engine design to summarize the whole design process. These aspects of the engine design were studied.

- Design parametric study
- Optimization of Design Point
- Gas path analysis of Engine
- Aerodynamic analysis of compressor

4.2 Engine Design Process

The software used for this study is GasTurb 13 which is a Commercial aircraft engine design software.

The assumptions made for simulating the engine design data are given below.

- Aircraft cruise is taken as the design point of the engine.

- Aircraft take-off is taken as the off-design point of the engine.
- The altitude at cruise is 10668m.
- The aircraft's cruise Mach number is 0.85.
- Air and flue gases were considered ideal gas.
- The engine operated in a stable state.
- The ambient temperature and pressure were taken as 101.325Kpa and 288.15K at the ground.
- Polytrophic efficiencies have been assumed based on the literature.

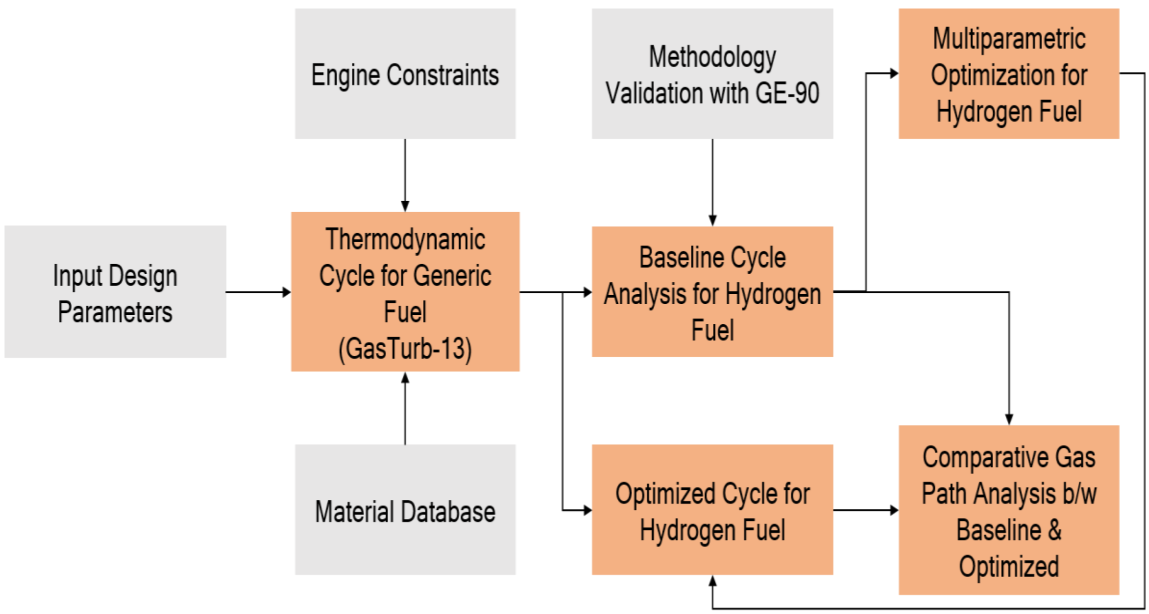

Figure 4. 1: Methodology used for design and optimization of GE-90 engine

4.3 Parametric Study

To get the design point, the parametric study involves the different thermodynamic cycle parameters. By using the range of fan Pressure ratios, LP compressor pressure ratio, Hp compressor pressure ratio, turbine inlet temperature (TIT), and the number of stages for compressor and turbine, a parametric study was carried out. TIT plays an important role in the sizing of the engine, as increasing the TIT would reduce the engine size and will increase the specific thrust. But due to material constraints, there are certain limits for the selection of TIT[1].

There are certain ranges to consider the parameters[2].

Table 4.1: Range parameters

Parameter	Range
Bypass ratio, [-]	8-11
Turbine Inlet temperature, [K]	1300 to 1900
Fan pressure ratio, [-]	1.1 to 2.0
Overall pressure ratio, [-]	30 to 65
HP compressor pressure ratio, [-]	<30
LP Compressor pressure ratio, [-]	<2

4.4 Engine gas path design

An aerodynamic study was carried out in this paper for the aerodynamic design of the LP compressor, HP compressor, HP turbine, and LP turbine. Inlet conditions can be defined from the diameter of the hub or tip, so the best location for each component must be considered. Inlet conditions of components are highly influenced by changing the hub or tip. Components are placed at a suitable position for a smooth gas path. Different combinations were studied through an iterative process. The acceptable range for parameters was selected to make the gas path smooth. There are two HP turbine stages and six LP turbine stages. The HP turbine is linked with an HP compressor rotating at 10000 RPM. The LP Turbine is attached to the LP compressor and Fan at around 2500 RPM. Turbines have higher stage loading limits than compressors, that is why 2 stages of turbines will rotate the 10 stages of the HP compressor. The RPM was selected from the GE90 Engine datasheet[1].

4.5 HP Compressor Design:

LP compressor is a bit easier to design than HP Compressor due to Low RPM and a smaller number of stages and low-pressure ratio. HP compressor is more challenging to design due to the limit of hub/tip and higher-pressure ratio. Though, the design procedure and optimization method for both compressors are the same. Stage loading and de-Haller number are the two deciding parameters for the number of stages. The design process encompasses of Stage-by-stage annulus diagram[3].

4.6 Engine Requirements

The requirements of the GE-90 engine are as follows:

- Engine Cruise Thrust ≈ 70kN
- SFC ≈ 15mg/ kN
- Takeoff Thrust ≈ 370kN

4.7 Overall Engine Dimensions Constraints

- Length of Engine: 286.9 in (7.29 m)
- Maximum Width of Engine: 152.4 in (3.87 m)
- Maximum height of engine: 155.6 in (3.95 m)
- Fan diameter of engine: 123 in (3.1 m)

Table 4.2: Input parameters for the simulation study

Symbol	**@Design Point (10688m) for hydrogen baseline case**	**@Design Point (10688m) for hydrogen optimized case**
$M_{air}, [-]$	0.85	0.85
$\pi_{intake}, [-]$	0.99	0.99
$\pi_{Inner\ Fan}, [-]$	1.65	1.998
$\pi_{Outer\ Fan}, [-]$	1.65	1.630
$\pi_{LP\ compreesor}, [-]$	1.14	1.177

$\pi_{HP\ compreesor}, [-]$	21.5	24.756
$\pi_{Bypass\ Duct}, [-]$	0.975	0.975
$\beta, [-]$	8.1	9.837
$TIT, [K]$	1435	1549.9
$\eta_{Burner}, [-]$	0.9995	0.9995
$Q_R, [MJkg^{-1}]$	118.429	118.429
$\pi_{Burner}, [-]$	0.95	0.95
$N_{LPT}, [-]$	6	6
$N_{HPT}, [-]$	2	2
$\dot{m}_{air}$	576.003	598.365
$\eta_{Poly.\ inner\ fan}, [\%]$	0.93	0.93
$\eta_{Poly.\ outer\ fan}, [\%]$	0.93	0.93
$\eta_{Poly.\ LPC}, [\%]$	0.90	0.90
$\eta_{Poly.\ HPC}, [\%]$	0.91	0.91
$\eta_{Poly.\ LPT}, [\%]$	0.91	0.91
$\eta_{Poly.\ HPT}, [\%]$	0.91	0.91
$\theta_{core\ nozzle}, [\circ]$	10	10
$\theta_{bypass\ nozzle}, [\circ]$	12	12
$N_{LPC}, [-]$	3	3
$N_{HPC}, [-]$	10	10

All the assumptions [4] required to simulate the GE-90 engine are given above and based on these values we have validated the model and then optimized the GE-90 engine model.

Summary

This chapter described the methodology applied for the modeling of GE-90 aero engine. The input parameters are given in this section. Based on input parameters, thermodynamic cycle analysis was performed, and then material database and design constraints were defined, in which engine overall dimensional constraints were given as input and then baseline cycle for the hydrogen fuel was designed by the given parameters for the hydrocarbon engine. Then multi-parametric optimization was performed on the engine and then optimized engine was compared with the baseline engine. All the methodology for obtaining the results is discussed in this chapter.

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Chapter 5

Results and Discussion

5.1 Model Validation

A comparative study is carried out for generic fuel (hydrocarbon) turbofan in this paper with [1]. Based on this engine data, we have simulated the engine and got the thermodynamic cycle results.

Table 5. 1: Model validation results of hydrocarbon-based GE-90 engine

Parameter	**Design Point @ 10668m for hydrocarbon**
Mach Number, [-]	0.85
Altitude, [m]	10668
HPC pressure Ratio, [-]	21.5
LPC pressure ratio, [-]	1.14
Fan pressure ratio, [-]	1.65
Overall pressure ratio, [-]	40.44
Ambient temperature [K]	218.9
Ambient pressure [kPa]	23.91
BPR, [-]	8.1
Fuel Heating Value, [$kJkg^{-1}$]	43.124
TIT, [K]	1435
Air inlet mass flow rate, [$kgsec^{-1}$]	576.001
Thrust, [kN]	69.49
Specific Fuel Consumption, [$g(kN*s)^{-1}$]	15.2133
Specific Thrust, [ms^{-1}]	123
Fuel to air ratio, [-]	0.019089
Propulsive efficiency, [%]	80.78
Core efficiency, [%]	55.84

Thermal efficiency, [%]	0.38182
Overall efficiency, [%]	0.3054

5.2 Baseline Case

5.2.1 Thermodynamic cycle for hydrogen fueled baseline engine

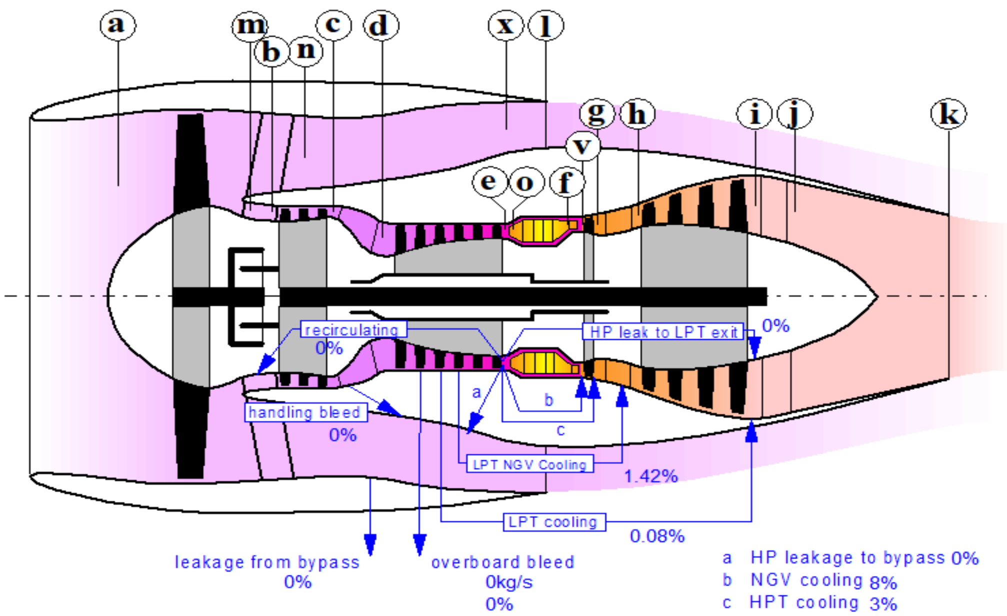

Figure 5. 1: Schematic and stations of GE-90 turbofan engine

The engine thermodynamic model for GE90 using the current operating parameters is analyzed. The pressure, temperature, velocity of air and flue gases, area of each station, Mach number, Exergy, Specific heat value are listed. The details of station numbers are given in nomenclature.

First, a thermodynamic study was carried out for the hydrocarbon fuel which is a preexisting model for the GE90 engine used in Boeing 777 airliner. After that fuel is been changed from Generic fuel to hydrogen fuel. The observed changes in the results were that

- The temperature and pressure at the outlet of the turbine are higher for hydrogen fuel in comparison to the generic fuel which shows that on the same input parameters, expansion of gases is less.
- The net thrust increases from 69.49kN to 73.79kN by changing the fuel to hydrogen which carries more energy than generic fuel
- The specific Fuel Consumption decreases from 15.2133 $g*(kN*s)^{-1}$ to 5.3615 $g*(kN*s)^{-1}$ because hydrogen fuel has almost 3 times the energy density than that of the generic fuel.
- The fuel flow decreases from $1.05722kgs^{-1}$ to $0.39561kgs^{-1}$.
- The core efficiency increased from 0.5584 to 0.5814.
- The propulsive efficiency remained unchanged by changing the fuel from generic to hydrogen.

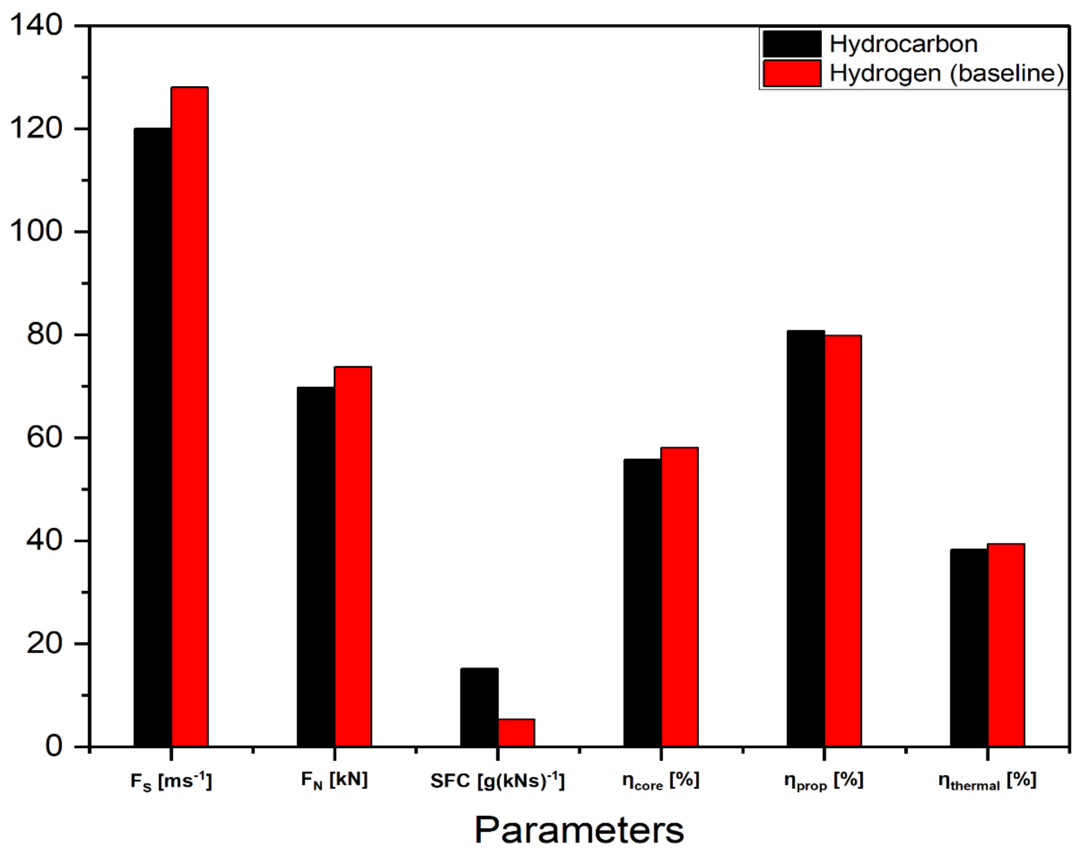

Figure 5. 2: Comparative analysis of thermodynamic parameters b/w hydrocarbon and hydrogen fuel (baseline)

- P5/P2 known as engine pressure ratio changed from 0.9702 to 1.1291.

- The bypass exit pressure/core exit pressure changed from 1.67174 to 1.43916.
- The area of Core A8 changed from 1.15239m^2 to 0.97079m^2.
- Geometric bypass nozzle throat area A18 changes remained unchanged.
- The ideal jet velocity that is a crucial parameter regarding engine noise changes from 0.99861 to 0.83804.

Station wise data of engine is shown in fig. 4. Mach number, mass flow rate of air, exergy, pressure, temperature, and area variations are shown through different components of the engine. After thermodynamic analysis, a detailed iterative parametric study was carried out to analyze the performance parameters of the engine.

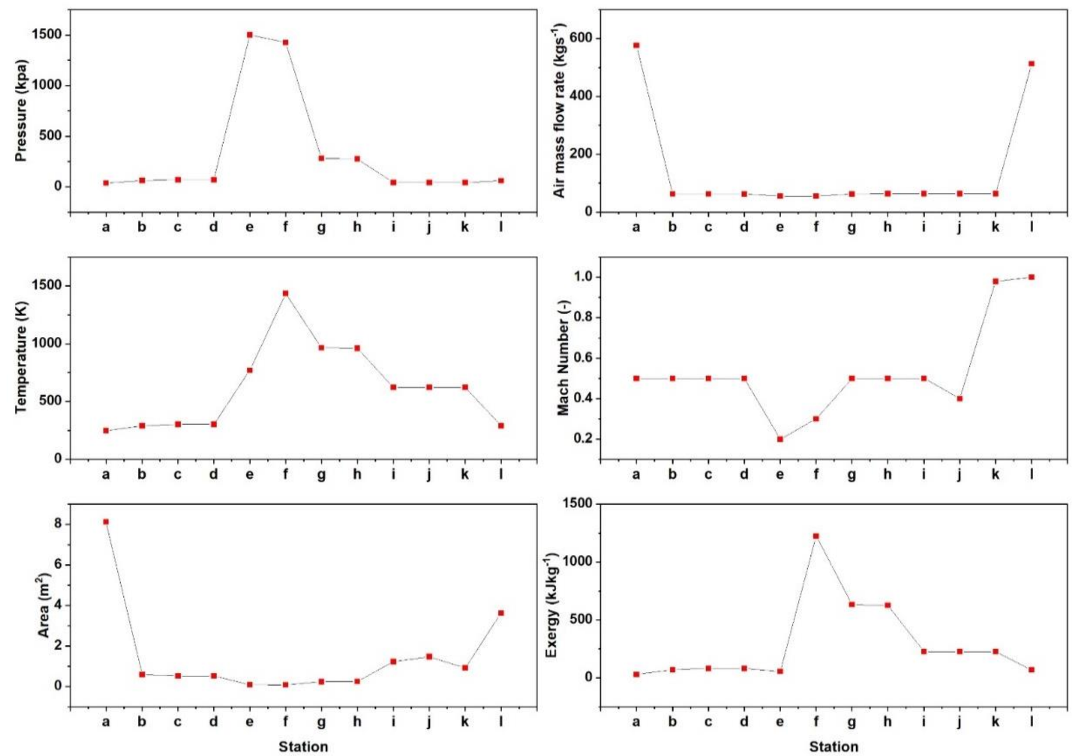

Figure 5. 3: Station wise data through each component (baseline case)

5.2.2 Parametric Study

Requirements to design an engine are given by the aircraft designer and the designer starts designing a new engine. The first and foremost aim is to study the different parameters in a wide range to find the most suitable ones to attain the maximum and suitable performance. This paper presents the parametric study to design the GE90 engine for hydrogen fuel.

The parametric study is comprised of the most important parameters for analyzing the performance such as overall pressure ratio, turbine inlet temperature, fan pressure ratio, HP compressor pressure ratio, LP compressor pressure ratio. For design, the polytropic efficiency of 91% for HP compressors and 90% for the LP compressor and interstage pressure losses were assumed. Tip clearance loss was assumed for the preliminary design phase.

5.2.2.1 Effect of TIT and FPR

In this study, the BPR and OPR are fixed for the hydrogen baseline case based on the literature review. Then by fixing the value effect of FPR and TIT on the specific thrust and specific fuel consumption was investigated. The chosen operating conditions determine the entry flow and combustion chamber airflow, so we choose the energy input and turbine inlet temperature fixed. FPR is used as a variable, and the effect of FPR on SFC and Specific thrust was observed. High hot thrust and low cold thrust can be achieved by using the low FPR and the energy required by the machine would be less. But on the other hand, if we increase the FPR, the specific fuel consumption would reduce but the energy required to drive the fan would increase causing an increase in cold thrust and reducing the hot thrust. FPR and TIT are taken as variables, and the effect of inner FPR and TIT on specific fuel consumption was observed. For the fixed value of TIT, the specific fuel consumption decreases as FPR increases, and specific thrust increases for increasing TIT at constant FPR and fixed OPR. But after an optimized point, the SFC starts increasing for increasing TIT and fixed OPR. The carpet plot shows that the existing engine GE90 which is being operated on hydrogen fuel is not fully optimized because the parameters are taken as same of generic fuel operated engine. The limit of pressure ratio for the single-stage fan is not more than 2. Above 2, the design of the single-stage Fan stays invalid.

5.2.2.2 Effect of LPC pressure ratio and TIT

At fixed BPR and OPR, the SFC and ST are analyzed. There are two iterative parameters, one is LPC pressure ratio, and the other is TIT. The feasible range of pressure ratio for LPC is between 1.1to 1.2. There is a constraint for TIT as well, and cannot exceed above 1700K. Specific fuel consumption decreases up to a specific point and then it starts increasing for increasing TIT. The LP compressor and Fan are attached to the LP turbine and its RPM is lower than HP Compressor and turbine. There is still room for optimization of LPCR as the design point for the hydrocarbon case is not optimized.

5.2.2.3 Effects of HPC pressure ratio and TIT

HPC is the key paramter in determining the OPR. The value for HPC PR for the baseline case is 21.5. At lower temperatures, the SFC will increase with lowering the specific thrust if the PR of HPC is increased. But if the temperature is increased upto a specific limit, SFC will reduce and specific thrust will increase. But after that specific optimization point, SFC starts increasing, increasing the thrust but lowering the range and performance of aircraft. OPR value above 65 is not possible because of size constraints. As we cannot increase the number of stages and other mechanical problems concise the designer options. A larger OPR will increase the diameter of the engine to meet the lower SFC which is beyond the study. To maintain a specific ground clearance for the engine, it is not feasible to increase the engine diameter.

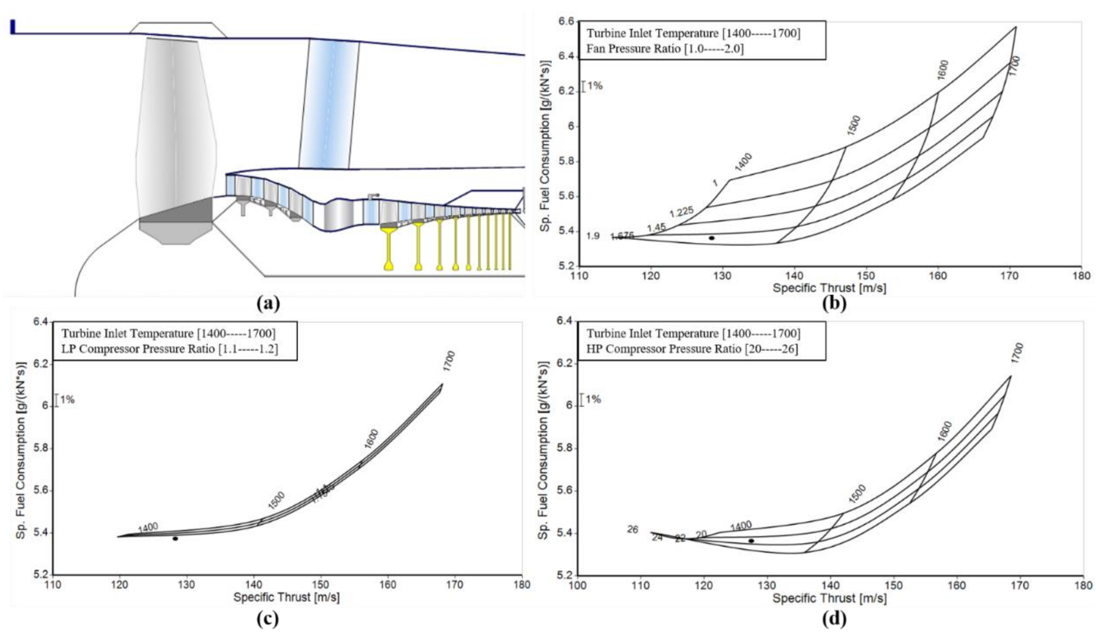

Figure 5. 4: (a) Gas path design of compressor (b) Effect of TIT and FPR on SFC and Fs (c) Effect of TIT and LPC pressure ratio on SFC and Fs (d) Effect of TIT and HPC pressure ratio on SFC and Fs (baseline case)

5.2.3 Gas Path Design

In preliminary design, the position of each component of engine configuration is very important. The inlet variables are changed by changing the radial position of each component. A good gas path design depends on the position of the hub and tip in the case of a compressor. The change in the hub or tip diameter changes the annulus area for the constant hub to tip ratio at the inlet to the compressor. Axial velocity and Mach number change the annulus area, so the performance of the compressor is affected. For a smooth and uninterrupted flow, the gas path was designed. The design process for defining the gas path is highly iterative which means we have to see that either to use a constant hub or constant tip configuration and similarly the hub diameter for IP and HP is adjusted so flow could enter the compressor with sufficient axial Mach number. The gas path within a component should be uninterrupted as well as for the components relative to each other like at the exit of one component and the entry of the other component.

Table 5.2: Aerodynamic stage wise data of LP Compressor (baseline case)

Stages	**Stage 1**	**Stage 2**	**Stage 3**
Calculated Reaction, [-]	0.896	0.5	0.5
Calculated Flow Coefficient, [-]	1.05	0.7	0.7
Calculated Loading, [-]	0.207	0.207	0.207
Rotor Tip Mach Number, [-]	0.776	0.688	0.620

At the inlet to the first stage, we increase the hub diameter with the same hub or tip ratio for the LP compressor causing the increase in area. For the same mass flow rate, the area requires less axial velocity (Mach No.). The Mach no. in the LP compressor should be around 0.5. The hub/tip ratio of 0.8 was determined to get the unique value of 0.5 Mach number. After determining the hub diameter of the LP compressor, the question that arises is that whether to keep the hub diameter constant or tip diameter constant or have the hub/tip ratio constant. We selected the design configuration for hub/tip ratio as a constant parameter and both hubs and tip radius are changing for stages across the compressor.

Table 5.3: Stage Wise data of HP compressor (baseline case)

Stages	Pressure ratio, [-]	Calculated Reaction, [-]	Calculated flow coefficient, [-]	Calculated Loading, [-]
Stage1	1.758	0.89	0.348	0.444
Stage 2	1.523	0.50	0.70	0.444
Stage 3	1.444	0.50	0.70	0.444
Stage 4	1.386	0.50	0.70	0.444
Stage 5	1.342	0.50	0.70	0.444
Stage 6	1.307	0.50	0.70	0.444
Stage 7	1.279	0.50	0.70	0.444
Stage 8	1.256	0.50	0.70	0.444
Stage 9	1.236	0.50	0.70	0.444
Stage 10	1.165	0.50	0.70	0.444

There are three stages in the LP compressor and stage-wise calculations for all three stages were performed during aerodynamic analysis. The detailed aerodynamic design of the LP compressor was investigated during the study and is shown below in table 6.

Table 5.4: Aerodynamic design (gas path) of HP compressor (baseline case)

Parameters	Rotor 1	Rotor 5	Rotor 10
Hub radius, [m]	0.4634	0.5283	0.5397
Mean radius, [m]	0.5461	0.5461	0.5461
Tip radius, [m]	0.6178	0.5631	0.5524

Chord, [mm]	279	33.03	13.03
Pitch, [mm]	279	33.03	13.03
Height, [mm]	154.46	35.05	12.74

The configuration of the HP compressor was the next step after determining the configuration of the LP compressor. Hub diameter of LP compressor is greater than HP compressor. To make the gas path smooth, Mach no. should be low. The relative hub/tip ratio configuration was used for better gas path of HP compressor. The gas path of engine's cold side was finalized after determining the HP compressor configuration.

Table 5.5: Aerodynamic design of LP compressor for each rotor and stator (baseline case)

Rows	**Rotor 1**	**Stator 1**	**Rotor 2**	**Stator 2**	**Rotor 3**	**Stator 3**
Inlet Pressure, [kPa]	62.4826	65.8714	65.1941	69.3656	68.8598	71.5799
Inlet Temperature	292.22	298.29	298.29	304.26	304.26	308.25
Inlet Mass Flow, [kgs^{-1}]	63.297	63.297	63.297	63.297	63.297	63.297
Exit Pressure, [kPa]	65.871	65.194	69.366	68.860	71.580	71.230
Exit Temperature, [K]	298.29	298.29	304.26	304.26	308.25	308.25
Inlet Area, [m^2]	0.574058	0.557304	0.79514	0.780709	0.819278	0.807889
Inlet Tip Radius, [m]	0.7735	0.7621	0.7912	0.7630	0.7421	0.7091
Inlet Mean Radius, [m]	0.7120	0.7015	0.7067	0.6766	0.6483	0.6117
Inlet Hub Radius, [m]	0.6446	0.6351	0.6106	0.5776	0.5384	0.4956
Height, [mm]	128.85	126.97	180.55	185.38	203.66	213.46
Pitch, [mm]	112.86	81.62	91.14	88.12	94.01	72.25

Chord, [mm]	112.86	81.62	91.14	88.12	94.01	72.25
Axial Chord, [mm]	85.90	81.23	74.53	72.06	70.25	69.27
Aspect Ratio, [-]	1.500	1.563	2.423	2.573	2.899	3.081
No. of Blades/Vanes, [-]	40	54	49	48	43	53
Inlet Axial Velocity, [ms^{-1}]	179.38	179.38	119.151	119.151	109.299	109.299
Inlet Relative Velocity, [ms^{-1}]	248.161	182.867	157.333	157.333	138.497	130.38
Exit Relative Velocity, [ms^{-1}]	225.073	179.38	136.927	136.927	138.497	109.299
Inlet Relative Mach Number, [-]	0.745	0.544	0.462	0.459	0.450	0.376
Inlet Relative Mach Number, [-]	0.669	0.533	0.399	0.398	0.399	0.314
Inlet Angle, [º]	90.00	78.79	60.48	49.23	67.49	56.96
Rel. Inlet Angle, [º]	133.71	127.16	130.77	119.52	135.40	127.89
Exit Angle, [º]	78.79	90.00	49.23	60.48	56.96	90.00
De Haller Number, [-]	0.907	0.980	0.870	0.870	0.889	0.838
Reynolds Number	1.04E06	5.61E05	5.59E05	5.46E05	5.92E05	3.84E05

After the design of the cold side of the engine, the next step was to design the turbine. The main consideration was to make the turbine inlet hub diameter close to the HPC hub diameter because this makes a good combination of configuration from HPC exit to combustion chamber and then towards HP turbine making the gas path uninterrupted. The range for Mach number at the inlet of HP is 0.2-0.3. The number of stages for the HP turbine is two and the Mach number at the inlet of the HP turbine is 0.3.

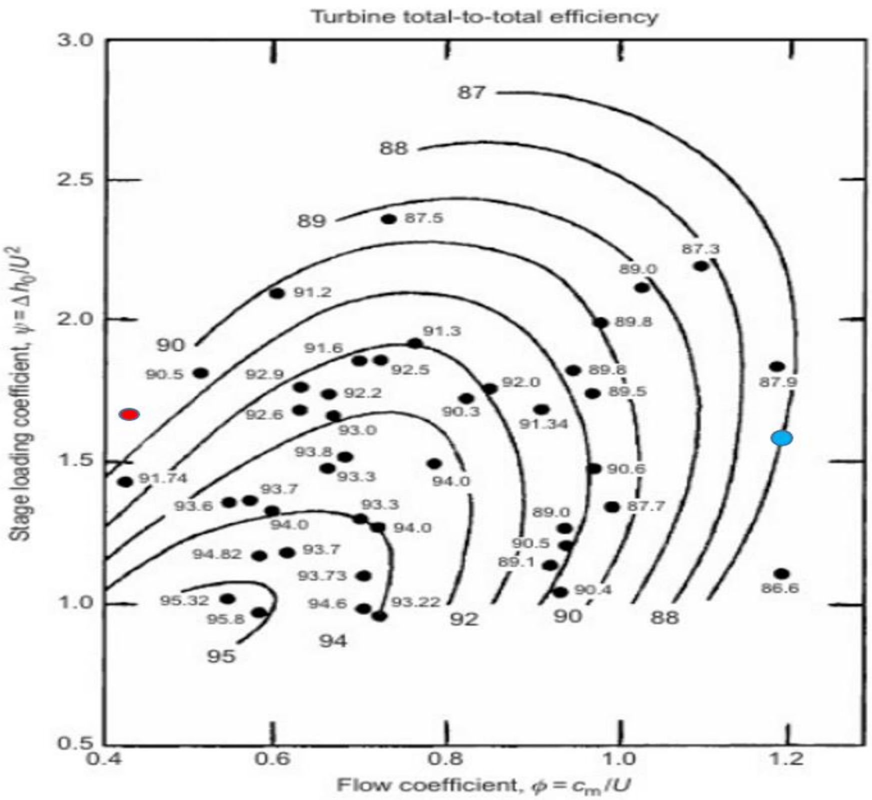

Figure 5. 5: Turbine efficiency smith chart (baseline case)

After defining the HP turbine, the next step is to analyze the geometry of the LP turbine. The six stages of LPT are driving the three stages of LPC and fan. The positioning of the LP turbine is in such a way that the gas path should be uninterrupted relative to the inter-duct and HP turbine. Fan tip speed is limited to $460ms^{-1}$ due to mechanical constraints which limit the RPM of the LP turbine. The RPM for LPT is 2300 and stage loading was given as 1.71 and the stage flow coefficient for LP turbine was 1.2. The RPM for the HP turbine is 9332 and stage loading was 1.85 and the stage flow coefficient was calculated as 0.4. The smith chart for the turbine is given below in fig. 6. The red point is showing HP turbine efficiency and the blue point is indicating LP turbine efficiency.

The above calculations show the complete engine layout, and the gas path of the whole engine is depending on the configuration and position of components. Two spool configuration improves the performance of the engine. It is lighter than the three-spool engine and provides more weight stability. The de-Haller number in the front stages is relatively higher than the mid and later stages indicating less flow turning to avoid the

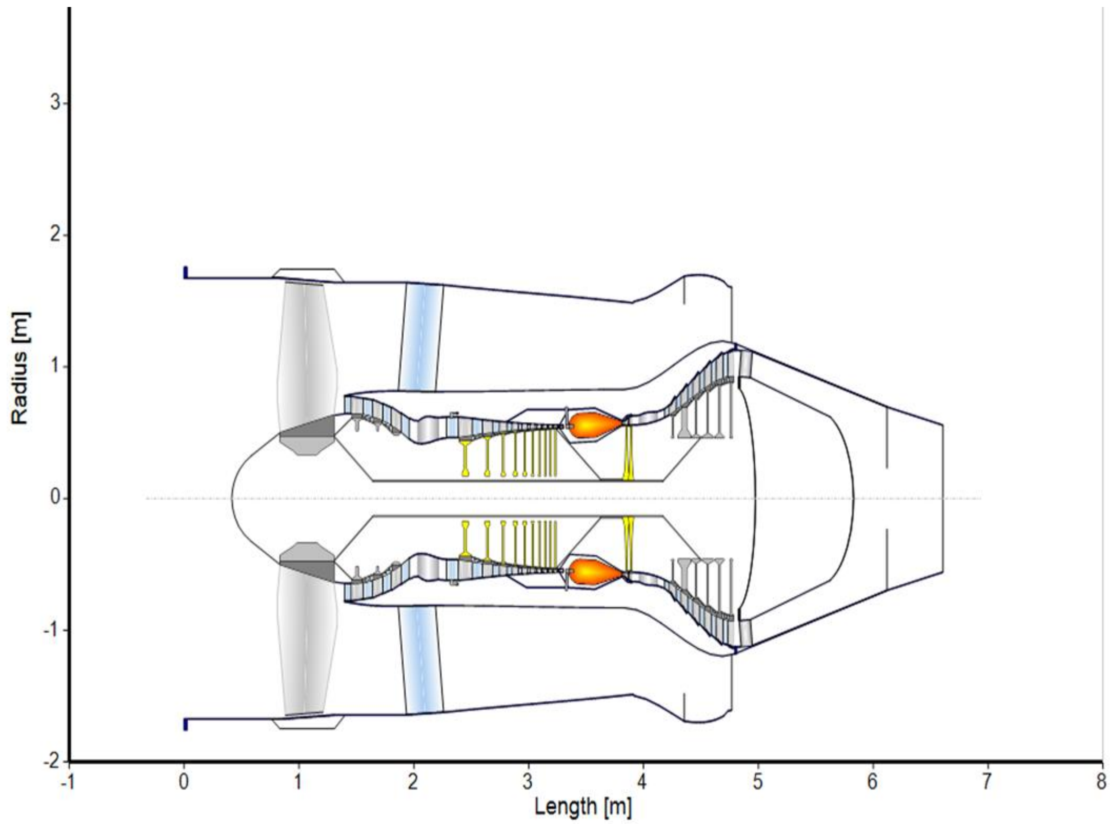

Figure 5. 6: Gas path and engine geometry (baseline case)

likelihood of stall due to any inlet distortions. In the later stages, the de-Haller starts to reduce to achieve a high compression ratio per stage. The total pressure across the stator reduces due to the friction, profile, and secondary flow losses.

5.3 Optimization case:

5.3.1 Thermodynamic cycle for hydrogen-fueled baseline engine:

The optimization tool available in GasTurb 13 was used for the optimization of the hydrogen turbofan engine. The figure of merit was taken as Specific fuel consumption to minimize the SFC. the thrust requirement was set as 70-80kN. A certain range was given for the different parameters like BPR, FPR, TIT, HPC pressure ratio, LPC pressure ratio and mass flow rate of air at inlet of fan to get minimum SFC for the required 73kN of thrust at design point. An iterative process was used to simulate all these parameters simultaneously and as a result an optimized engine was designed as output. The thermodynamic analysis of the optimized turbofan engine is given below.

Thermodynamic analysis of optimized hydrogen turbofan engine:

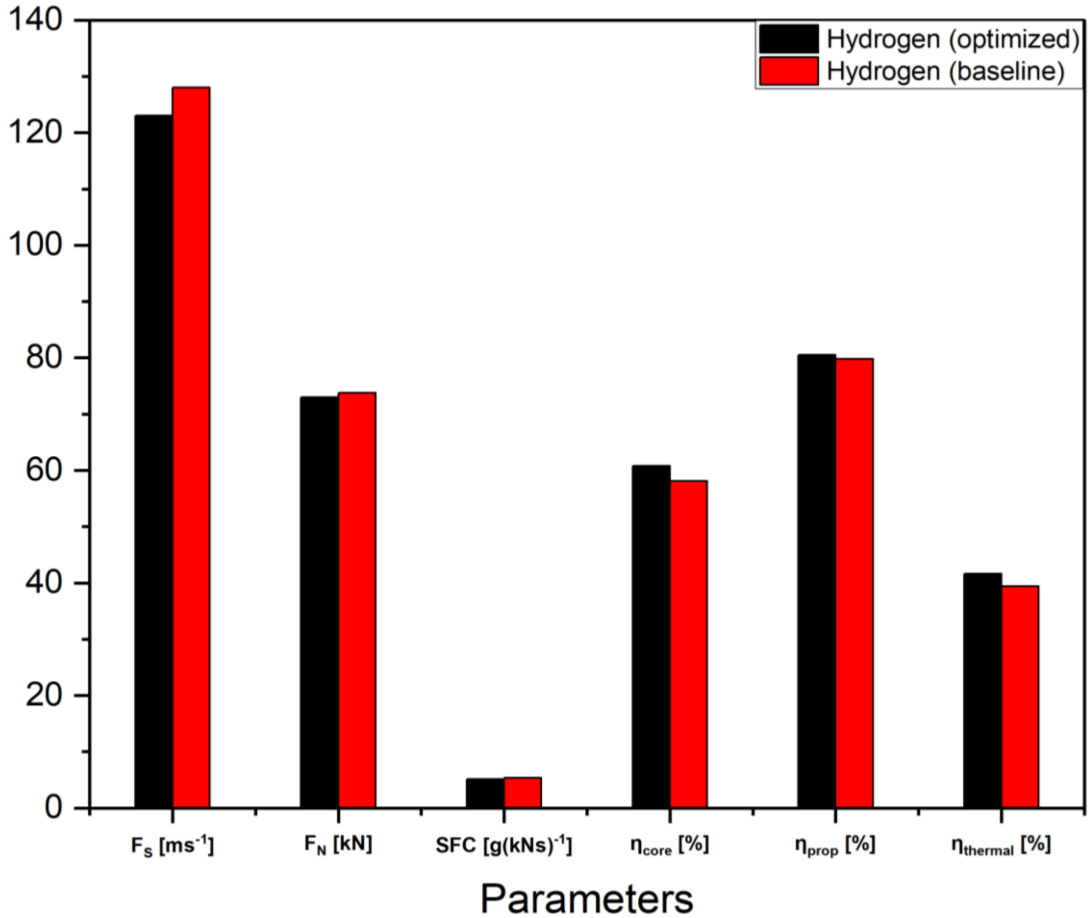

Figure 5. 7: Comparative analysis of thermodynamic parameters b/w hydrocarbon and hydrogen fuel (optimized)

- The temperature and pressure at the outlet of the turbine is higher for hydrogen fuel in comparison to the generic fuel which shows that on the same input parameters, expansion of gases is less.
- After optimization, the net thrust decreased from 73.39 kN to 73.02 kN while taking SFC as minimum and thrust required as 70 kN.

- T-SFC is reduced from 5.3615 $g(kN*s)^{-1}$ to 5.0994 $g(kN*s)^{-1}$ by optimizing the hydrogen turbofan engine.

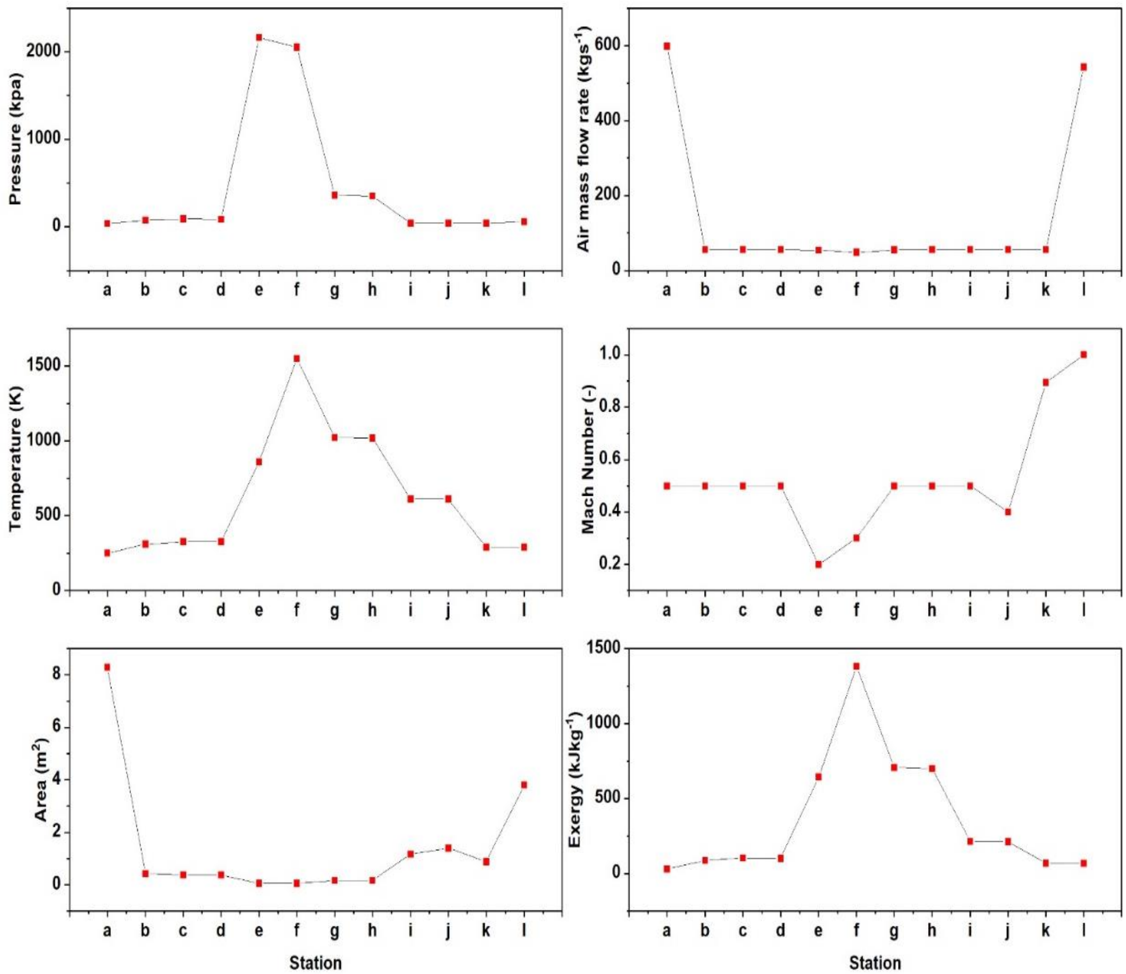

Figure 5. 8: Station wise data through each component (optimized case)

- The fuel flow decreased from 0.39561 kgs^{-1} to 0.37238 kgs^{-1}.
- The core efficiency increased from 0.5814 to 0.6077.
- The propulsive efficiency remained unchanged at 0.80 by the optimization of hydrogen turbofan.
- P5/P2 known as engine pressure ratio changed from 1.1291 to 1.596.
- The bypass exit pressure/core exit pressure changed from 1.43916 to 1.58992.
- The area of Core A8 changed from 0.97079m^2 to 0.90913m^2.
- Geometric bypass nozzle throat area A18 remained unchanged.

- The ideal jet velocity that is a crucial parameter regarding engine noise changes from 0.83804 to 0.8828.

Station wise data of engine is shown in fig. 9. Mach number, mass flow rate of air, exergy, pressure, temperature, and area variations are shown through different components of the engine. After thermodynamic analysis, a detailed iterative parametric study was carried out to analyze the performance parameters of the engine.

5.3.2 Selection of Bypass ratio

In the optimized case, for fixed Mach number and BPR, specific fuel consumption decreases, and net thrust increases when we change the fuel from hydrocarbon to hydrogen. This refers that an optimized hydrogen-fueled turbofan engine will produce the same amount of thrust while consuming less fuel than the previously designed engine. By increasing the bypass ratio, the amount of cold thrust will increase, and the diameter of turbofan will increase, impacting an increase in the mass flow rate of air which will decrease the hot thrust. With the decrease in hot thrust, turbine outlet temperature (TOT) and turbine outlet pressure will decrease leading to the decrease in core nozzle flow speed, temperature, and pressure. Fuel to air ratio is independent of change in BPR.

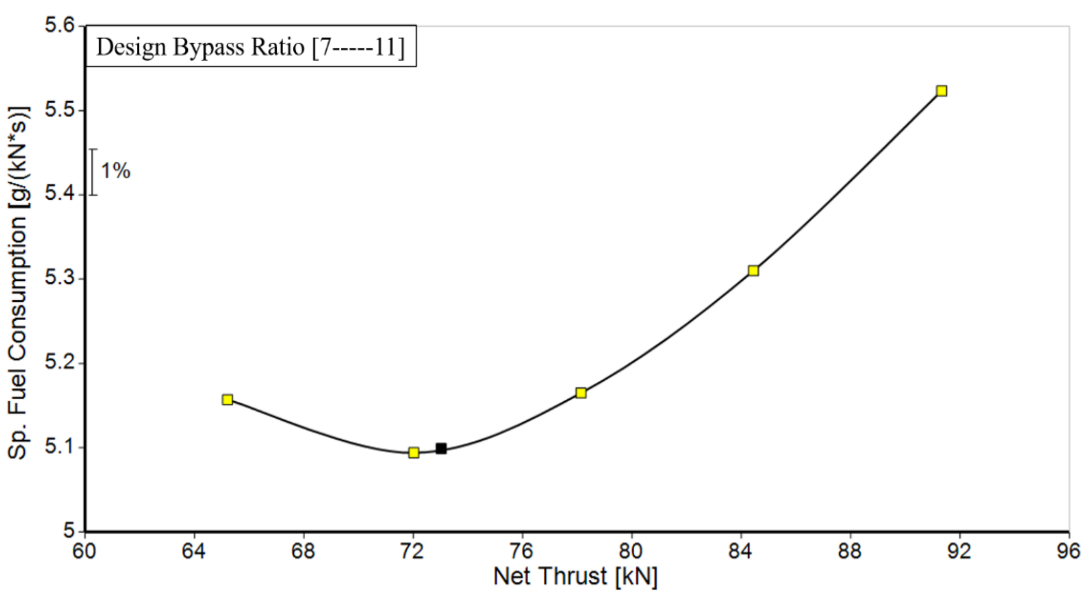

Figure 5. 9: Effect of bypass ratio on SFC and FN for optimized case

5.3.3 Effect of Mach Number

For the fixed value of TIT, BPR, FPR, OPR for a turbofan, a decrease in Mach number will decrease the Speed of incoming air, compressors outlet pressure, and temperature and increase in Mach number will produce a reverse effect. Any change in Mach number does not affect the TIT which results in a decrease of A/F ratio with an increase of Mach number which causes an increase in air flow rate and SFC will increase, causing the decrease in net thrust. Combustor inlet temperature and pressure increase with an increase in Mach number. So, it increases NOx emissions. With the decrease in altitude, the ambient temperature and pressure will increase, and Combustor inlet pressure and temperature will increase which will reduce the NOx emissions.

5.3.4 Parametric study

5.3.4.1 Effect of TIT and FPR:

Keeping the BPR and OPR constant, the effect of TIT and Inner Fan pressure ratio is observed for hydrogen fuel for an optimized turbofan engine. The parametric carpet plot shows that these parameters are not optimized shown in the hydrogen baseline case. These parameters determine the air inlet flow and fuel flow for the combustion chamber. At specific Mach number and TIT and BPR, the effective speed at the outlet of fan nozzle and pressure and temperature will increase with an increase in fan pressure ratio. Increase

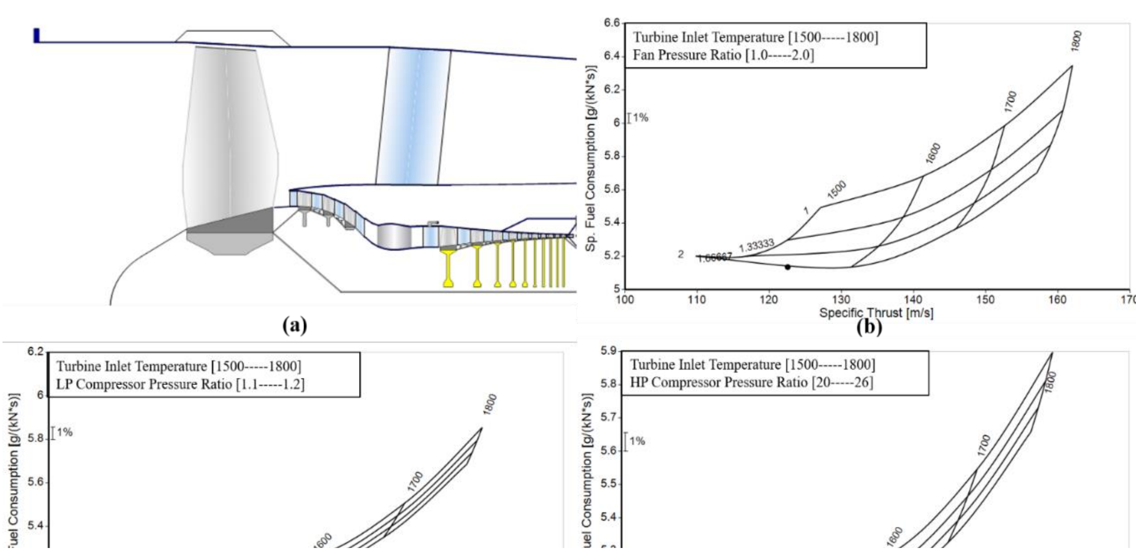

Figure 5. 10: (a) Gas path design of compressor (b) Effect of TIT and FPR on SFC and Fs (c) Effect of TIT and LPC pressure ratio on SFC and Fs (d) Effect of TIT and HPC pressure ratio on SFC and Fs (optimized case)

BPR and FPR will increase the power required to operate the fan. Any change in FPR should be according to the designed BPR because the power required by the fan and compressor must be fulfilled from the turbine. The work input required by the fan also increases and as the turbine output remains the same, this leads to a less efficient system. Therefore, there is a limit of 2.0 for an increase in fan pressure ratio. If the fan pressure ratio is further increased, it will reduce the speed at the core nozzle's outlet causing an effect on drag force. The effect of Inner FPR and TIT is observed on specific fuel consumption and Specific thrust.

5.3.4.2 Effect of LPC pressure ratio and TIT

During this parametric study, two variables Low-Pressure Compressor Pressure ratio and Turbine inlet temperature are varied from 1.1 to 1.2 and 1400k to 1800k respectively. The baseline value for the LPC pressure ratio is 1.14 and it is not an optimized value in the case of hydrogen fuel. To get an optimized value, LPC pressure ratio is varied from 1.1 to 1.2. With the increase in LPC pressure ratio, the specific fuel consumption is reduced against an identical net thrust but there are certain limits for mechanical parts and turbomachinery that LPC pressure ratio cannot be chosen beyond that limit. Another factor is that as we increase the LPC pressure ratio, the power required to drive the low-pressure compressor will increase and hot thrust will reduce. Because if pressure ratio is higher, it will increase the work per stage in the compressor and the more power required to rotate at the specific speed.

5.3.4.3 Effect of HPC pressure ratio and TIT

In OPR, the major contributor is the HPC pressure ratio and there are certain limitations in choosing the HPC pressure ratio because of sizing and turbomachine constraints. The carpet plot shows that the value chosen as 21.5 is not the optimized value for the hydrogen-fueled engine and by increasing the HPC compressor ratio to somewhere around 25, it will give the best possible design point where the SFC will be minimum and net thrust will improve and the overall geometry size of the engine will reduce. Overall geometry sizing is also dependent on the number of stages. A higher-pressure ratio will lead to a larger diameter of the engine, and it is not feasible at the manufacturing level. For a fixed Mach number and altitude, an Optimized hydrogen turbofan engine will emit less emissions than the baseline hydrogen turbofan engine. From thermodynamic analysis, it can be concluded that when OPR is increased SFC will reduce at a fixed BPR, TIT, and Mach number because OPR majorly affects the fuel-air-ratio, and its effect on net thrust is smaller. So, emissions are directly influenced by higher compressor outlet temperature and pressure. As OPR is increased, NOx index emissions are increased and with the decrease in OPR, emissions would reduce but for better and optimized turbomachine design and lowering the size of engine, OPR will increase.

5.3.5 Gas Path Analysis for Optimized Turbofan engine

For an optimized turbofan engine, the gas path becomes a critical part of the study because the fan pressure ratio is increased, which means more work has been extracted from the fan. Tip clearance, hub diameter, and tip diameter are the crucial parameters for the designing of the fan. The gas path is designed in such a way that the flow of working fluid goes uninterrupted and due to hydrogen burning there is no backlash. After that, the LP compressor is optimized to extract more work from the LPT. Annulus area change also affects the Mach number and axial velocity and compressor performance as well. The hub positioning also defines entry flow in the compressor, so flow could enter in compressor with allowable Mach number and axial velocity. By increasing the hub diameter for the same hub/tip ratio at the inlet, the cross-sectional area will change. The gas path results for axial LPC are given below.

Table 5.6: Aerodynamic stage wise data of LP Compressor (optimized case)

Stages	**Stage 1**	**Stage 2**	**Stage 3**
Calculated Reaction, [-]	0.869	0.5	0.5
Calculated Flow Coefficient, [-]	1.0	0.7	0.7
Calculated Loading, [-]	0.262	0.262	0.262
Rotor Tip Mach Number, [-]	0.75	0.64	0.57

After calculating the gas path for LPC, the gas path of HPC must be calculated. The axial velocity should be in the range of 150-200 ms^{-1}. The Mach number should be 0.5 for the smooth gas path of flow. The stage loading should not exceed 0.5 and the calculated flow coefficient should range in 0.7 for a smooth gas path.

The number of stages for the Preliminary design was already determined from the available model. The blade angles are chosen based on the best suitable performance on design point and off-design as well. There are three steps to determine the geometry of the Compressor.

1. The mean line design is used to design the compressor for a given pressure ratio.
2. The next step is to determine the blade angle to make the gas path smooth to achieve optimum performance
3. The final step is to assess the off-design performance of the compressor.

An iterative process is used to determine the layout of the HP compressor. The axial Mach number decides that whether a constant hub, constant tip, or constant hub to tip ratio configuration will be used. Constant hub diameter has less annulus area than the constant tip diameter for the same hub to tip ratio at the inlet. So, the Mach number increases which will also increase the axial velocity. At the inlet of the HP compressor, to achieve the Mach number between 0.3-0.5, an iterative study was performed to decide which configuration will be suited for a smooth gas path. Another major factor to decide is that the increase in annulus area will decrease the Mach number when hub diameter is increased for the same hub/tip ratio. A detailed and iterative study was carried out to determine the hub radius and tip radius and best remains uninterrupted for a suitable configuration. The mean line design configuration was chosen as the best configuration. The number of stages for HPC is 10. The aerodynamic design is studied for optimized hydrogen fuel. The impact of fuel change can be seen on the aerodynamic design of HPC. The stage loading, flow coefficient, calculated reaction, Inlet and exit velocities, and de-Haller number are the parameters to be observed. Stage-wise data of HPC is shown below.

Table 5.7: Aerodynamic design of LP compressor for each rotor and stator (optimized case)

Rows	Rotor 1	Stator 1	Rotor 2	Stator 2	Rotor 3	Stator 3
Inlet Pressure, [kPa]	75.668	80.782	79.940	85.935	85.351	89.5183
Inlet Temperature, [K]	309.90	317.38	317.38	324.62	324.62	329.64
Inlet Mass Flow, [kgs^{-1}]	55.213	55.213	55.213	55.213	55.213	55.213
Exit Pressure, [kPa]	80.783	79.941	85.936	85.352	89.518	89.102
Exit Temperature, [K]	317.38	317.38	324.62	324.62	329.64	329.64
Inlet Area, [m^2]	0.4258	0.4105	0.6078	0.5944	0.6286	0.6178
Inlet Tip Radius, [m]	0.7506	0.7385	0.7593	0.7287	0.7052	0.6692
Inlet Mean Radius, [m]	0.7040	0.6929	0.6926	0.6606	0.6303	0.5912
Inlet Hub Radius, [m]	0.6541	0.6440	0.6189	0.5846	0.5451	0.5012
Height, [mm]	95.50	94.51	140.40	144.08	160.04	168.03
Pitch, [mm]	82.01	60.10	67.59	63.50	68.08	51.07
Chord, [mm]	82.01	60.10	67.59	63.50	68.08	51.07
Axial Chord, [mm]	64.34	59.68	55.42	52.07	52.09	48.54
Aspect Ratio, [-]	1.500	1.584	2.533	2.767	3.072	3.461
No. of Blades/Vanes, [-]	54	72	64	65	58	73

Inlet Axial Velocity, [ms^{-1}]	184.728	184.728	116.78	116.78	106.26	106.26
Inlet Relative Velocity, [ms^{-1}]	250.747	190.009	157.242	151.063	151.063	131.669
Exit Relative Velocity, [ms^{-1}]	223.088	184.728	131.998	131.998	129.517	129.517
Inlet Relative Mach Number, [-]	0.73	0.54	0.44	0.44	0.42	0.36
Inlet Relative Mach Number, [-]	0.64	0.53	0.37	0.37	0.36	0.36
Inlet Angle, [^{o}]	90.00	76.46	62.22	47.96	67.31	53.81
Rel. Inlet Angle, [^{o}]	132.5	124.10	132.04	117.78	135.30	124.87
Exit Angle, [^{o}]	76.46	90.00	47.96	62.22	53.81	90.00
De Haller Number, [-]	0.871	0.972	0.839	0.839	0.857	0.807
Reynolds Number, [-]	8.34E05	4.73E05	4.61E05	4.39E05	4.64E05	3.07E05

The RPM for LP turbine is 2300 and stage loading was given as 1.736 and the stage flow coefficient for LP turbine was 1.2. The RPM for the HP turbine is 9332 and stage loading was 1.85 and the stage flow coefficient was calculated as 0.395. The smith chart for the turbine is given above in fig. 8. The red point is showing HP turbine efficiency and the blue point is indicating LP turbine efficiency.

Table 5.8: Stage wise data of HP compressor (optimized case)

Stage	**Pressure ratio, [-]**	**Calculated Reaction, [-]**	**Calculated flow coefficient, [-]**	**Calculated Loading, [-]**
Stage1	1.740	0.84	0.424	0.312

Stage 2	1.558	0.50	0.70	0.312
Stage 3	1.472	0.50	0.70	0.312
Stage 4	1.410	0.50	0.70	0.312
Stage 5	1.33	0.50	0.70	0.312
Stage 6	1.326	0.50	0.70	0.312
Stage 7	1.296	0.50	0.70	0.312
Stage 8	1.271	0.50	0.70	0.312
Stage 9	1.250	0.50	0.70	0.312
Stage 10	1.195	0.50	0.70	0.312

The can of the combustor is designed in GasTurb 13 for which exit to inlet radius is calculated as 1.05. Length to inlet radius is 1 and can width/can length be 0.4.

Table 5.9: Aerodynamic design (gas path) of HP compressor (optimized case)

Parameter	**Rotor 1**	**Rotor 5**	**Rotor 10**
Hub radius, [m]	0.3937	0.4495	0.4587
Mean radius, [m]	0.4640	0.4640	0.4640
Tip radius, [m]	0.5249	0.4800	0.4692
Chord, [mm]	87.49	30.21	9.53
Pitch, [mm]	87.49	30.21	9.53
Height, [mm]	131.24	32.51	10.43

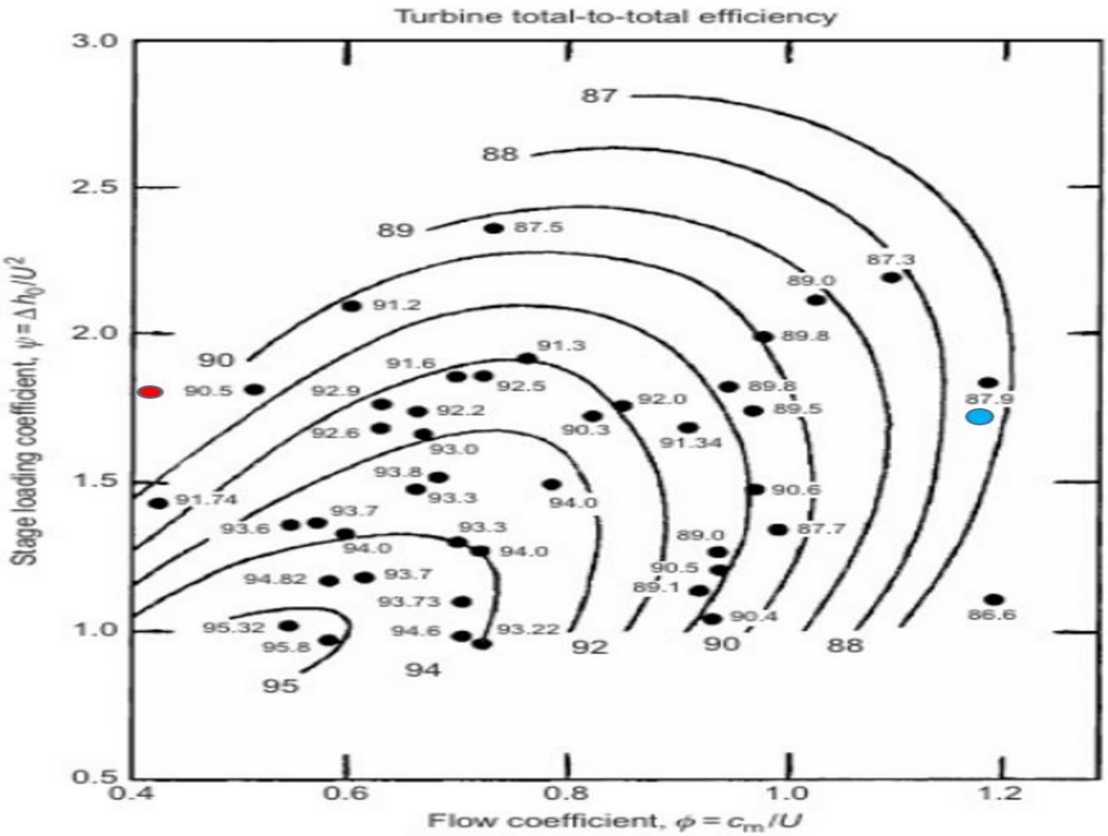

Figure 5. 11: Turbine efficiency smith chart (Optimized Case)

The inner and outer casing of the can is 0.002m and 0.005m respectively. The thermal expansion coefficient of a can is 10E-6 (J*kg. K^{-1}). This is the whole engine layout and LP, and HP shaft thickness is 0.005m and shaft material density is $8000kgm^{-3}$. The front LP shaft cone length is 0.395095m and the middle LP shaft length is 2.05642m. The Middle LP shaft radius is 0.09189m and rear LP shaft cone length is 0.22639m and the HP shaft cone length is 0.3568. The total length of the engine is 5.8894m and its maximum diameter is 3.73196m.

Here is a comparative analysis between the baseline engine and the optimized engine. The baseline engine is greater in size than the optimized engine because the turbomachinery of the baseline engine is based on low OPR and fewer stage loadings and flow coefficients. Moreover, the bypass ratio is more in the optimized case which ultimately leads to the higher cold thrust and lower hot thrust. Cold thrust is the major contributor to overall F_N. The FPR, LPC pressure ratio, HPC pressure ratio is increased which results in a higher OPR of 57.09 than the baseline case of 40.44.

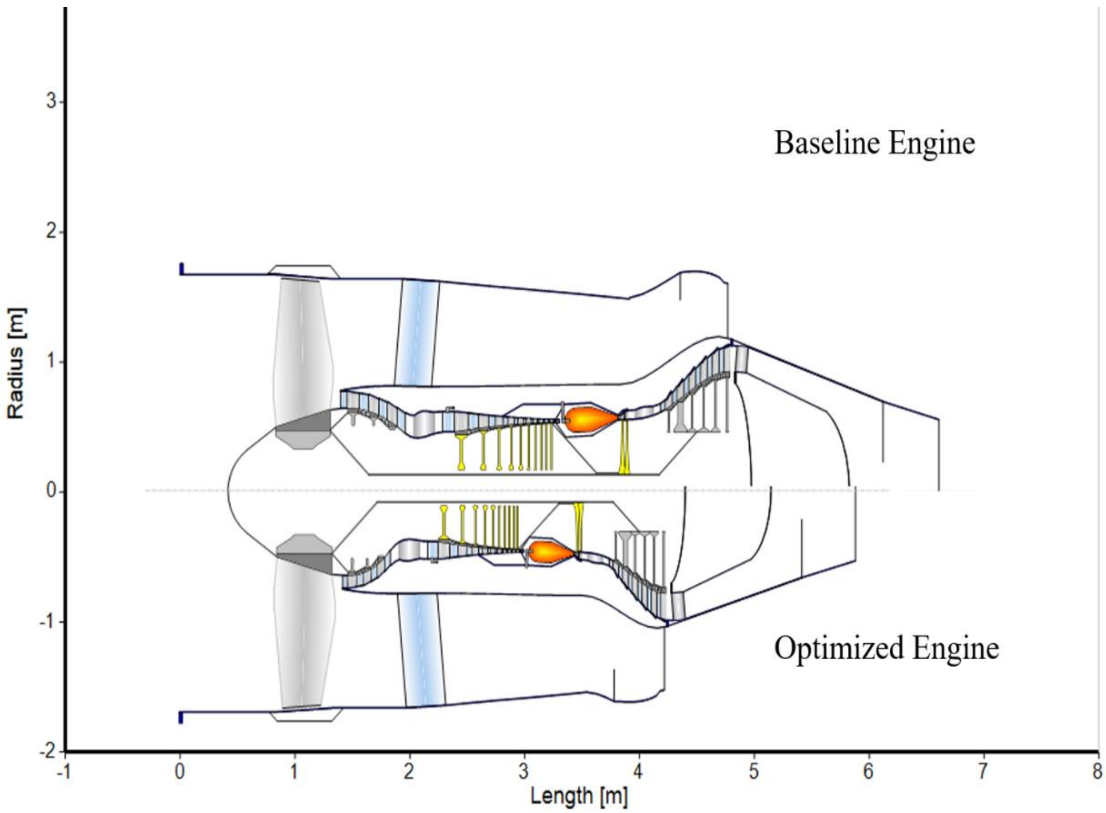

Figure 5. 12: Comparative engine geometry for bassline and optimized engine

Summary

This chapter presents the comparative analysis between the baseline and optimized engine using the thermodynamics analysis parameters. Model validation is done through existing model and then a hydrogen fueled base line case is analyzed with the existing parameters. Study found that the GE-90 turbofan engine is not fully optimized for hydrogen fuel. Then multi-parametric optimization is carried out and optimal performance of engine was fetched out as output results. Gas path of HPC, LPC and turbine section was analyzed to get an overview that flow is flowing optimally without interruption and engine size was reduced in terms of length through optimization. A geometric analysis between baseline engine and optimized engine for optimal performance is carried out.

References

[1] P. Derakhshandeh, A. Ahmadi, and R. Dashti, “Simulation and technical-economic-environmental optimization of the General Electric GE90 hydrogen turbofan engine,” Int. J. Hydrogen Energy, vol. 46, no. 5, pp. 3303–3318, 2021, doi: 10.1016/j.ijhydene.2020.10.182.

Chapter 6

Conclusions and Recommendations

6.1 Conclusions

The General Electric GE90 engine was studied during this study. The engine was thermodynamically simulated on GasTurb 13 for model validation. Then, fuel has been changed from generic (kerosene) to hydrogen fuel on the same parameters on which the hydrocarbon-fueled engine was operating. Then, a parametric study was carried out along with the gas path assessment of the baseline engine which shows that parameters are not optimized for hydrogen fuel. Then a multi-parametric optimization was carried out which includes fan pressure ratio, LPC pressure ratio, HPC pressure ratio, turbine inlet temperature, bypass ratio, and mass flow rate of the air. Through multi-parametric optimization, optimal performance and size reduction of the engine were achieved.

(i) The thrust-specific fuel consumption decreases by 4.88% due to the optimized parameters for hydrogen fuel. The thermal efficiency of the optimized hydrogen-fueled engine increases by 5.53% because more work is produced while less fuel is burnt due to the efficient turbomachinery and design of the machine

(ii) The fuel flow required to produce the required thrust decreases by 5.87% because, during optimization, a figure of merit was the minimization of fuel consumption at an identical net thrust.

(iii) The core area decreases by 6.35% because the bypass ratio is increased, and more cold thrust is produced from the engine.

(iv) The overall length of the engine decreases by 10.84%.

(v) The engine diameter increases 1.94% because of the higher BPR than the baseline engine.

However, multi-parametric optimization reduces the fuel consumption and the size of the engine at the design point having 10668m altitude and 0.85 Mach number. The study shows GE90 can perform better with hydrogen fuel rather than hydrocarbon fuel in terms of thermodynamic performance and aerodynamic performance, which ultimately leads to green aviation having less harmful emissions for future aircraft.

6.2 Future Prospects

This study presents the comparative analysis between hydrogen fueled GE-90 engine on the existing model and design and an optimized design. The optimization is multi-parametric including mass flow rate, TIT, BPR, FPR, LPC pressure ratio, HPC pressure ratio to get the optimal results of the hydrogen fueled GE-90 engine.

There is a very little research in the combustion dynamics of hydrogen fuel for aero engine combustor and to analyze its effects on the turbomachinery and other thermodynamic parameters. They can be found by doing the off-design analysis by varying the altitude and varying the thrust of aircraft. Under the different conditions a complete compressor chart and turbine chart can explain that either compressor and turbine are stable or not. Further, hydrogen fuel can be incorporated on different spool configuration and a comparative analysis can be performed on effects of hydrogen fuel combustors on different sizes of engines and aircrafts.

Acknowledgment

Firstly, I would like to thank Allah Almighty for providing me knowledge, determination, opportunity, and strength to complete this venture. Without His blessings, all of it would not have been possible.

I would like to express my gratitude to my supervisor Dr. Majid Ali and co supervisor Dr. Adeel Javed for allowing me to conduct my thesis under their supervision.

I also want to thank my GEC committee members Dr. Mustafa Anwar, and Dr. Hassan Abdullah Khalid. I feel proud and honored that you have accepted to be on my committee.

Finally, and most importantly, I express my profound gratitude to my parents Mr. & Mrs. Prof. Muhammad Ijaz for providing me with unfailing support and continuous encouragement throughout my years of study and through the process of researching and writing this thesis.

Appendix

A.1 Publication 1

Multi-Parametric Optimization and Gas Path Analysis of a civil Turbofan Aero-engine Incorporating Hydrogen Fuel for Sustainable Aircraft Applications

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Abstract

With growing environmental concerns, hydrogen is being promoted as a clean fuel of the future for sustainable aircraft application. In this context, a multi-parametric optimization and gas path analysis of a civil turbofan aeroengine operating on hydrogen fuel has been presented in this paper. Key design parameters including the bypass ratio, fan and compressor pressure ratios, turbine inlet temperature, and mass flow rate of the air have been evaluated in GasTurb software to obtain an optimal performance and gas path design of the aeroengine. A comparative analysis has been performed between the baseline hydrogen fueled turbofan (based on the General Electric GE90 high-bypass turbofan) and the optimized hydrogen fueled turbofan aero-engines at cruise condition as design point. As a result, the optimized hydrogen fuel-based turbofan aero-engine delivered a 4.88% decrease in thrust-specific fuel consumption and an increase in thermal efficiency by 5.53%. Furthermore, an optimized gas path for an aeroengine operating on hydrogen fuel exhibits a 6.35% smaller core area and a shorter engine length by 10.84% compared to the baseline. A theoretical and engineering platform for design and evaluation of hydrogen fueled civil turbofans is thus established

Keywords: Civil turbofan aero-engine, sustainable aircraft, hydrogen fuel, gas path design, multi-parametric optimization, modeling, and simulation

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