DESIGN AND PRODUCTION OF A TURBOJET ENGINE FOR VARIED APPLICATIONS

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MPhil

2020

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This thesis was submitted to the

DEPARTMENT OF NUCLEAR ENGINEERING,

SCHOOL OF NUCLEAR AND ALLIED SCIENCES

UNIVERSITY OF GHANA

By

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(10279262)

In partial fulfilment of the requirements for the degree of

MASTERS OF PHILOSOPHY

in

NUCLEAR TECHNOLOGY APPLICATIONS IN PETROLEUM AND MINING INDUSTRIES

October, 2020.

DECLARATION

This thesis is the result of research work carried out by Dzormeku Courage Etornam in the Department of Nuclear Engineering, School of Nuclear and Allied Sciences, University of Ghana, under the supervision of Dr. Andrew Nyamful and Dr. Seth K. Debrah.

I hereby affirm that, no part of this work has been presented in part or whole to any other University for the award of a diploma, or degree at any level. Accordingly, other works and/or researches done by other researchers cited in this work have been duly acknowledged under references.

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ABSTRACT

It is acknowledged that turbojets were built with the traditional objective to run aerospace machines. A Turbojet Engine is an air-breathing engine. It produces thrust by ejecting high-energy gas stream from the engine exhaust nozzle.

For a while now, Turbojet Engines do not only see operation in the air; they have also become highly essential on the ground. They are mostly used in generating electrical power in the Oil Fields, Mining Sectors and the Heavy Manufacturing Industries. Some Agricultural Industries employ the high heat energy generated from the nozzle of a Turbojet Engine as heat source for drying purposes.

Software tools for designing and fabricating machines were some of the major tools used in this project for the construction of the Turbojet Engine. The built Turbojet Engine generated a maximum Thrust of 3.5N, at 100000 Revolution Per Minute (RPM) at a Temperature of 780^{O}C.

DEDICATION

I dedicate this work to the Glory of God Almighty, my mother Miss Dzikunu Bernice Justine, My siblings Jessica and Joan, all friends and loved ones.

ACKNOWLDGEMENTS

My utmost gratitude is to Jesus Christ for His Grace, Favour and Leadings throughout my studies.

The Ghana Atomic Energy Commission (GAEC) and Leadership of School of Nuclear and Allied Sciences are herein acknowledged for granting me access to the Mechanical workshop of GAEC for my research work.

Profound thanks to my supervisors, Dr. Andrew Nyamful, and Dr, Seth Kofi Debrah all of School of Nuclear and Allied Sciences for their guidance and support. I would like to express my gratitude to Prof. Christian K. Dagadu, Dr, K. A. Danso and all lecturers of the Department of Nuclear Engineering for their advice and inputs.

To Mr. Emmanuel Amoakohene of the Nuclear Application Centre (NAC), all Non –Destructive Testing (NDT) staff members and Mr. Kwadwo Asamoah Manu for the skilled assistance.

Lastly, to all family and friends, I say a big thank you for their kind gestures. God bless you all.

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NOMENCLATURE

Symbols		**Units**
Roman Letters		
P	Pressure	[N/m^2]
Mτ	Shear stress	[N/m^2]
V	Velocity	[m/s]
Qin	Heat transfer rate	[J]
V_i	Axial Velocity	[m/s]
$C_{\theta 2}$	Absolute tangential velocity	[m/s]
ρ	Air flow density	[Kg/m^3]
I_{sp}	Specific Impulse	[-]
T_{sp}	Specific Thrust	[N]
M	mass	[g]
T_0	Ratio of total temperature (degrees celcius)	[℃]
H_c	Combustion Chamber Height	[m]
g	gravitational acceleration	[m/s^2]
A_e	Exit Area	[m^2]

D_i	Inducer diameter	[mm]
H_t	Theoretical head pressure	[N/m^2]
D_c	Compressor diameter	[mm]
Y_{th}	Theoretical specific supply	[-]
F_n	Thrust	[N]
A_1	Cross sectional Area	[m^2]
P_e	Pressure at exit	[Kpa]
v_e	Velocity at exhaust	[m/s]
P_a	Atmospheric pressure	[Kpa]
v_a	Atmospheric Air Velocity	[m/s]
Wc	Compressor shaft power consumption	[J/s]
M	Mach Number	[-]

Greek Letters

γ	specific heat capacity	[J kg^{-1}K^{-1}]
α , β, γ	Constants for number of holes in combustion chamber zones	[-]
η	Thermal efficiency	[kJ/kg]
ω_1	relative velocity	[m/s]

η_p	Propulsive efficiency	[-]
η_{ov}	Overall efficiency	[-]
c_1	Absolute velocity	[m/s]

CHAPTER 1

INTRODUCTION

Turbine engine is a rotary device driven by gas (SKYbrary, 2017). Its characteristic high-energy output is used to power aircrafts, hovercrafts (Takebe et al., 1977), speed trains, speed boats (Mills et al., 1960) etc. Jet engines are air-breathing devices. They are mainly made up of three sections, compressor section, combustion section and the turbine section (Cosmos, 2020).

Jet turbine engines have several configurations, turbofan, turboprop, turboshaft and the turbojet engines. Though jet turbine engines have different configurations, their operations are governed by the same thermodynamic cycle (the Brayton cycle) and Newton's Laws of motion (Jim Rauf, 2019).

1.1 General Concept

Jet engines can be classified as internal combustion engines. They are known for their characteristic high force generation (Prabjot Singh Virdi et. al., 2017). They produce much heat energy as a result of the heavy burning taking place within the combustion chamber. Some of the energy generated by the turbine is used to drive the compressor through a crankshaft and the rest of the energy used as thrust (Dennis G, 1956; Gordon C. Oates, 1985).

1.1.1 Air inlet vent

The air intake (Figure 1.1) where the inducer is located serves as the channel through which ambient air is drawn into the compressor section.

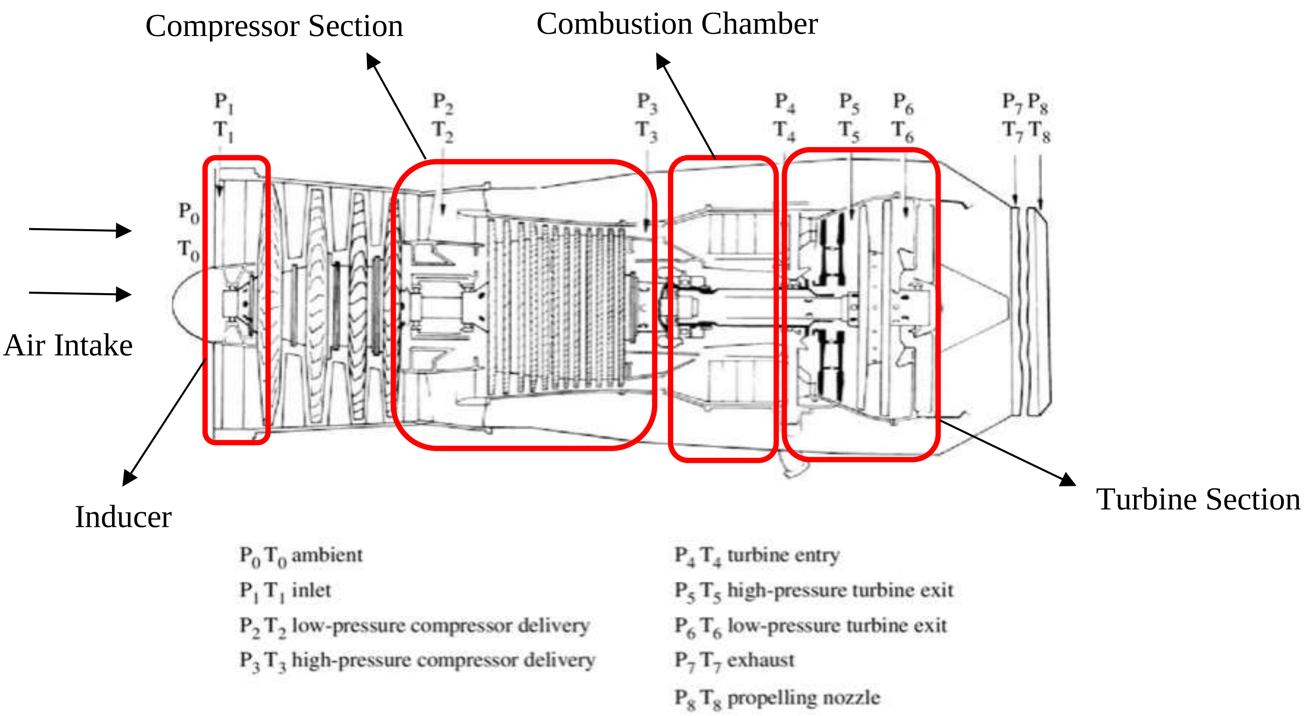


Figure 1.1: Schematic diagram of a turbojet engine (source: researchgate.net)

1.1.2 Compressor section

Air admitted via the inducer is highly compressed by series of compressor blades. The compressed air is directed by the stator vanes into the combustion chamber (Cosmos, 2020).

1.1.3 Combustion Chamber

The compressed air introduced from the compressor section is mixed with fuel and ignited. The ignited hot gas expands with very high force (Cosmos, 2020).

1.1.4 Turbine Section

The high force generated as a result of the expansion of the ignited hot gas in the combustion chamber drives the turbine blades in the turbine section to generate thrust and this is known as “pushing power” of the turbojet engine (Cosmos, 2020).

1.2 Areas of Application

Offshore Oil fields, Mining sectors, Food processing industries and the Heavy manufacturing industries are the major areas where turbojet engines are used. Many Offshore Oil fields as well as the Mining sectors generate electrical power through the use of turbojet engines because of the characteristic high force associated with such engines (Offshore, 2017). However, in the Heavy manufacturing industries, turbojet engines are used to run high speed trains, speed boats (Mills et al., 1960), aircrafts and hovercrafts (Takebe et al., 1977). Some Food processing industries make use of the high heat energy produced from the nozzle of a turbojet engine as heat source for drying purposes (Plant Engineering, 2015).

1.3 A Brief History

Dr. Hans Von Ohain and Sir Frank Whittle are recognized as being the co-inventors of the jet engine. While Von Ohain is considered the designer of the first operational turbojet engine, Whittle was the first to register a patent for his schematics of a prototype in 1930. Von Ohain obtained a patent for his prototype in 1936, and his jet was the first to fly in 1939. Whittle’s jet took off for the first time in 1941 (Bellis, 2019).

1.4 Problem Statement

There has been a great absence of skills for designing and building turbojet engines in the developing countries. The acquisition of this expertise would create jobs and grow the economy of these developing countries.

1.5 Objective

The main objective is to design and build a portable and economical turbojet engine that works under optimal conditions.

1.5.1 Specific Objectives

- To design a turbojet engine with SOLIDWORKS, a Computer Aided Design (CAD) software.
- To build a fully operational turbojet engine
- To establish optimal working conditions by using accurately measured parameters.

1.6 Justification

Our economy is many at times dependent on imported fuel, for this reason building a turbojet engine that runs on different fuels would take away over dependence on a single fuel type. This bring a variety in choice of fuel when certain fuel types are in scarcity (Brainkart, 2021).

Many communities in Ghana are divided by water bodies, this makes movement a great challenge. Producing a turbojet engine that runs a hovercraft and speedboats would help transport people and goods safely (Afukaar et al., 2017).

1.7 Scope of Research Work

The thesis is divided into five (5) sections. The first chapter gives an overview of jet engines, their mode of operation, areas of application, brief history on the evolution of jet engines, problem the research seeks to remedy, the objective and specific objective for research work and justification for the thesis work.

The second chapter which is the literature review outlines in detail history, concept of turbojet engine's working cycles and mechanics of operation, the engine performance parameters and how they are affected by the varying engine operation conditions; the various engine components and their varying types, the fragmented engine systems and most importantly related works by other researchers on turbojets (gas turbines).

The chapter three is the Methodology, and this describes techniques, tools, materials and tests conducted through the design and fabrication processes. The various governing equations for the design and component fabrication were also outlined.

The fourth chapter which is the Results and Discussion session shows the outcome from the methodology, the expected results and accomplished objectives stated in chapter one, that includes the outcome from the design and production phase of the research.

Chapter five entails the conclusion drawn from the design and fabrication of the turbojet engine. A brief introduction of the thesis, the accomplished objectives and how these results would meaningfully impact society. It also presents the recommendations made for future research work.

CHAPTER 2

LITERATURE REVIEW

This chapter reviews the development and important concepts of turbojet engines. It highlights the working cycles and mechanics of operation, engine performance parameters and how they are affected by the varying engine operation conditions. The various engine components and their varying types, the fragmented engine systems and their communal effort to full engine functionality are also presented. Finally the chapter reports on related works by other researchers on turbojets (gas turbines).

2.1 Background

To touch briefly on the subject concerning jet engines (i.e. turbojet emanating from jet engines), it goes way back into time when Leonardo da Vinci in 1500 developed a paddle wheel that was driven by channeling hot air to rotate a barbecue spit (Klause Hunecke, 2003). Then came Giovanni Branca an Italian engineer who developed a turbine wheel running on a steam jet (Klause Hunecke, 2003) afterwards, Sir Isaac Newton also came up with the laws of motion, these laws became the basis for all the recently developed jet propulsion machines. These laws include:

- **First law of motion;** a body remains at rest, or motion of constant velocity in a straight line, until an external force acts on the body.
- **Second law of motion;** the net force acting on a system equals the product of the system's mass times acceleration produced by the force.
- **Third Law of motion**; to every action on a body, there is an opposite and equal reaction on that body along the same line of action as the original force.

Scientists who applied these laws for jet propulsion work include; Swedish Patrik de Laval in 1883, French Armangaud Brothers in 1898, German Hans Holzwarth in 1908, French engineer Lorin in 1913, American Sanford Moss in 1918 and British Frank Whittle in 1930 (Klause Hunecke, 2003).

Today Jet engines (gas turbines) have become one of the world's sources of economic development as a result of the diverse fields of its application.

2.2 Engine Classification

There are various models when it comes to turbine engines, but these models operate with similar principles. Their diversity boils down to the range of task for which the engineer requires it to accomplish. There are basically four types of turbine engines; turbojet, turbofan, turboprop and turbo shaft.

The turbojet, which is the main focus on which this research work is being done, is one of the earliest among propulsion engines. It is quite simple in design as compared to other engine types and comprises of the following components; a compressor, combustor and single or multi -stage turbine (Figure 2.1).

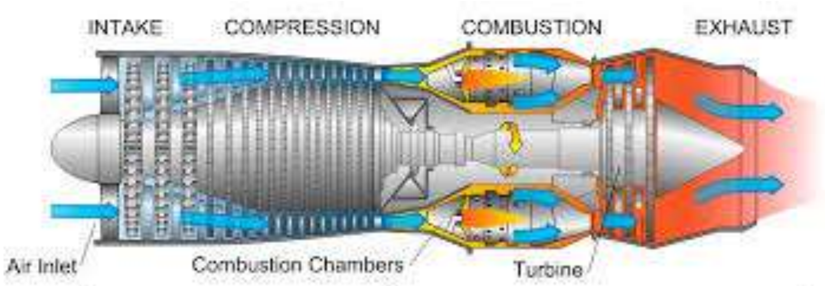


Figure 2.1: The Turbojet Engine [source: aerospaceengineeringblog.com]

The turbofan also called fanjet is a jet engine whose thrust is generated by jet core efflux and air accelerated by a fan that is driven by the jet core. It has an intake fan, compressor, combustor and a turbine (Figure 2.2).

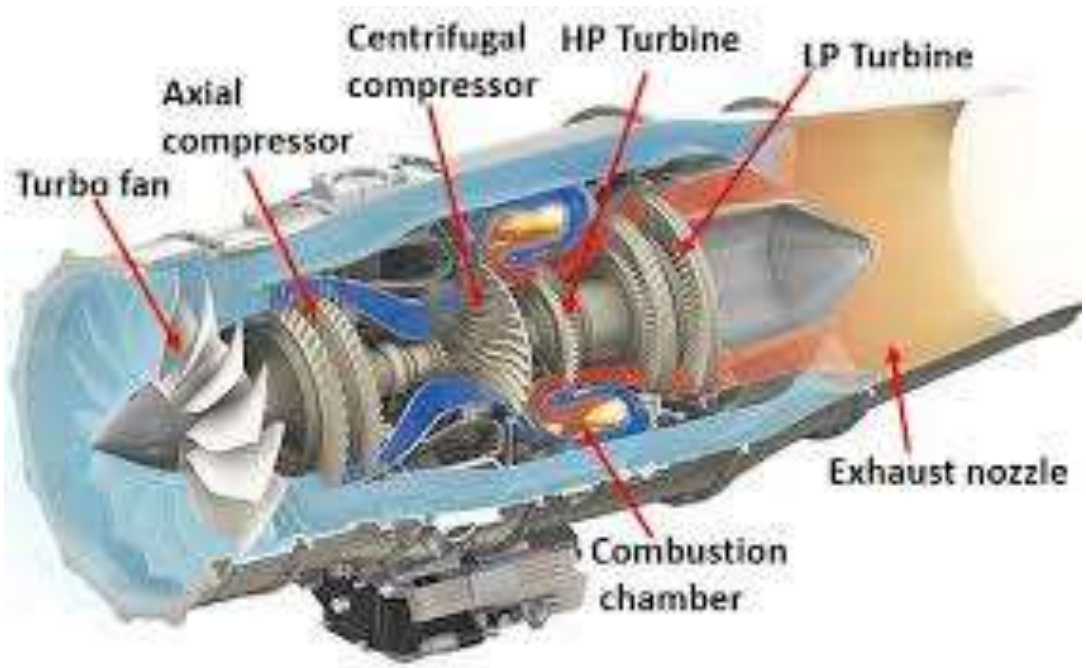


Figure 2.2: The Turbofan Engine (source: researchgate.net)

The turboprop is a type of jet engine with an inbuilt propeller. It has an intake, compressor, combustor, turbine and a propelling nozzle (Figure 2.3).

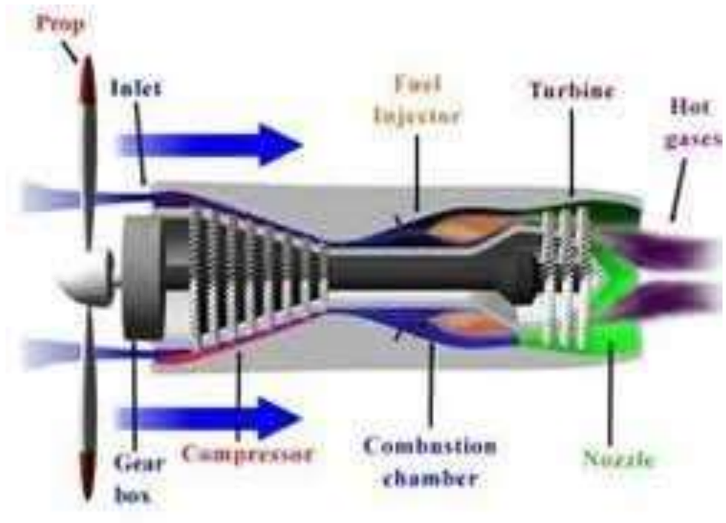


Figure 2.3: The Turboprop Engine (source: researchgate.net)

The turboshaft is a jet engine designed to generate shaftpower instead of a jet thrust. It is almost similar to the turbojet engine. As compared to the turbojet the exit nozzle of the turboshaft has a protruding shaft that provides the shaftpower required to move other machineries (Figure 2.4).

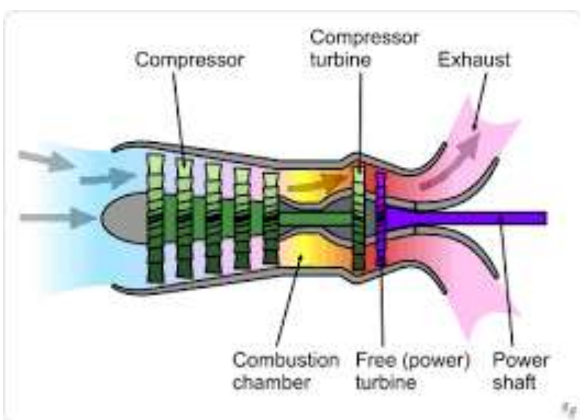


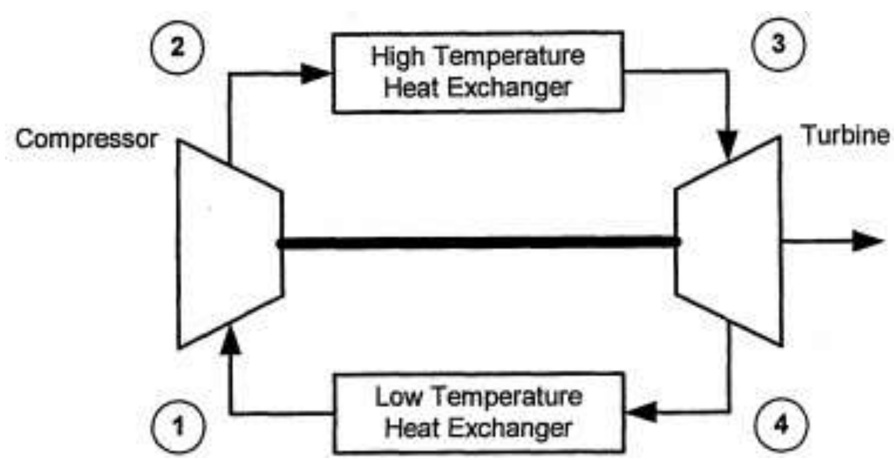
Figure 2.4: The Turboshaft Engine (source:dreameraviation.com)

2.3 Working Cycle and Mechanics

The turbojet engine's operation is regulated by certain principles; these principles are scientific in nature and serve as a guide for the utmost efficient running of the jet engine. These principles include the following; Newton's laws of motion (stated in 2.1), thermodynamic cycles (Brayton cycle and Carnot cycle), laws of conservation of energy and laws in fluid dynamics.

2.3.1 Brayton Cycle

The Brayton cycle or joule cycle or gas turbine cycle as it can be called makes use of gas as its working fluid and rotates it through four states as illustrated in Figure 2.5 and 2.6.



$= W_T \ + W_c$

Figure 2.5: The Ideal gas closed Brayton Cycle with states labeled (source: Keane T. Nishimoto, 2003)

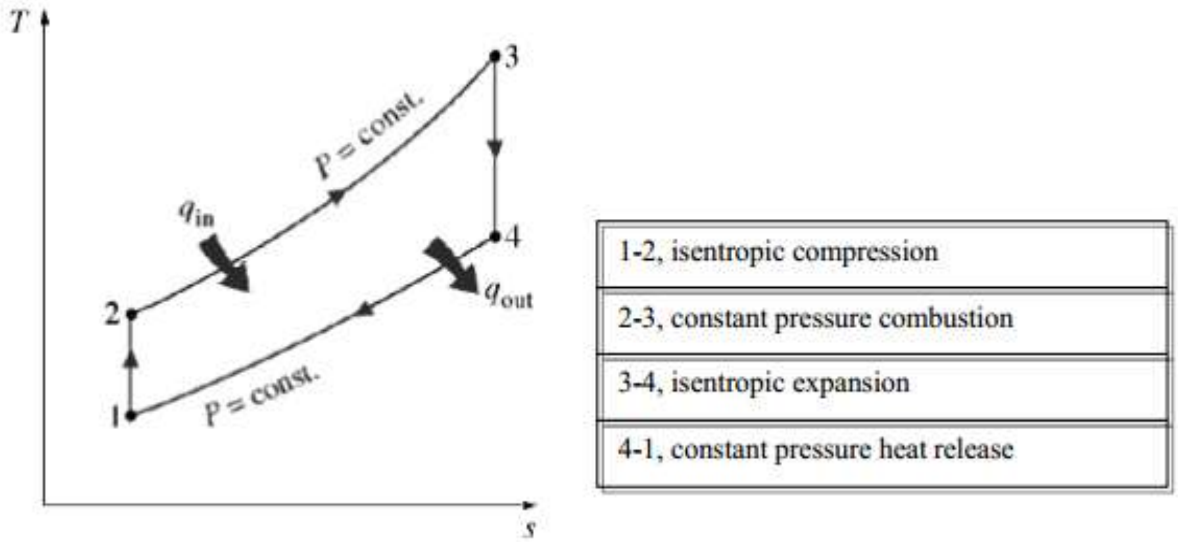


Figure 2.6: T-S diagram for the Brayton Cycle (source: Santosh Yarlagadda,2010)

The gas goes through an isentropic, adiabatic compression from state 1 to state 2 to highly raised conditions, pressure, temperature and density. There is addition of heat to the gas at a constant pressure by means of heat exchanger or a combustion procedure, this occurs from state 2 to 3. Afterwards the gas runs through to state 4 via an adiabatic and isentropic turbine, where there is a drastic fall in temperature and pressure causing the working fluid to expand.

Brayton efficiency can be denoted as:

$$\eta = \frac{Wnet}{Qin} = \frac{Wturbine + Wcompressor}{Qin} \qquad (2.1)$$

Where,

η = thermal efficiency of cycle,

Wturbine = turbine shaft power output,

Wcompressor = Compressor shaft power consumption,

Qin = Heat transfer rate in high temperature heat exchanger (Keane T. Nishimoto, 2003).

2.3.2 Laws in Fluid Dynamics

Fluid dynamics phenomena inform us that the flow passing through a tube can be steady or unsteady. When fluid parameters such as pressure, temperature, velocity stay constant at any point within a tube it depicts that the flow is steady. This parametric values may change from one point to another along the flow path but the general streamline pattern remains the same with time. Flow parameters remain constant everywhere during cruising flight moments of a jet engine. During discharge by compressor, high pressure of airflow, increased temperature and minimal velocity is experienced as a result of compression action. At the turbine, discharge parameters also remain constant, characterized by high temperature and velocity by lower pressure. When flow parameter within a cross-sectional area at any given point in time changes with time we consider the flow as unsteady (Klause Henecke, 2003).

2.3.3 StreamLine and Streamtube

When fluid in motion's path through a tube (exhaust nozzle) is viewed microscopically it is observed that they are composed of undoubtedly a large quantity of molecular particles in motion. We observe their movement along streamlines. Streamtubes encapsulate streamlines moving through closed curves transverse to the flow. In this case we can describe a streamline as a tube possessing gaseous walls in which fluid flows. Streamtubes behave like real tubes made up of everchanging particles at steady flow conditions. That is streamlines approach closer to one another as streamtube area decreases, indicating accelerating flow (illustrated in Figure 2.7). This is one phenomenom that occurs within the compressor, combustor, turbine and exit nozzles of the turbojet. Figure 2.7 shows occurrence in a convergent nozzle.

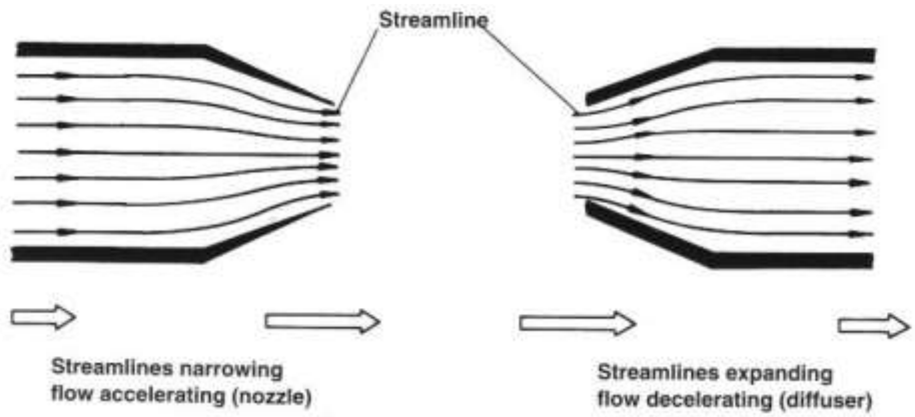


Figure 2.7: Occurrence in a convergent nozzle (source: Klause Henecke, 2003)

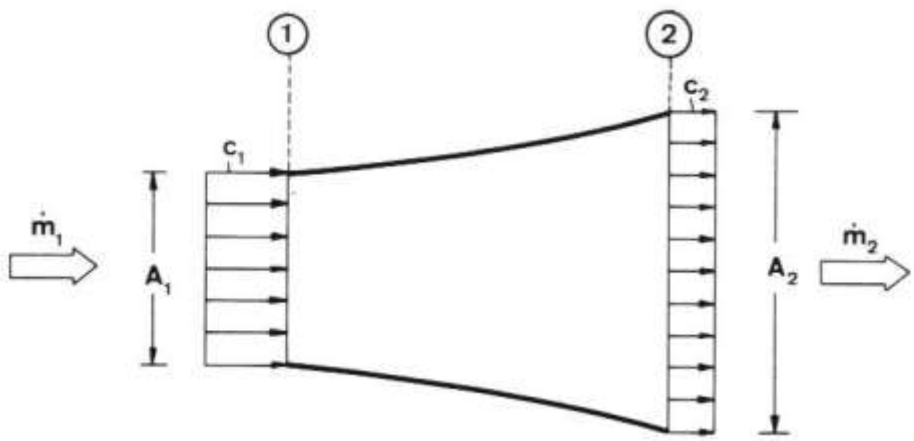


Figure 2.8: Occurrence in a convergent nozzle (source: Klause Henecke, 2003)

Contrary to occurrence in Figure 2.7, streamlines move from each other as cross-section area of stream tube increases (as shown in Figure 2.7), this indicates a decelerating flow normally associated with the diffuser.

2.3.4 Conservation of Mass

The law of conservation of mass states that mass in an isolated system is neither created nor destroyed as stated by Antoine Lavoisier (Lumen, 2020). This is a very good fact to determining the outcome of fluid flow behavior. The concept of streamlines is the most preferred in describing the continuity of matter in steady state fluid motion. Continuity of matter states; nothing passes from one step to another without passing through all the intermediate states (Farlex, 2020). That means fluid cannot varnish within a tube example an exhaust nozzle where it is seen as a streamtube, with respect to the reality of the continuity of matter in this case, flow characteristics in the exhaust nozzle can easily be calculated. We first assume fluid velocity v_1 is distributed across the inlet streamtube area A_1 (Figure 2.8). Fluid flow of Volume V per second, channeled to a streamtube of cross-sectional area A_1 produces a flow rate of:

$$\textbf{Flow Rate} = \boldsymbol{v_1 A_1} \qquad \textbf{(2.2)}$$

We obtain Mass flow rate ḿ by finding the product of the volumetric flow rate and density ρ

$$\acute{m}_1 = \boldsymbol{\rho_1 v_1 A_1} \qquad \textbf{(2.3)}$$

In the same manner, airflow leaving the tube is calculated:

$$\acute{m}_2 = \boldsymbol{\rho_2 v_2 A_2} \qquad \textbf{(2.4)}$$

From mass conservation law, mass flow rates are equal hence exhaust velocity υ_2 immediately follows;

$$\upsilon_2 = \frac{\rho_1}{\rho_2}\frac{A_1}{A_2}\upsilon_1 \quad (2.5)$$

Additional information is required on density ρ_2 at streamtube discharge. Example

$\rho_1 = \rho_2$ Incompressible flow meaning the density is constant

$A_1=2A_2$ twice the inlet area gives us the exhaust area

$\upsilon_2 = {}^{1}/_{2}\,\upsilon_1$ Our result is exhaust velocity is half that of inlet velocity (Klauce Henecke, 2003).

2.3.5 The working cycle of Turbojet

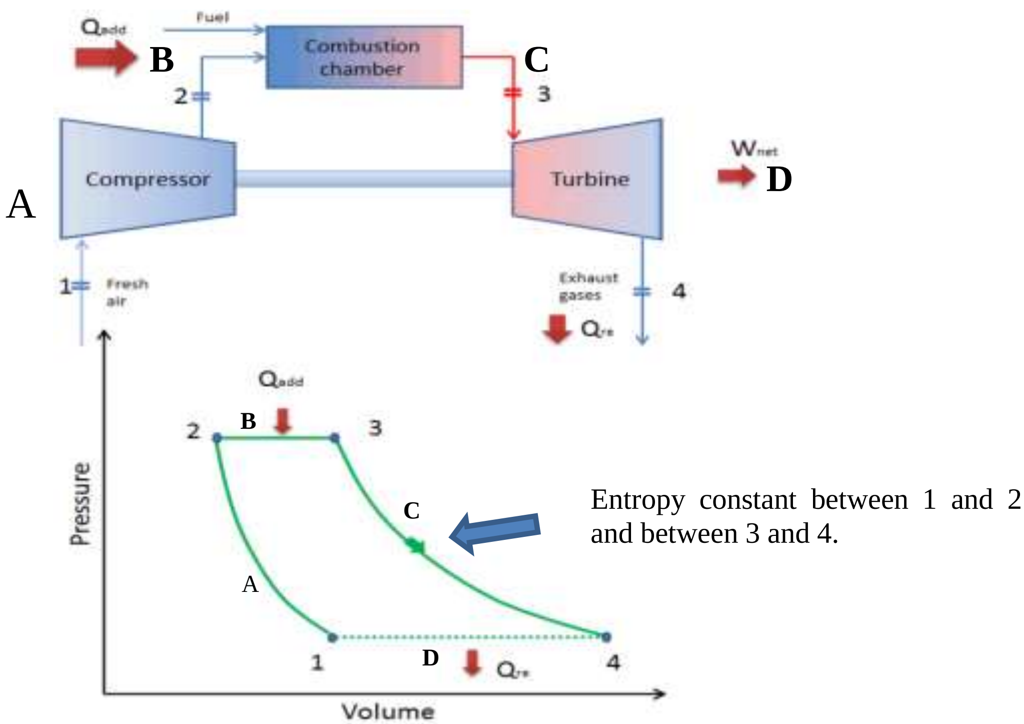


Figure 2.9: An Ideal Brayton Cycle Diagram (Nuclear-power, 2020)
NB: Net Workdone (W_{net}), Heat added (Q_{add}) and Heat released (Q_{re})(Figure 2.9)

Pressure Volume diagram in Figure 2.9 vividly represents the working cycle on which a jet engine operates. Point A which represents air found outside the intake or the inducer (opening into the compressor). This atmospheric air is drawn via the inducer and compressed along line AB which is the compressor. The combustion process is represented between B and C, at constant pressure there is burning of air and fuel mixture within the combustor, having a tremendous increase in volume of air admission. Loss of pressure in the combustor is seen in the drop between B and C. As the gases jet and expand out through the turbine and exit nozzle back to the atmosphere pressure totally drops between C and D meanwhile some of the energy from the gas at high velocity is converted into mechanical energy by the turbine for propulsive jet. Turbojet is a heat engine therefore the higher the temperature of the burning gas the greater the energy possessed by expanded gases. The application of air-cooled blades within the turbine accommodates higher temperatures and this produced the high thermal efficiency desired.

2.4 Engine performance parameters

Thrust or Specific thrust and specific fuel consumption are the main performance parameters an aircraft designer would be much concern with when it comes to accessing his engines' prowers. There are other parameters that can be considered to attain the goal of knowing the ultimate performance and efficiency of a turbine engine such as thermal efficiency, propulsive efficiency and overall efficiency can be computed to analyze engines' performance. The above mentioned parameters' values are always influenced by variation in pressure, volume and temperature of working fluid conditions.

2.4.1 Thrust

Thrust is basically the propulsive force generated by a jet engine driven machinery.

Calculation of the thrust is achieved using the following formula:

$$\textbf{Thrust} = (A * P) + \frac{Mvi}{g} \qquad \textbf{(2.6)}$$

Where A = Area of flow section in m^2.

P = Pressure in kg/ms^2.

W = Mass flow in kg/s.

$\boldsymbol{vi}$ = Velocity of flow in m/s.

g = Gravitational constant 32.2 $NKg^{-2}m^2$.

2.4.2 Specific Thrust

Specific Thrust is derived by the amount of output thrust per unit mass flow entering the engine.

Its unit is kN produced by 1 kg/s airflow:

$$T_{sp} = \frac{output\ Thrust}{per\ unit\ mass\ flow} \qquad \textbf{(2.7)}$$

2.4.3 Specific Impulse

Specific Impulse (I_{sp}) is one significant parameter that helps determine the amount of thrust produced for a given amount of fuel burnt. Specific Impulse is inversely proportional to Specific fuel consumption.

$$I_{sp} = \frac{\textit{Thrust force}}{\textit{Weight flow of fuel burned}} = \frac{T}{mfg} \qquad \textbf{(2.8)}$$

2.4.4 Specific Fuel Consumption (SFC)

This is the mass of fuel burnt per unit time per unit of output power of thrust.

$$SFC = \frac{\textit{Pounds of fuel burned per hour}}{\textit{Pounds of thrust}} = \frac{3600}{Isp} \qquad \textbf{(2.9)}$$

The SFC generally goes up us engine moves from takeoff to cruise, as the energy required to produce a pound of thrust goes up with increased percentage of stagnation pressure losses and with the increased momentum of the incoming air (Brian J. Cantwell, 2019).

2.4.5 Thermal Efficiency

Thermal efficiency (η_{th}) for jet engines is defined as the rate of addition of kinetic energy to the air divided by the rate of fuel energy supplied, usually expressed as a percentage. The energy in the jet is proportional to the difference in the squares of jet and flight velocities. Generally thermal efficiency increases as pressure ratio and temperature increase together, as these results in a higher jet velocity for a given energy input (Yalagandda, 2010).

$$\eta_{th} = \frac{\text{Increase in kinetic energy}}{\text{heat energy added}} \qquad (2.10)$$

2.4.6 Propulsive Efficiency

Propulsive efficiency (η_p) is the ratio of the propulsive power generated by the engine to the rate of kinetic energy addition to the air, expressed in percentage as:

$$\eta_p = \frac{F_N * V_o}{\text{Increase in kinetic energy}} \% \qquad (2.11)$$

Power is defined as force (F_N) times Velocity (V_o)

2.4.7 Overall efficiency

Product of the thermal and propulsive efficiencies of the engine gives us the overall efficiency (η_{ov}).

$$\eta_{ov} = \eta_{th} + \eta_p \qquad (2.12)$$

2.5 Engine Components

The turbojet engine is basically composed of the compressor turbine, combustion chamber and the turbine. These are the three main components, auxiliary components that form much essential role in the production of a turbojet engine include; the air intake, inducer and exhaust nozzle. (Klause Hunecke, 2003).

2.5.1 Air Intake

Airflow into the engine makes its way through this section first. The intake being the initial point for the engine operation is carefully designed to provide the appropriate amount of airflow which would be needed by the engine, and also ensures that the fluid allowed via the intake to the compressor is in uniformity with compressor design capacity, stable and of high quality. Intake design is dependent on the air intake process that the engine requires; either subsonic flow or supersonic flow; for this reason special attention is given to the intake design for effective correlation with requirements of engine.

2.5.1.1 Supersonic Flow

Supersonic flow is the experience a body has when moving through air faster than the speed of sound. This is vastly different as compared to what the same body would experience when flying at subsonic speed. One essential property of this nature of flows is it compressibility. The design of supersonic air intakes, there is the need to consider flow conditions over wedge and cone since these are simple geometric bodies and relatively easy to manufacture (Klause Hunecke, 2003).

2.5.2 Compressor

Compressor stands as one vital component when it comes to jet engines. As the air intake supplies mechanical energy (air) to the compressor hence resulting in the rotation of blades, this increases the pressure of the airstream; compressed air is then released into the combustion

chamber where combustion takes place at very high temperature. The compressor is designed to increase total pressure of the gas stream to the required optimum for the engine, meanwhile absorbs the minimum shaft power as well (Yalagadda, 2010). The performance parameters associated with the compressor are compressor efficiency, compressor total pressure ratio and air-flow rate.

Efficiency informs on the magnitude of energy supplied to the compressor from the turbine via the work of the rotor shaft and the ratio of the total pressure at compressor discharge and at compressor entry. The volume of airflow that the compressor easily processes per unit time is referred to as the airflow rate. The compressor is of two types the centrifugal-flow and axial-flow.

2.5.2.1 The centrifugal-flow

The model radial compressor was “made to measure”. It is built to be robust and easy to construct, this advantages makes it still a usable option (Thomas Kemps, 2004). The centrifugal-flow comprises of rotating impeller, a fixed diffuser and a manifold that receives and cycles compressed air coming from the intake inlet. It is also referred to as the radial compressor.

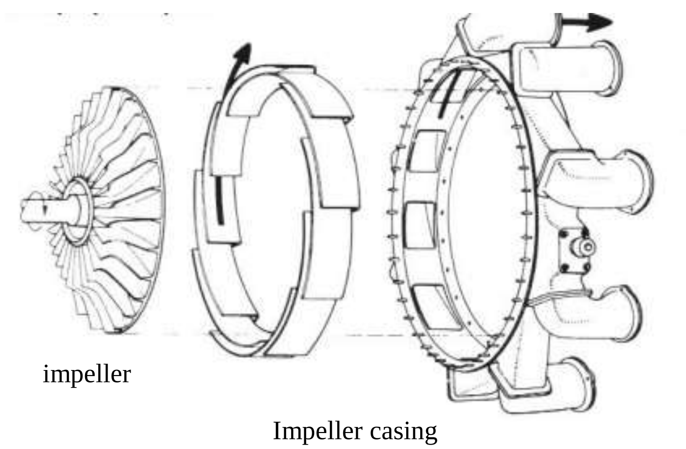


Figure 2.10: Components of a Centrifugal-flow Compressor (source: Klause Hunecke, 2003)

2.5.2.2 Axial-flow compressor

The axial-flow compressor is more renowned in modern generation engines, its preference to the centrifugal compressor is due to its ability to deliver high mass flow rates in conjunction with high pressure ratios at the same time, It is also useful internally, since the airflows in a uniform path avoiding the necessity of turning the flow, and externally, because its minor cross-section minimizes aerodynamic drag of the engine nacelle. It comprises of the following parts;

compressor front frame, compressor casing with stator vanes, rotor with blades and compressor rear frame.

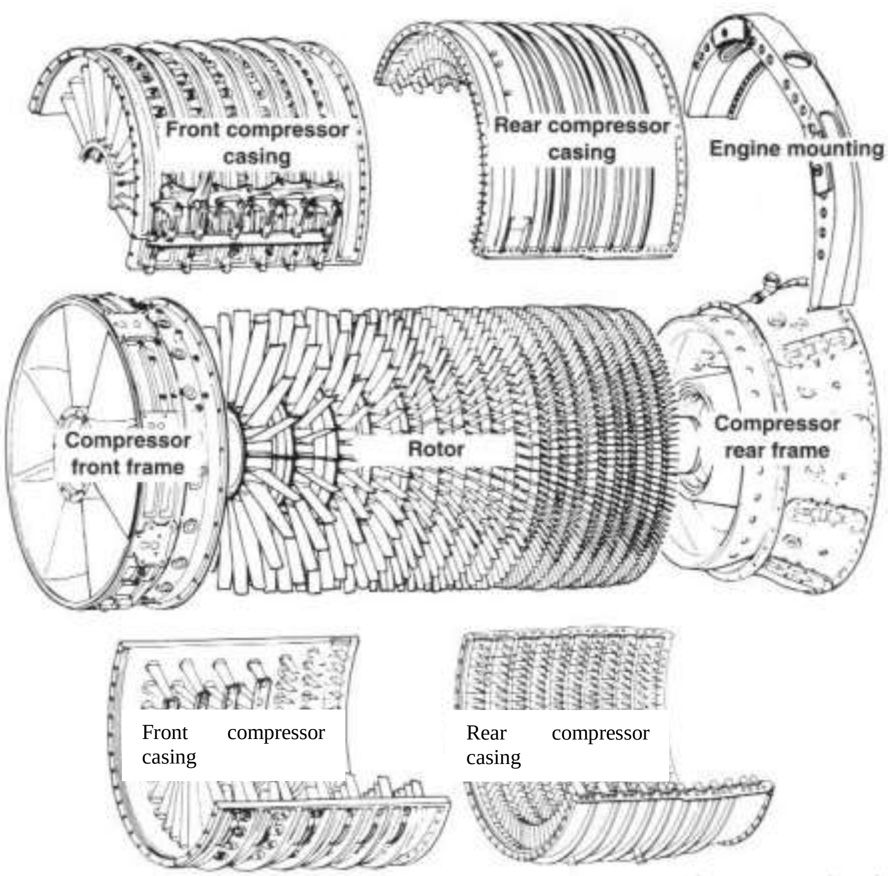


Figure 2.11: Axial Compressor Assembly (source: Klause Hunecke, 2003)

2.5.3 Diffuser

The diffuser is located right before the combustion chamber at the end of the compressor, it forms the divergent portion of the engine after the compressor. It reduces the velocity of the working fluid at high flow rate discharged from the compressor to a much lower velocity. This conditions the flow rate to a lower velocity, to cause the air arriving in the flame burning section of the combustor enhance a continuous burning of the combustion flame. A high velocity air discharged into the combustion chamber has a high tendency of extinguishing the flame.

2.5.4 Combustion Chamber

"Combustor" also referred to in gas turbines and jet engines. It is arguably the most sophisticated component to design among the components of a jet engine design. There are various various elements that needs keen monitoring, regulation and observation in order to get all parameters right. From derivation of holes in the inner casing (flame tube) to the ratio of air to fuel proportioning for flame combustion sustenance to accurate combustor size, all this are to be observed to eliminate the occurrence of flame extension into the turbine housing that would eventually damage turbine blades. Series of trials and tests are performed on the combustion chamber be ascertaining its reliability and efficiency.

The Combustor is basically made of an outer casing and an inner liner (flame tube).There are three types of combustion chambers; the can type, the can annular type and the annular type

2.5.4.1 Can Type

A substantial number of single burners are arranged radially around the axis of the engine. There is supply of air to each chamber by an air duct that links upstream to the compressed outlet.

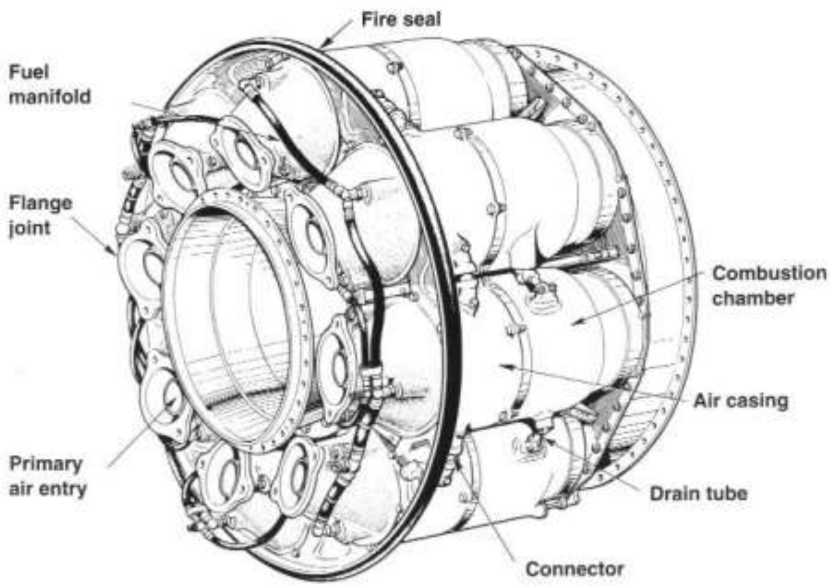


Figure 2.12: Circumferentially arranged Can-Type (source: Klauce Hunecke, 2003)

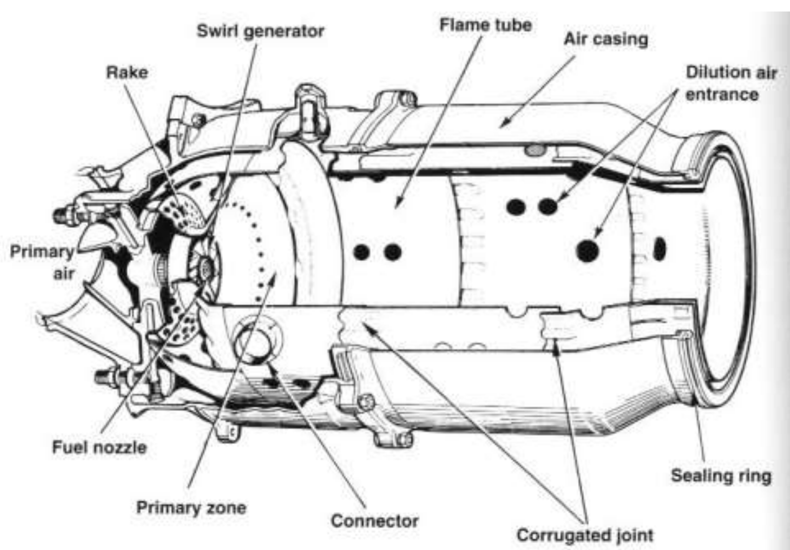
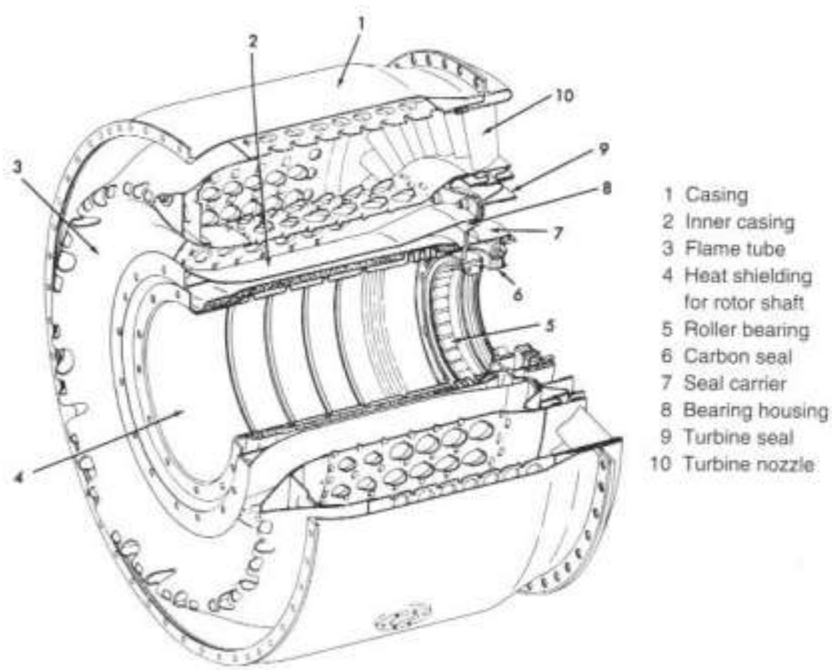


Figure 2.13: Typical Can-Type burner (source: Klauce Hunecke, 2003)

2.5.4.2 Annular or Basket Type

This type of combustion chamber, consists basically of a housing and a liner, and provides the efficient use of volumetric space. The spools are surrounded by a burner with single concentric tubes.



2.5.4.3 Can – Annular Type

Like the cFigure 2.14: Annular-Type Combustion Chamber (source: General Electric CJ610) this instance the rotor shaft housing being the axis. The burner section is concerned with a removable steel shroud.

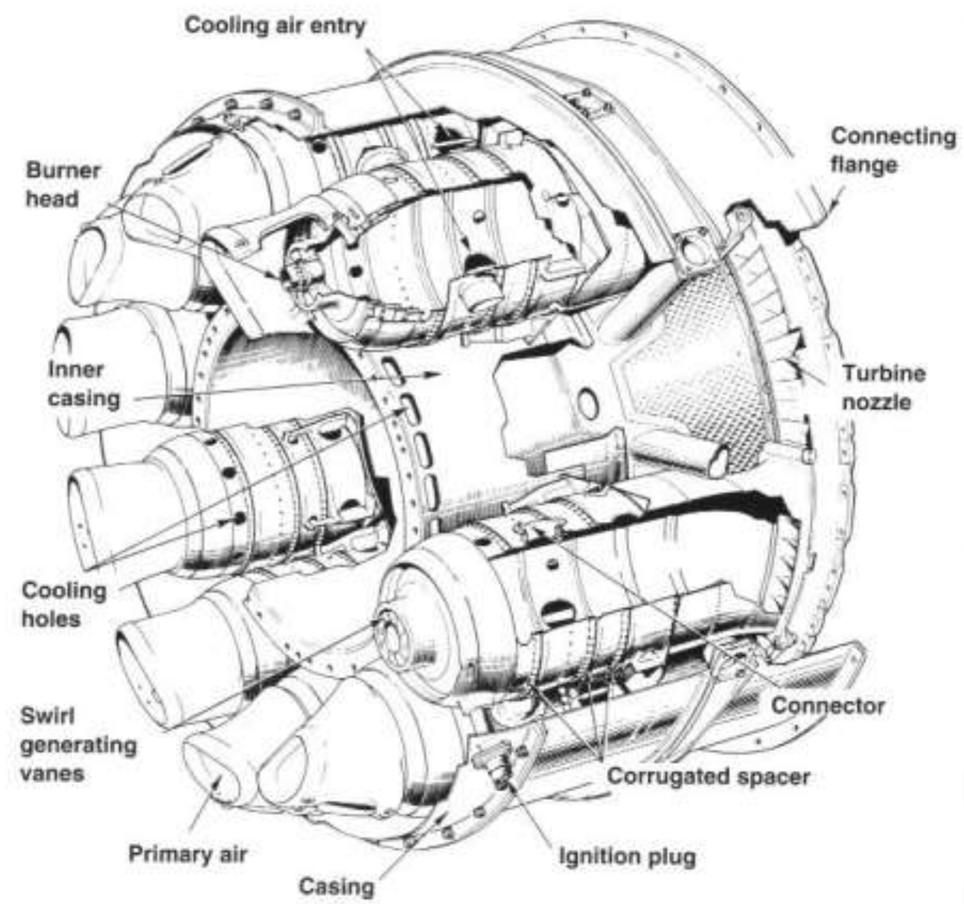


Figure 2.15: Typical Can-Type burner (source: Klauce Hunecke, 2003)

2.5.5 Turbines

The turbine is the final section of the engines structure. Here mechanical energy is generated from the kinetic energy of the hot exhaust gases released from the combustion system and expanding them to a lower pressure and temperature. The mechanical energy is then utilized to drive the compressor and accessories and in the case of engines which do not make use solely of a jet for propulsion, of providing shaft power for a propeller or rotor.

The process within the turbine involves high stresses and the turbine blade tips would require rotational speeds over 1,500 m/s, for efficient operation. Temperatures within the range of 850 and 1,700 degree celcius of constant movement of gas to which exposes turbine may reach a velocity of over 2,500 feet per second in parts of the turbine.

For generation of the driving torque, the turbine comprises of several stages each having a row of stationary nozzle guide vanes and a row of moving blades. These stages are dependent on the relationship between the power required from the gas flow, the rotational speed at which it must be generated and the diameter of turbine employed. The number of shafts, therefore turbines, varies with engine type. That is high compression ratio engines usually have two shafts, driving high and low pressure compressors. Some engine's driving torque is derived from a free-power turbine which allows the turbine to run at its optimum speed because it is able to operate solo without other turbine and compressor shafts.

2.5.5.1 Turbine blades

The conditions that are necessary to be factored when molding turbine blades will rightly guide us on the relevant choice of blade material. The red-hot blades should have the ability to manage the heavy centrifugal loads due to high speed rotation. A small turbine blade weighing only two ounces may exert a load of over two tons at top speed and it must withstand the high bending loads applied by the gas to generate the thousands of turbine horsepower needed to drive the compressor (Rolls Royce, 1996). Fatigue, thermal, corrosion and oxidation resistance are traits that should be associated with turbine blades. This is to ensure their utmost endurance during influence of high frequency fluctuations in gas conditions. Blades must be fabricated with materials that can be accurately modeled and machined by modern manufacturing methods.

2.5.6 Exhaust system

The modification of a turbine system is done with lots of factors to be considered. The exhaust system should be modeled to channel hot gases to the atmosphere to result in thrust, should be able to withstand high temperatures and pressure so the need for careful material selection for its fabrication. Jet propulsion is highly influenced by pressure and velocity erupting through the exhaust, this makes the exhaust fabrication and design a very instrumental portion in the jet engine design. Its areas and outlet nozzle affect the turbine entry temperature, mass air flow, velocity and pressure of the exhaust jet. Temperatures between 550 and 850^{o}C are associated with the gas entering the exhaust system (Rolls Royce, 1996). A basic exhaust system is shown in Figure 2.16.

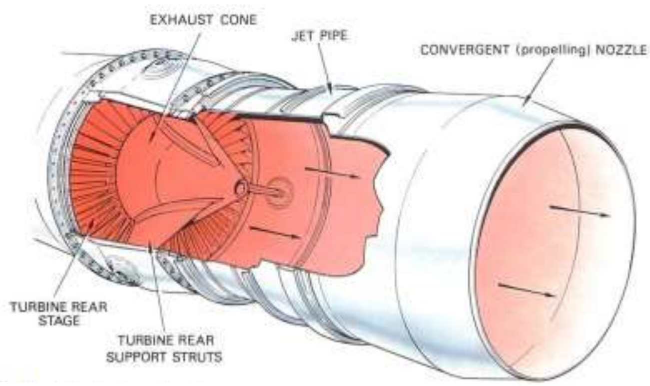


Figure 2.16: Exhaust system (source: Rolls Royce: 1996)

2.5.7 Lubrication

With the presence of gears, splines and bearings within the engine, lubrication becomes very necessary for engine efficiency. Lubrication removes the adverse effect of friction on the moving parts and cools system. It removes dirt within the system as well (Rolls Royce, 1996).

The lubricated components manufactured from non-corrosion resistant materials require oil protection as well. This task is accomplished by the lubricant without significant deterioration (Rolls Royce, 1996).

Most gas turbine engines by the mechanism of pumps use a self-contained re-circulatory lubrication system where oil is delivered through the engine and returned back into the oil tank. The total loss or expendable system is also applied by certain engines where oil is spilled out after it has gone through engine for lubrication (Rolls Royce, 1996).

2.5.7.1 Types of Lubricating Systems

"Pressure relief valve" system and the "full flow" system are the two basic re-circulatory systems. The only difference between these two systems is how control of oil flow to the bearings occur. In both systems the temperature and pressure of the oil are critical to the correct and safe running of the engine. Provision is therefore made for these parameters to be indicated in the cockpit (Rolls Royce, 1996). Below in Figure 2.17 and 2.18 is a pressure relief type of valve system and a full flow system.

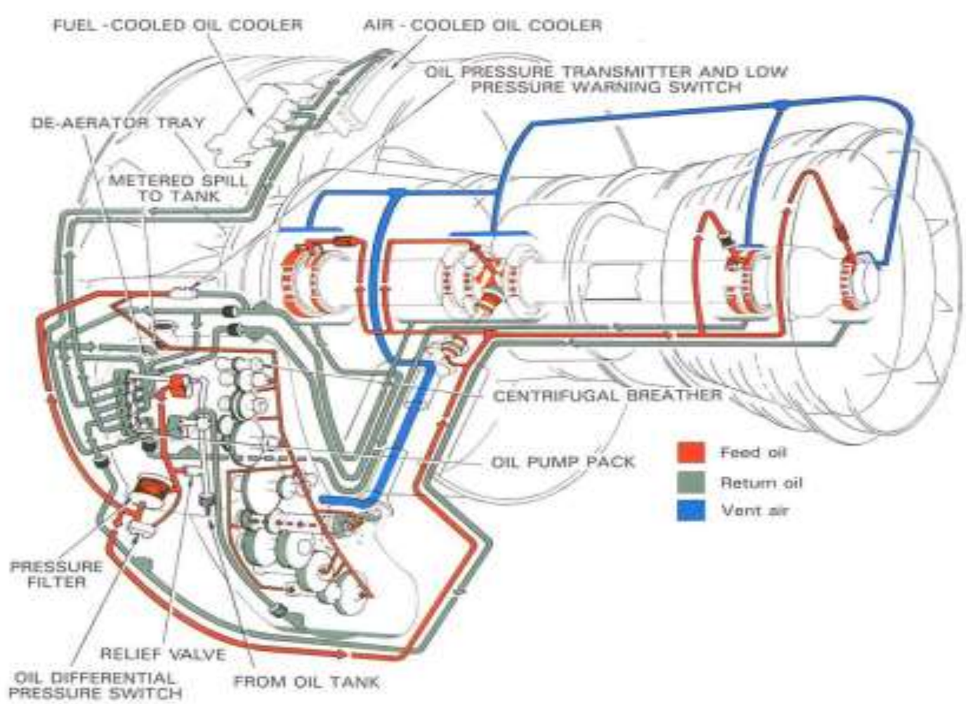


Figure 2.17: Full flow type oil system (source: Rolls Royce: 1996)

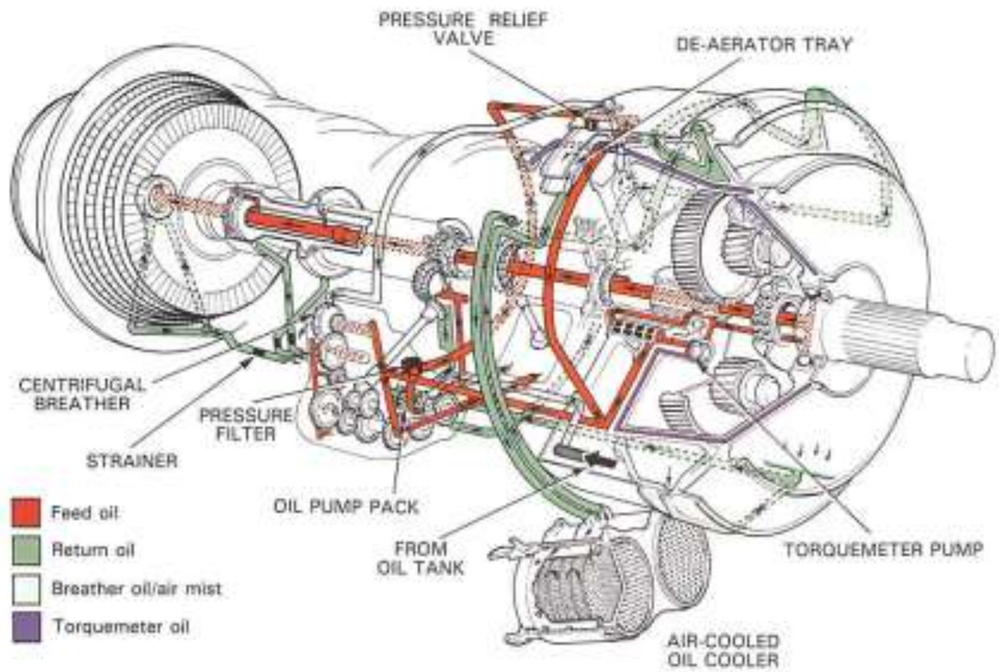


Figure 2.18: A pressure relief type of valve system (source: Rolls Royce: 1996)

2.5.7.2 Oil system components

The oil system normally comprises of an oil tank (Figure 2.19), oil pump, an oil filter and hose for oil channeling is normally an isolated unit even though it is an integral aspect of the lubrication system. It must have provisions to allow the lubrication system to be drained and replenished. A sight glass or a dipstick must be available to regularly check oil system contents. The filler can be either the gravity or pressure filling type. Since air is mixed with the oil in the bearing chambers, a de-aerating device is incorporated within the oil tank which removes the air from the returning oil (Rolls Royce, 1996).

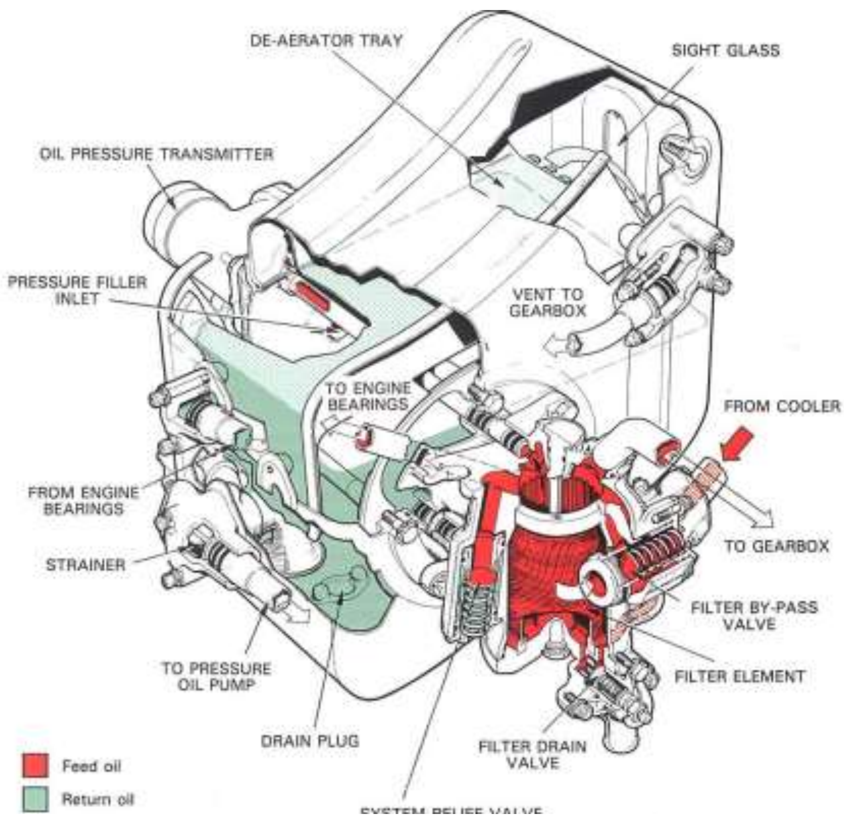


Figure 2.19: A well labeled Oil Tank (source: Rolls Royce: 1996)

The oil pump is the most significant aspect of the oil system, it absence results in an instant shutdown of the engine. For this reason, the oil pump's driveshafts do not incorporate a weak shear neck because they must continue to supply oil for as long as possible regardless of damage. During the distribution of feed oil to all the lubricated parts of the engine, a marginal amount of sealing air mixes with it, increasing its volume (Rolls Royce, 1996).

2.5.8 Fuel system

The fuel quantity that is released for combustion is controlled within the fuel system. There is the need to regulate fuel flow in order to have the proportionate ratio to air for complete combustion and to have operation of engine within safe temperature boundaries. The RPM of the compressor regulates the supply of air drawn into the combustion chamber and affects its density at the inducer. The fuel system is responsible for fuel supply to the engine in a suitable form to ensure complete combustion and regulate the flow required for ignition , acceleration and stabilized running, at all conditions of engine operation (Rolls Royce, 1996).

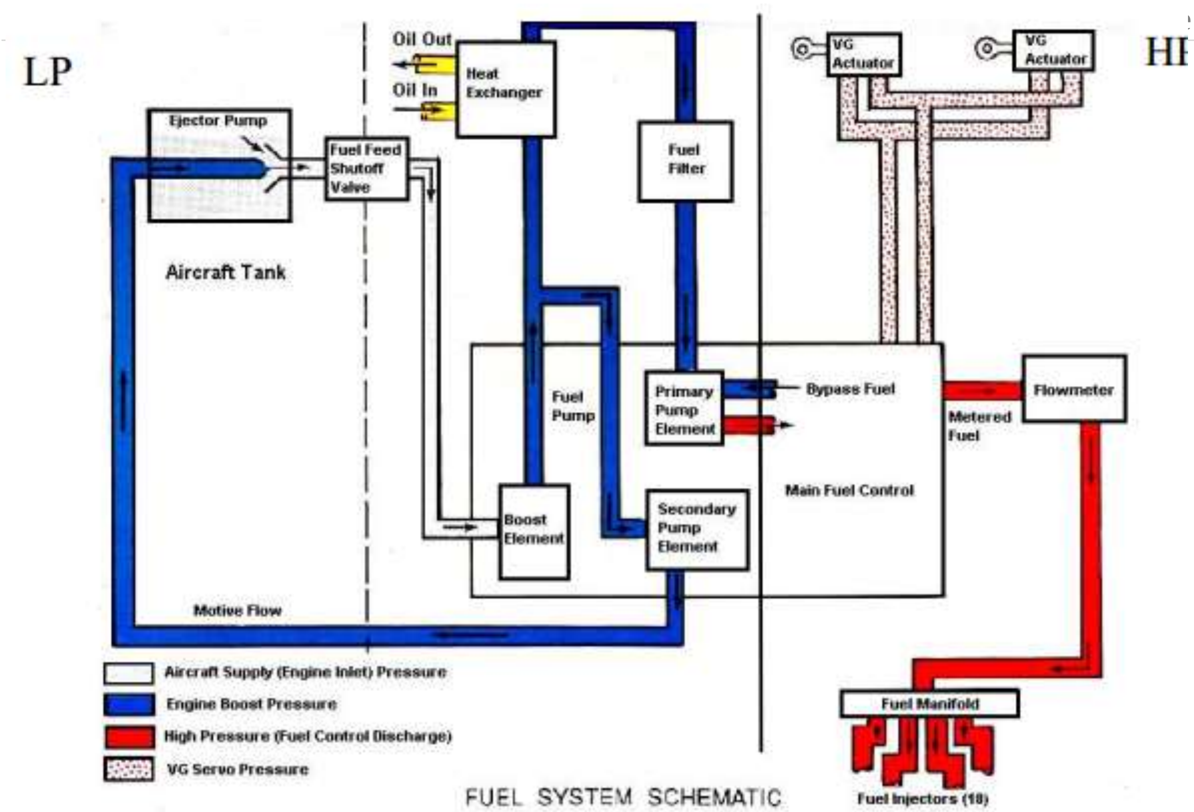


Figure 2.20: Fuel System Schematic Diagram (source: Rolls Royce: 1996)

For the occurrence in Figure 2.20, certain components are required in the fuel system's set up that include: a fuel pump to deliver fuel to the atomized spray nozzles that lead into the combustion chamber, a fuel shut off valve control lever that controls fuel movement from source through the fuel lines, installation of automatic safety devices as an emergency control system against engine gas temperatures, rotating assembly speed and compressor delivery pressures from exceeding their maximum limits. Fuel tanks are also used to store sufficient fuel for engine's operation. Fuel filter system (Figures 2.21 and 2.22) also plays an essential role of sieving foreign materials from entering the engine that would retard combustion and also end up clogging the fuel line (Rolls Royce, 1996). The fuel system setup is represented in Figure 2.20.

Figure 2.21: Fuel filter (source: Rolls Royce: 1996)

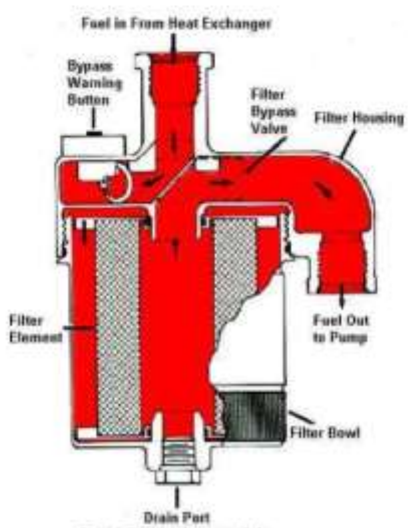


Figure 2.22: Fuel filter Assembly (source: Rolls Royce: 1996)

2.5.9 The Turbocharger Turbojet Engine

Compressor and turbine coupled by a solid shaft are embedded within a turbocharger. In a turbocharger turbojet engine, there is no need to separately build a compressor and a turbine since they are already assembled in the turbocharger. They serve same purpose and function as the axial compressor and turbine.

Hot air under pressure from the combustion chamber drives the turbine blades of the turbocharger and then discharges excess energy via the exhaust nozzle to generate thrust.

Since major turbojet engines produced in the early days consumed much fuel, turbochargers have been modeled as a single unit to minimize fuel consumption. Figure 2.23 shows a diagrammatic view of a turbocharger turbojet engine

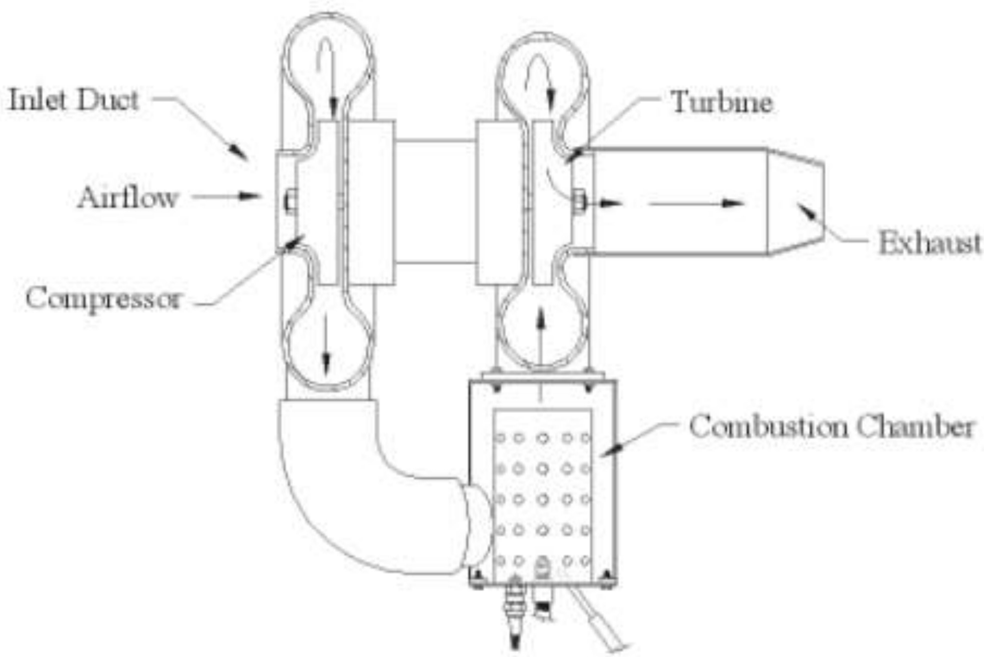


Figure 2.23: Diagrammatic View Of Turbocharger Turbojet Engine (source; Edwin H. Springer, 2001)

2.6 Related Works

Information available in literature on detailed design procedures for the major components of turbojet engine is very minimal. However, a few of the related findings from available literature are summarized below.

2.6.1 The MEMS Gas Turbine Engine Project.

Kang et al., (2004) worked on bilding a MEMS micro gas turbine generator quite similar to the MIT micro-engine project. They were focused on designing, building, and testing a turbocharger to characterize the performance of the turbomachinery. Their design also employs a **2-D** centrifugal compressor and turbine but contrary to the MIT design had the compressor and turbine placed on the same side of the rotor - with the compressor on the outside. The above procedure was employed to alleviate some of the challenges associated with the alignment of the two high speed rotors. Their design is also fabricated from six wafers, two of which are Pyrex glass (the second and fifth levels). The fabrication process relies on deep RIE, anodic bonding, and precision mechanical drilling and wet etching for the glass. For rotor dynamic support, the rotor relies on hydrostatic thrust bearings and a hydrostatic journal bearing. This device has been designed and fabricated and testing is underway. The similarity in this work to the work done in this thesis is the use of a turbocharger for the building of the turbojet engine.

2.6.2 The Micro machined Gas Turbine Generator Project

Isomura et al., (2002) developed a palm sized micro gas turbine. Their engine is not fabricated using MEMS techniques; instead it is made by 5-axis micro milling which produces fully 3-dimensional geometries. The engine consists of a turbocharger possessing a 10mm diameter centrifugal compressor, a combustor and a 10 mm diameter radial inflow turbine. The target cycle calls for a mass flow rate of 2 g/s, a compressor pressure ratio of 3:1, a combustion exit temperature of 1050 0C and is expected to have a thermal efficiency of 6% outputting 100 watts of electric power. The effort has been split into three separate categories. The first is the development of a micro turbocharger with a design rotational speed of 870,000 rpm. The second is the development of a micro combustor which can achieve stable self-sustaining combustion with appropriate thermal isolation. The third is the development of fabrication techniques for the turbines, which are required to operate at high temperatures.

The turbocharger consists of a compressor and turbine which are separated by a shaft. The entire rotor is made of titanium and both the compressor and turbine are fully 3-dimensional. The shaft relies on herring bone grooves for the journal bearing and a thrust disk with spiral grooves for thrust bearings. This hydrodynamic setup is accompanied by hydrostatic gas bearings that are only used during startup and stopping procedures.

For the combustor, two separate designs were examined: a doughnut shape combustor and a canister shape combustor. The doughnut shape design exhibited a higher heat loss and as a result the canister shape was selected for the baseline design. A 2 cc canister shape combustor was tested with hydrogen and achieved 99.9 %efficiency. The similarity in this work to the work done in this thesis is the use of a turbocharger for the building of the turbojet engine.

2.6.3 The Micro machined Gas Turbine Project.

Matsunaga et al., (2003) developed technologies to produce a 100 watt fist sized gas turbine. **T**he team built and tested a micro turbocharger with a centrifugal compressor and turbine. Two rotors designed to spin at **800,000** rpm **(500** m/s tip speed) were of 12mm in diameter. They are mounted back-to-back on a shaft which is overhung from a conventional ball bearing. The 3-dimensional size rotors were made from silicon nitride **by** employing a Mold **SDM** process developed at Stanford University. A compressor **2.38** g/s flow rate, a pressure ratio of **3:1** and an adiabatic efficiency of **65** % was designed. This device was successfully tested up to 420,000 rpm. Experimental compressor maps were developed and compared positively with **CFD** predictions. Due to its larger size it was possible to also include thermocouples to deduce efficiency which also compared favorably with **CFD** predictions. The device was not spun to higher speeds due to rotor dynamic instabilities. The similarity in this work to the work done in this thesis is the use of a turbocharger for the building of the turbojet engine.

2.6.4 The Ultra Micro Gas Turbines Project.

Nagashima et al., (2002) Developed of **a** button size gas turbine engine**.** The manufactured engine design consisted of a wave rotor with 8mm diameter centrifugal turbo machinery, a recuperator, and an ultra-thin-type generator. As part of the development process, the team also built and tested a **ten** times -size engine as well as the development of the components of the original size engine. The team has successfully demonstrated combustion in a canister type combustor for both the original size and **ten** times-size combustors using hydrogen as the fuel, achieving 1500K combustor exit temperatures. The team has built and tested ten times size turbines (3-dimensional and 2-dimensional) and compressors (qausi 2-dimensional). Finally, the team tested the entire **ten** times size engine design under ignition conditions but did not achieve self-sustained operation.

2.6.5 Satish Peruri et al, 2015 Theoretical design and mass modeling of a Single spool micro - Turbojet Engine suitable for drone and UAV propulsion.

Satish Peruri et al., (2015) designed a micro gas turbine. Analysis was performed on its turbine and compressor to find out the maximum stress and to estimate the total deformation. Using Titanium Alloy for turbine and compressor, the CFD analysis shows that the compressive yield strength and tensile yield strength is 930 MPa and 1070 MPa.

2.7 Conclusion Remarks

The chapter described the literature behind the turbojet engine make up; the background concept of turbojet engine's working cycles, mechanics of operation, the engine performance parameters and how they are influenced by engine operation conditions; the various engine components and their varying types, the fragmented engine systems and their communal effort to full engine functionality and most importantly related works by other researchers on turbojets (gas turbines).

CHAPTER 3

METHODOLOGY

The design tools, design procedures, equations applied, fabrication tools, fabrication techniques, equations governing fabricated parts, tests done on the fabricated parts and test procedures are well detailed in this chapter.

3.1 Turbojet Engine Design

The design for the turbojet engine fabrication was developed using SOLIDWORKS (2019) with interface illustrated in Figure 3.1. The software generates dimensions, allows input of equations and is capable of bringing together designed parts. With the help of this software, various parts of the engine were designed separately and assembled as one whole engine.

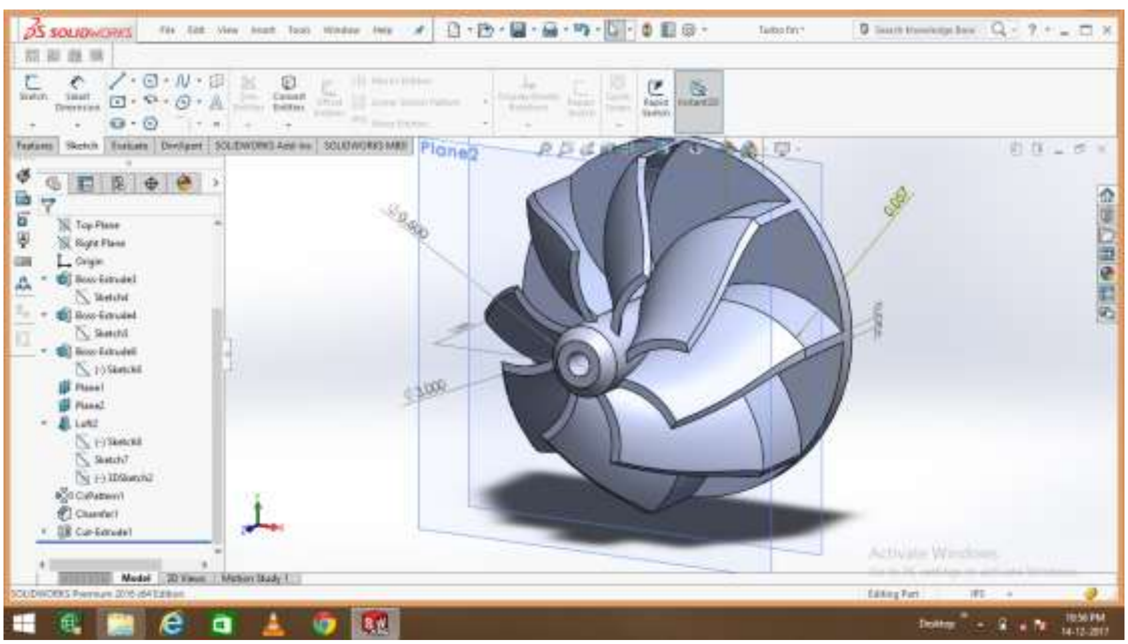


Figure 3.1: SOLIDWORKS Design interface of turbocharger impeller

JETSPECS software with interface illustrated in Figure 3.2, was used to design the flame tube.

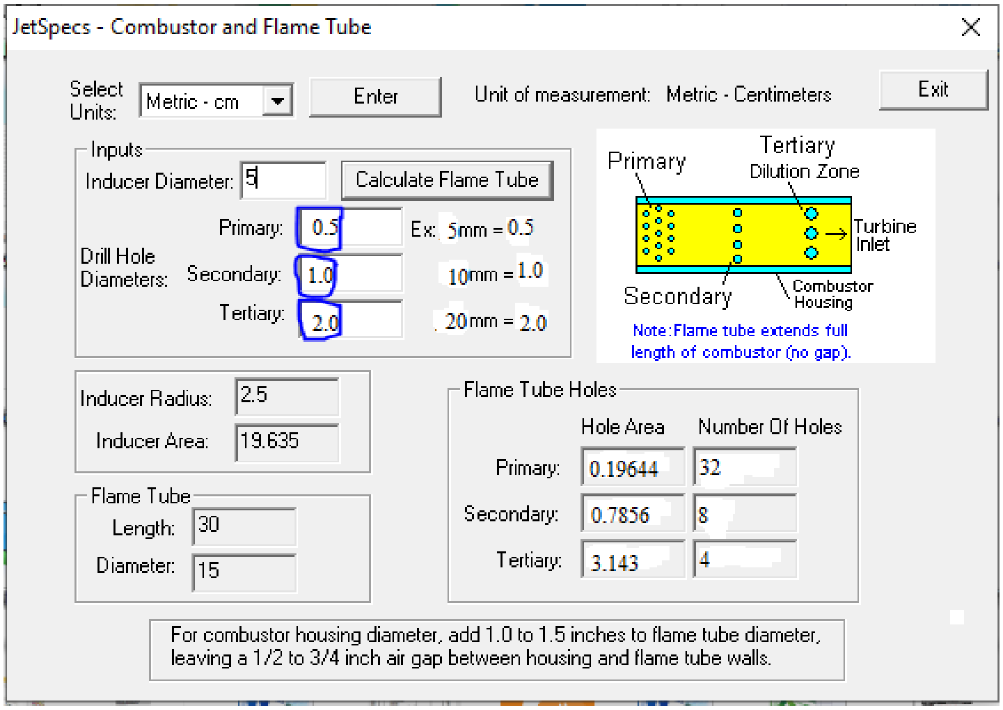


Figure 3.2: JETSPECS Design interface (Jetspecs 2018)

3.2 Materials and Tools Selection

The major metalwork tools used for the fabrication process are as follows;

- A Cutting disc,
- An Angle Grinding tool,
- A Lathe Machine of Bed width 580mm and length 2700mm,
- A 19mm Capacity Pillar Drilling Machine,
- A Stainless Steel Argon TIG Welding Machine,
- A sheet metal roller bending Machine and
- A Professional Single Horn Anvil.

The Materials selection for the fabrication was made with respect to thermal and corrosion resistance. A grade 316 Stainless steel plate able to withstand temperatures of up to about 927^0C and a Zebra Dura Transparent Clear Plastic Sheet of thickness 2.5mm used for pattern making were selected.

3.3 Selection of Turbocharger

Figure 3.3 shows the design of the turbocharger selected. The turbocharger has three main sections. The inducer section, compressor section and the turbine section. The inducer section (Figure 3.3), has inner diameter of 177.50mm. The compressor section houses a compressor impeller of diameter 100mm. The selected compressor impeller is made of cast aluminium. The turbine section comprises a turbine impeller of diameter 76.50mm. In this project, the turbine impeller is made of hastelloy C276 nickel alloy and can withstand temperature up to about 1093^0C.

In the operation of the turbojet engine, air drawn by the compressor impeller through the inducer, enters the compression section axially. This act of drawing air through the inducer into the compressor section axially by the compressor impeller is governed by Equation 3.2.

The drawn air after compression is released tangentially under very high pressure into the combustion chamber. The tangential release of compressed air at the ends of the compressor impeller under very high pressure into the combustion chamber obeys Equation 3.1.

Tangential velocity at inlet, $V_t = \frac{2\pi r}{t}$ (Toppr, 2021). (3.1)

Where, V_t is tangential velocity, **r** is radius of impeller and t is time

Axial velocity at inlet, $V_a = \tan(\alpha) * V_t$ (Sai Kiran, 2014). (3.2)

Where, V_a is Axial velocity and **α** is inlet blade angle.

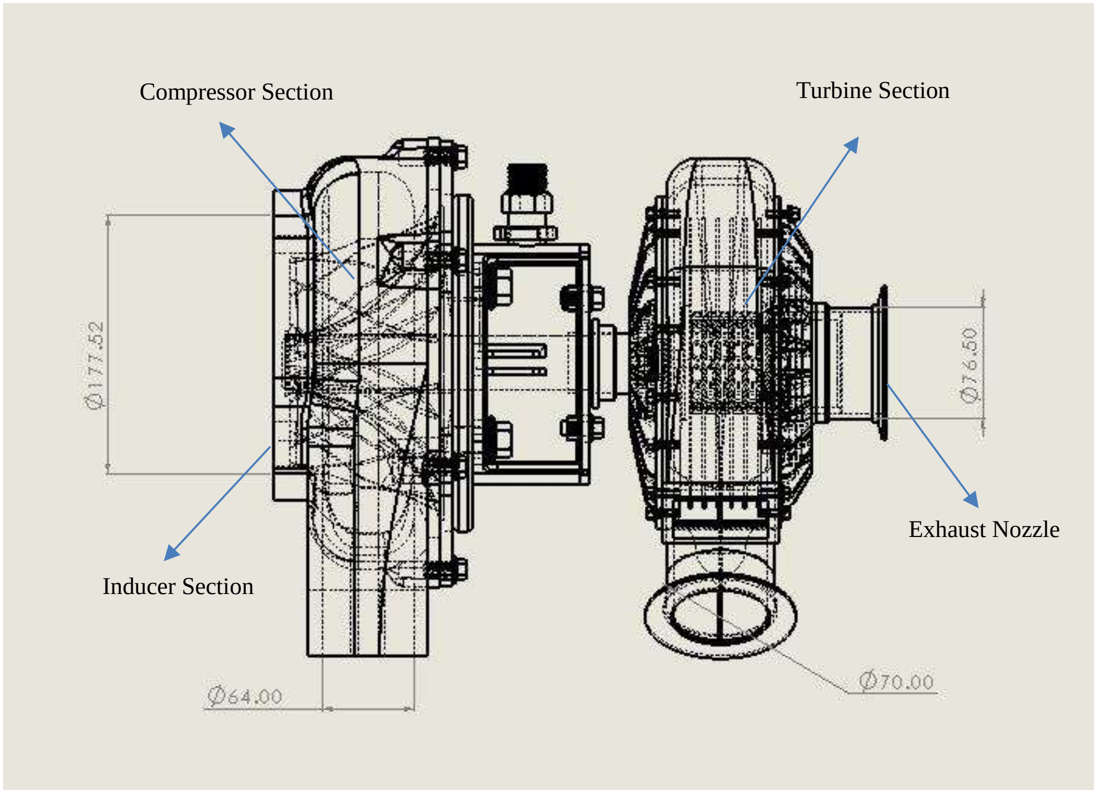


Figure 3.3: Design of turbocharger using SOLIDWORKS

3.3.1 Fluid Flow

The one-dimensional equations governing the flow of air through the inducer system are conservation of mass, conservation of linear momentum, and conservation of energy.

3.3.1.1 Conservation of Mass – Continuity

The one-dimensional continuity equation states that the mass must remain constant for steady, quasi-one-dimensional flows. This can be stated alternatively as the mass flow entering the system (Eqn 3.3) must equal the mass flow exiting the system (Leipmann, 2001).

Air flow density (ρ), Air flow velocity (u), Area of inducer (A)

$$\textbf{Flow rate} = \rho u A = \text{const} \tag{3.3}$$

3.3.1.2 Conservation of Linear Momentum

$$(\rho_2 u_2^2 A_2 - \rho_1 u_1^2 A_1) = (P_1 A_1 - P_2 A_2) + \int_1^2 P\,dA \tag{3.4}$$

Equation (3.4) takes into consideration flow of air at a compressed state via a one-dimensional duct where the area rises as a function of position having the air flow proceeding from a point to another point. The linear momentum equation at the left hand side details the change of inertial forces occurring via inlet towards the outlet and at the otherside of the equal sign the equation details the sum of the pressure forces having pressure force at the inlet to be P_1 A_1 and exit pressure force to be P_2 A_2. The integral indicates the force due to the pressure moving along the side of the body and is approximated by splitting the fluid body into many tiny fluid bodies and making a summation of the delta pressures and delta areas for each of the tiny pieces in the one dimensional model (Leipmann, 2001).

3.3.1.3 Conservation of Energy

$$H + \frac{1}{2} m u^2 = \text{const} \tag{3.5}$$

Where H represents Potential Energy.

When the flow is assumed to be adiabatic and have no shaft work, the energy equation reduces to the statement that the total enthalpy is constant (Eqn 3.5) (Leipmann 2001).

3.4 Combustion Chamber Design

The Combustion Chamber was the most critical part of the design of this gas turbine. The chamber had to be designed so that the flame is self - sustaining and the temperature of the products of combustion is sufficiently below the maximum working temperature of the turbine (Lauren Tsai, 2004). The Combustion Chamber or the Combustor which is primarily a pressure vessel was constructed from a grade 316 stainless steel plate. The Combustor consisted of an inner and outer hollow cylindrical tubes.

3.4.1 Design of the Outer Casing

The Outer casing design (Figure 3.4).

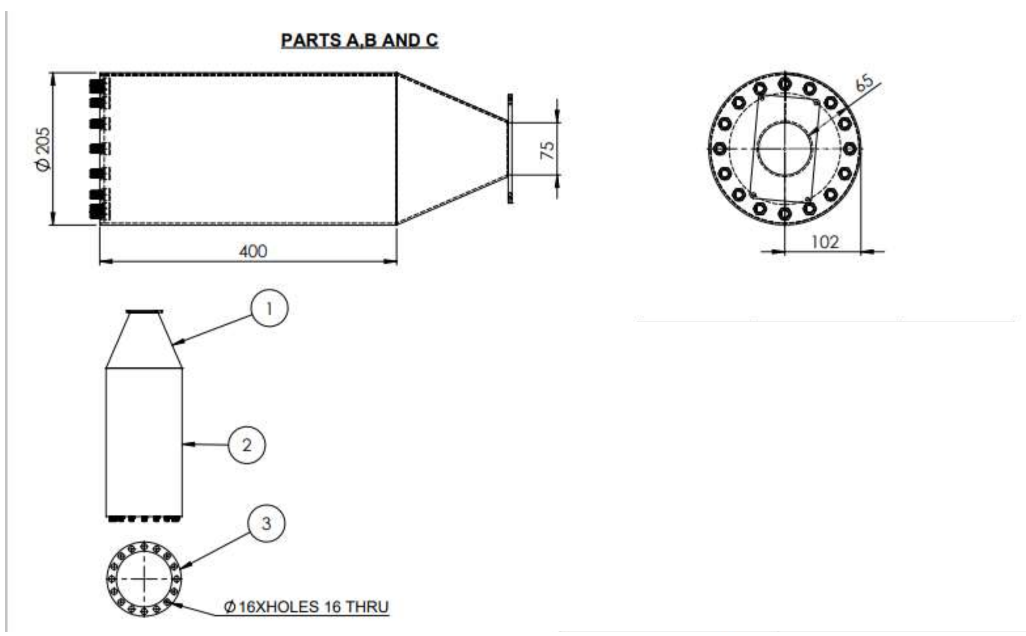


Figure 3.4: Outer Casing Design

3.4.2 Fabrication of the Outer Casing

A pattern of a truncated conical frustum of vertical height 150mm, circular top and bottom, outer diameters 75mm and 205mm respectively, was designed making use of the Zebra Dura Transparent Plastic Sheet. A copy of it was cut from a 2.5 mm grade 316 stainless steel plate. The cut plate was then folded and welded. The seat for the turbocharger was formed and then welded to the circular top of the truncated conical frustum as shown in Figure 3.5.

Figure 3.5: Part A of the Outer Casing

A pattern of a hollow cylinder of external diameter 205mm and height 400mm was designed and a copy of it was cut from the 2.5mm stainless steel plate. The plate was folded and welded; following the method used by (J. Hartman, 2014). The designed hollow cylinder is as shown in Figure 3.6.

Figure 3.6: Part B of the Outer Casing

A circular flat flange of inner and outer diameters, 150 mm and 195 mm respectively, and of thickness 6 mm was machined from the stainless steel plate. With the aid of a 19 mm Capacity Pillar Drilling Machine, 16 holes each of inner diameter 16 mm equally spaced were drilled in the flange at a radius of 87.5mm from the centre of the flange; similar to the method used by (Mondal and Singh, 2014). The finished flange is shown in Figure 3.7.

Figure 3.7: Part C of the Outer Casing

3.4.3 Outer Casing Assembly

Parts A, B and C from Figures 3.5, 3.6 and 3.7 respectively were put together and welded as shown in Figure 3.8.

Figure 3.8: Welding of parts together

A circular hole of diameter 62.9mm was cut from the side of the cylindrical outer casing very close to the base (ie. position of the flange) such that the distance from the base to the center of the cut hole was 41.45mm. A cylindrical 316 stainless steel pipe of thickness 1mm and inner diameter 62.9mm and length 410mm was welded to one end of a 316 stainless steel cylindrical elbow pipe of thickness 1mm and inner diameter 62.9mm as shown in Figure 3.9. Figure 3.10 shows the outer case design with elbow pipe connected. The design procedure follows the method used by Lee Han et al. (2016).

Figure 3.9: Welding tube for side of the cylinder

Figure 3.10: Outer Casing Design

3.4.4 Design of the Inner Liner

The inner liner is the main component that needs careful design, for, this component contains the combustion process and affects the performance of the Combustion Chamber the most. The inner liner was made of three parts. Namely, parts D, E and F. Figure 3.11 represents the

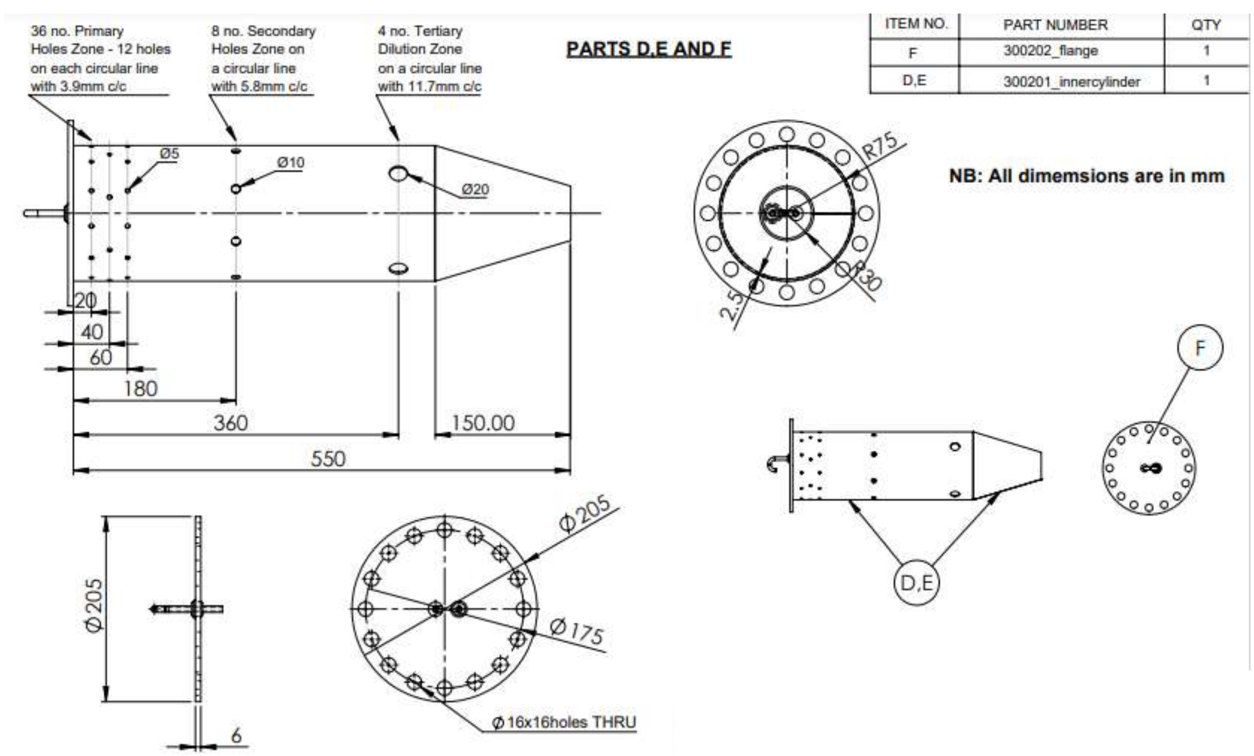


Figure 3.11: Inner Casing Design

SOLIDWORKS design of the inner liner.

3.4.5 Fabrication of Part D of the Inner Liner

A pattern of a truncated cone of vertical height 150mm with inner and outer arc lengths 188.70mm and 471.75mm respectively was designed and a copy of it was cut from the 2.5mm grade 316 stainless steel plate. The cut plate was folded and welded as shown in Figure 3.12.

Figure 3.12: Part D of the inner Liner

3.4.6 Fabrication of Part E of the Inner Liner

A pattern of a hollow cylinder of length 471.75mm and width 400mm was designed (Figure 3.13) and a copy of it was cut from the 2.5mm stainless steel plate. Straight Lines were drawn on the cut metal plate using one of the longer sides as a datum line.

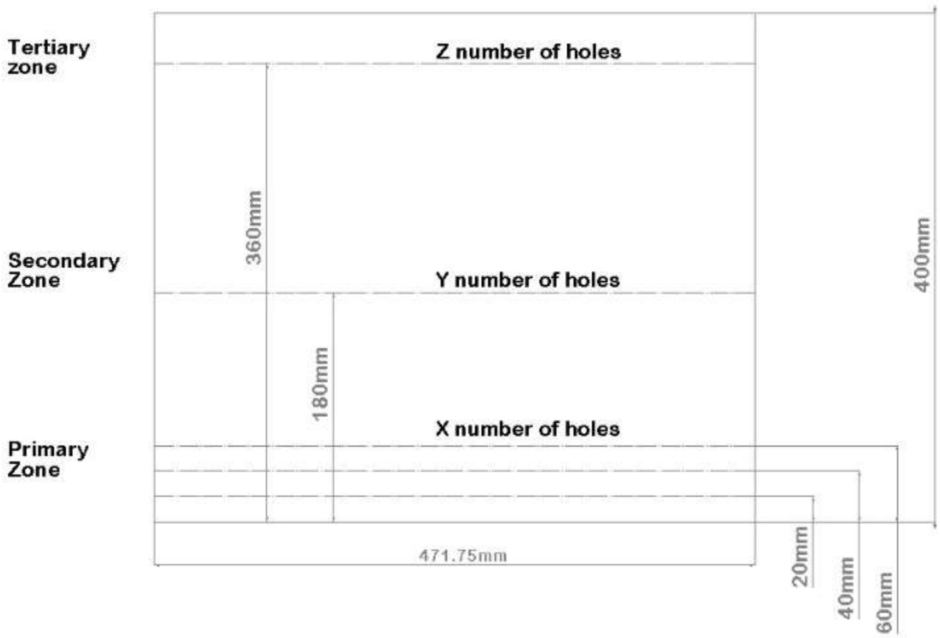


Figure 3.13: Hollow Cylinder Pattern

The diameters of holes D_1, D_2 and D_3 drilled in the primary, secondary and tertiary zones respectively were chosen such that they followed a Geometric Progression (3.6) of nth term:

$$\mathbf{D_n = ar^{n-1}} \tag{3.6}$$

where a = 5mm (a chosen diameter for a hole in the primary zone), r = 2 (a constant ratio) and n = a zone (where n_1=1, n_2=2 and n_3 =3 for primary, secondary and tertiary zones respectively).

The software, jetspec mentioned in Figure 3.1, needs two parameters, the inducer diameter D_o and a diameter of a hole in a zone (which could be D_1 or D_2 or D_3) in order to generate the number of holes (X or Y or Z) for a zone. To achieve complete combustion (propane - air stoichiometric ratio i.e. 1: 15.67 by mass) in the combustion chamber, equation (3.7) below must be followed.

$$\boldsymbol{XD_1^2 + YD_2^2 + ZD_3^2 = D_0^2} \tag{3.7}$$

X, Y and Z represent the number of holes in the primary, secondary and tertiary zones. With known X, Y and Z values generated by the jetspec, holes were drilled in the respective zones.

The perforated plate in Figure 3.14 was rolled and welded. The designed hollow cylinder (perforated) is as shown in Figure 3.15 (Han Ju *et al*, 2016).

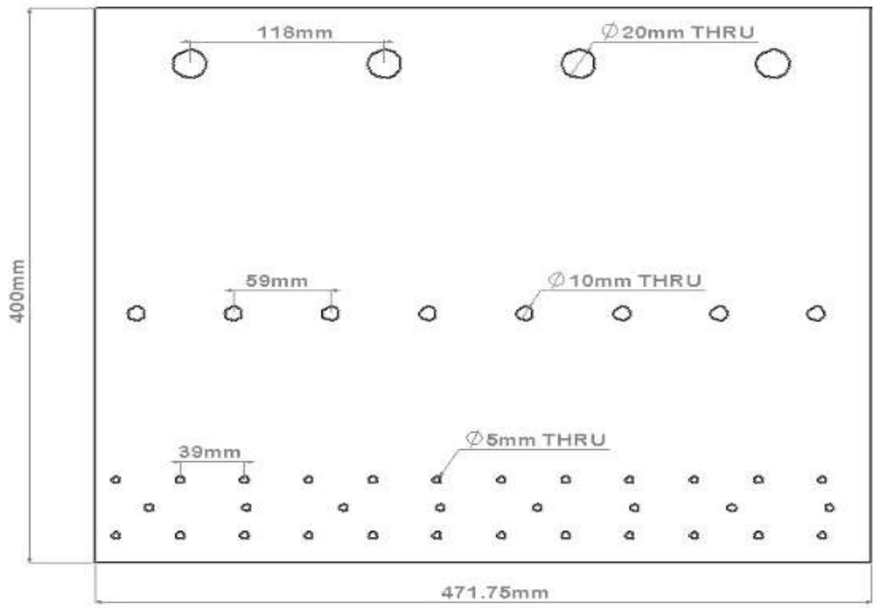


Figure 3.14: Perforated cut metal plate

Figure 3.15: Part E of the Inner Liner

3.4.7 Fabrication of Part F of the Inner Liner

A flat disc of diameter 200mm and thickness 6mm with16 holes, each of diameter 16mm equally spaced drilled at a radius of 87.5mm from the center of the disc was machined from the 316 stainless steel plate. Tube for introducing fuel into the engine and a spark plug system were placed in the center of the disc by modifying the method used by Hartman (2014). Figure 3.16 represents the part F of Inner liner.

Figure 3.16: Part F of the Inner Liner

3.4.8 Inner Liner Assembly

Parts D, E and F from Figures 3.12, 3.15 and 3.16 respectively were put together and welded as shown in Figure 3.17.

Figure 3.17: The Inner Liner Assembly Design

3.4.9 Combustion Chamber Assembly

The complete combustion chamber (Figure 3.18) was achieved by placing the inner liner in Figure 3.17 in the outer casing in Figure 3.10.

Figure 3.18: The Combustion Chamber

3.4.8 Exhaust Nozzle Design

The exhaust nozzle design (Figure 3.30). The exhaust nozzle was modelled to facilitate the generation of thrust (F_n) represented by Equation (3.8).

$$F_n = \dot{m}\, v_e - \dot{m}\, v_a + v_e(p_e - p_a) \quad (3.8)$$

Where,

ṁ= Mass flow,

v_a = Atmospheric air velocity, ,

v_e = Velocity at exhaust, ,

3 A_e = Exit Area, ,

P_a = Atmospheric Pressure,

P_e = Pressure at exit

Figure 3.19:The Exhaust Nozzle Design

3.5 Quality Assurance Test

In order to uphold quality assurance there was the need to perform tests to the fabricated components and materials used. The procedural steps for which the tests were performed are outlined in subsection 3.4.7.

3.5.1 Non-Destructive Testing (Dye Penetrant)

There were lots of joining and assembly work done through welding, hence the need to ascertain that this joints and welds would not render the whole fabricated system vulnerable to expansion leaks during engine operation. The technique makes use of capillary action to detect discontinuities. The steps for the testing are listed below.

- The surface was thoroughly cleansed to remove dirt and foreign materials,
- A penetrant dye (ADROX 907 PB), Figure 3.22, was sprayed on welded surfaces.
- The dye was left on the surface for a dwell time of twenty (20) mins (Figure 3.21).
- A solvent washable agent (ARDROX 9PR5) was sprayed on the surface and a dry linen used to clean the dye.
- A developer (ARDROX 9D1B) (Figure 3.20) was applied to the surface for a ten (10) minutes dwell time to draw out the die to detect any discontinuity.

Figure 3.20: Applying the Dye Penetrant

Figure 3.21: Applying the developer

3.5.2 Engine Test and Parameter Readings

Instruments used include: a tachometer for RPM measurement, thermocouple for Temperature and Torsional spring for the thrust of the engine. Table 3.1 presents the error margins of the

Figure 3.22: Materials used for liquid penetrant testing

instruments used.

Table 3.1: Error margins of Instruments.

Instrument	**Error Margin**
Thermocouple type K	± 0.075K (Artmann Nikolai et al, 2008)
Torsional Spring	± 0.1N (E.Rodriguez and M. Paredes, 2004)
Stop Clock	± 0.2s

3.6 Concluding Remarks

The Chapter outlined the designs for the individual parts of the turbojet engine. The Tools that were used for the fabrication of parts were fully detailed. The techniques and types of materials that were used for engine production were described. All tests done on the engine were comprehensively outlined.

CHAPTER 4

RESULTS AND DISCUSSIONS

This Chapter presents the output design and fabrication of the turbojet engine. In addition to the design and fabrication output, some important parameters to properly characterize the turbojet engine have been presented and discussed.

4.1 Turbojet engine design

Figure 4.1 shows turbojet engine design. The individual parts with the overall turbojet engine assembly unit were designed using SOLIDWORKS computer aided design (CAD) tool.

Figure 4.1: Turbojet overall Design

4.1.1 Turbojet Engine Fabrication

4.1.1.1 Turbocharger

The purchased turbocharger (Figure 4.2) unit had the following parameters; inducer diameter (177.50mm), shaft length (150mm), Compressor diameter (100mm), number of compressor blades (14), Exit turbine diameter (76.50mm) and turbine blade number (12) as summarized in Table 4.1 The impeller of the turbocharger is shown in Figure 4.3.

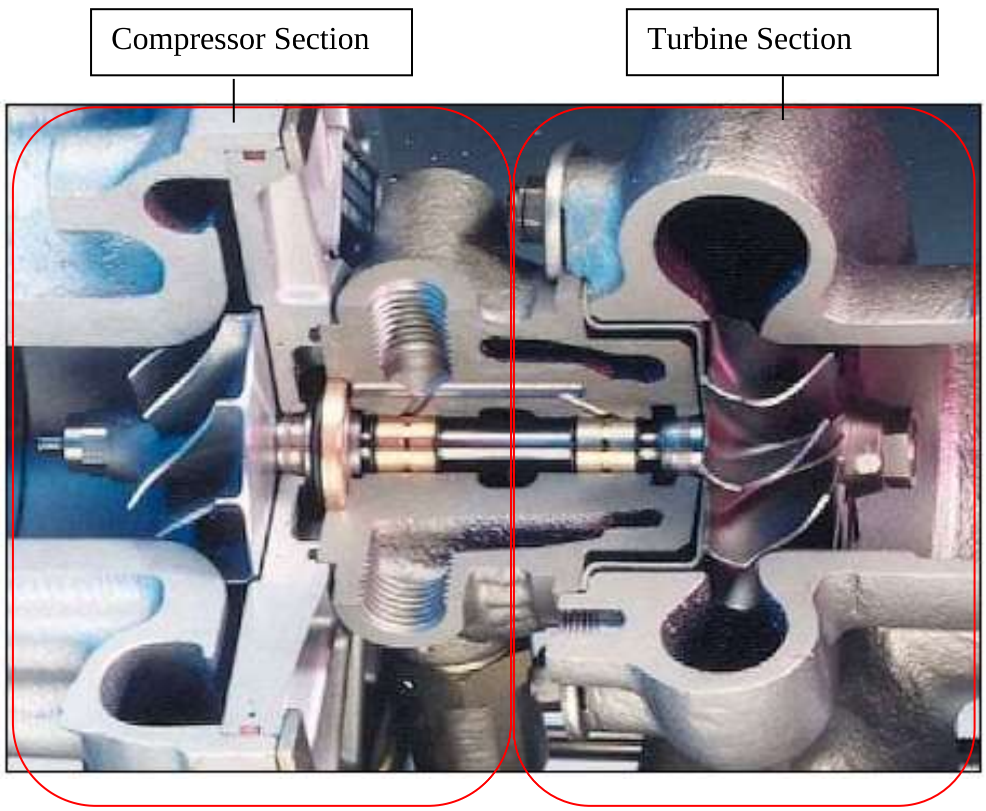


Figure 4.2: Sectional view of turbocharger

Table 0.1: Parameters for Turbocharger

Parameters	**Values**
Inducer diameter	177.50 mm
Shaft length	150.0 mm
Impeller diameter	100.0 mm
Number of compressor blades	14
Exit turbine diameter	76.50 mm
Number of turbine blades	12

Figure 4.3: Impeller of Turbocharger

4.1.1.2 Combustion Chamber

The annular type model was chosen for the combustion chamber design (see Figure 4.4). The inner liner and outer casing were separately fabricated and then assembled as shown in Figure 4.5. The complete fabricated combustion chamber with the internal parts are also shown in Figure 4.6. The dimensions of the combustion chamber are represented in Table 4.2.

Figure 4.4: Inner (A) and Outer (B) Tubes

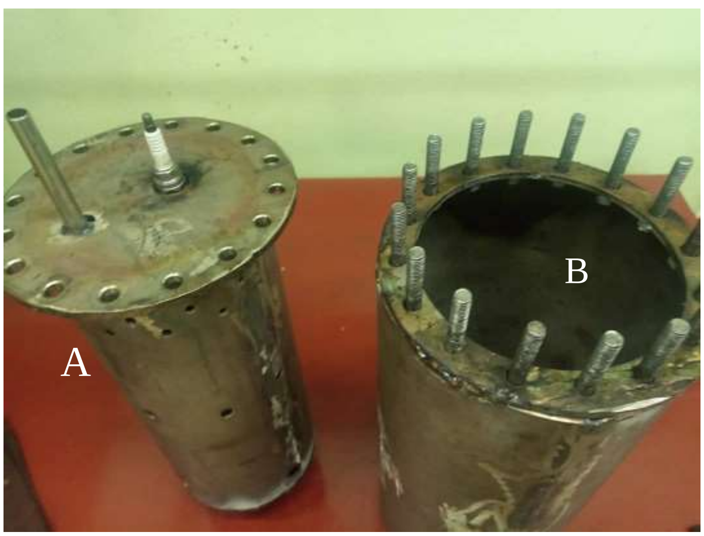


Figure 4.5: Base view of Inner (A) & Outer (B) Tubes

Combustion Chamber

Figure 4.6: The Combustion Chamber

Table 0.2: Combustion chamber dimensions

Parameters	Values
Inner tube diameter	150.0 mm
Outer casing diameter	200.0 mm
Combustion Chamber Height	550.0 mm
Inner tube holes	32, 8, 4 Primary secondary and tertiary zones respectively

4.1.1.3 Exhaust nozzle

The fabricated exhaust nozzle is as shown in Figure 4.7. The exhaust nozzle was of length 500mm and inner diameter of 76.50mm at tubine outlet and inner diameter of 50.0mm at exit nozzle.

Figure 4.7: The Exhaust Nozzle

4.1.1.4 Turbojet Assembly

The resulting turbojet assembly is as shown in Figure 4.8, following modification by M Usman Butt, (2019). The Figure shows the casing that holds the engine and its peripheral components.

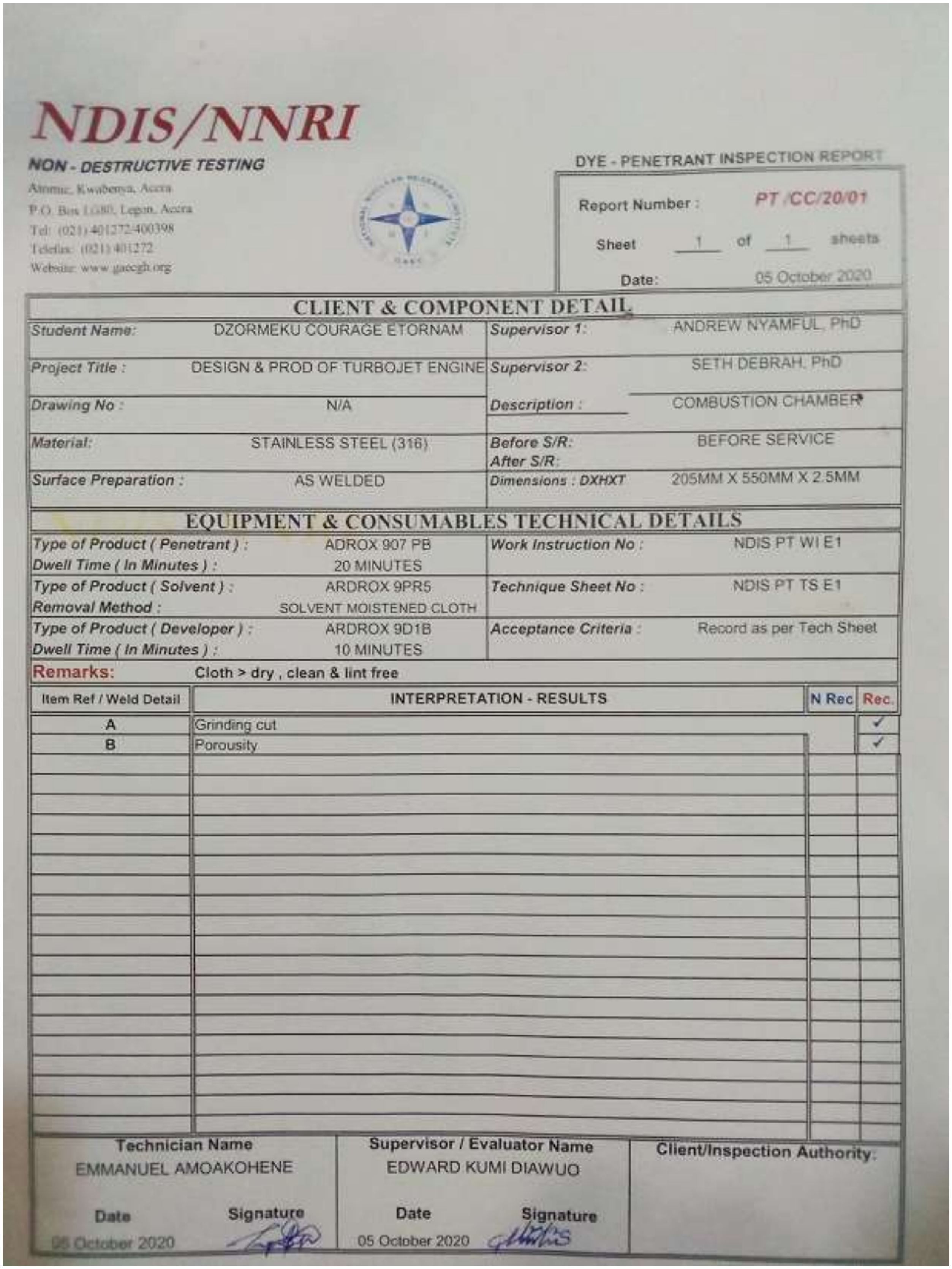
Figure 4.8: Turbojet Engine Full Assembly View

4.2 Non Destructive Evaluation (Dye Penetrant Test Result)

The dye penetrant test on the combustion chamber welded parts revealed grinding cuts (labeled A) and certain porosity laps (labeled B) in Figure 4.9 and a report (Figure 4.10) from the Non Destructive Testing (NDT) Laboratory of the Ghana Atomic Energy Commission (GAEC) was produced on the test results.

These areas were repaired and the final test report from the NDT Laboratory (GAEC) confirmed no recordable indications (see Figure 4.11).

Figure 4.9: Result of the dye Penetrant test.



NDIS/NNRI

NON - DESTRUCTIVE TESTING

Atomic, Kwabenya, Accra
P.O. Box LG80, Legon, Accra
Tel: (021) 401272/400398
Telefax: (021) 401272
Website: www.gaecgh.org

DYE - PENETRANT INSPECTION REPORT

Report Number : PT /CC/20/01

Sheet 1 of 1 sheets

Date: 05 October 2020

CLIENT & COMPONENT DETAIL

Student Name:	DZORMEKU COURAGE ETORNAM	Supervisor 1:	ANDREW NYAMFUL, PhD
Project Title :	DESIGN & PROD OF TURBOJET ENGINE	Supervisor 2:	SETH DEBRAH, PhD
Drawing No :	N/A	Description :	COMBUSTION CHAMBER
Material:	STAINLESS STEEL (316)	Before S/R: After S/R:	BEFORE SERVICE
Surface Preparation :	AS WELDED	Dimensions : DXHXT	205MM X 550MM X 2.5MM

EQUIPMENT & CONSUMABLES TECHNICAL DETAILS

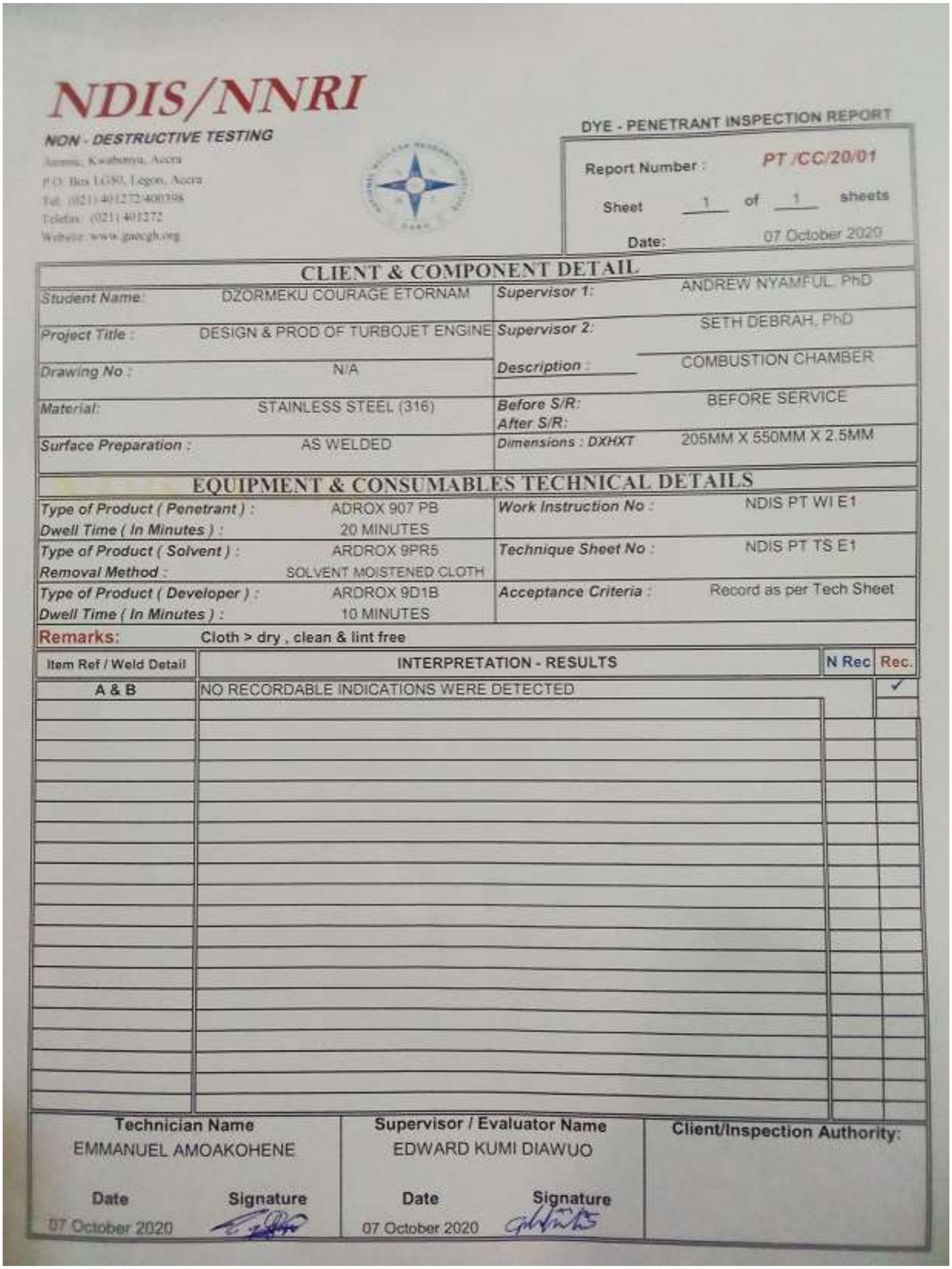
Type of Product (Penetrant) : Dwell Time (In Minutes) :	ADROX 907 PB 20 MINUTES	Work Instruction No :	NDIS PT WI E1
Type of Product (Solvent) : Removal Method :	ARDROX 9PR5 SOLVENT MOISTENED CLOTH	Technique Sheet No :	NDIS PT TS E1
Type of Product (Developer) : Dwell Time (In Minutes) :	ARDROX 9D1B 10 MINUTES	Acceptance Criteria :	Record as per Tech Sheet

Remarks: Cloth > dry , clean & lint free

Item Ref / Weld Detail	INTERPRETATION - RESULTS	N Rec	Rec.
A	Grinding cut		✓
B	Porousity		✓

Technician Name	Supervisor / Evaluator Name	Client/Inspection Authority:
EMMANUEL AMOAKOHENE	EDWARD KUMI DIAWUO	
Date: 05 October 2020 Signature	Date: 05 October 2020 Signature	

Figure 4.10: Report on findings on dye penetrant testing



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NON - DESTRUCTIVE TESTING

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Website: www.gaecgh.org

DYE - PENETRANT INSPECTION REPORT

Report Number : PT /CC/20/01

Sheet 1 of 1 sheets

Date: 07 October 2020

CLIENT & COMPONENT DETAIL

Student Name:	DZORMEKU COURAGE ETORNAM	Supervisor 1:	ANDREW NYAMFUL, PhD
Project Title :	DESIGN & PROD OF TURBOJET ENGINE	Supervisor 2:	SETH DEBRAH, PhD
Drawing No :	N/A	Description :	COMBUSTION CHAMBER
Material:	STAINLESS STEEL (316)	Before S/R: After S/R:	BEFORE SERVICE
Surface Preparation :	AS WELDED	Dimensions : DXHXT	205MM X 550MM X 2.5MM

EQUIPMENT & CONSUMABLES TECHNICAL DETAILS

Type of Product (Penetrant) :	ADROX 907 PB	Work Instruction No :	NDIS PT WI E1
Dwell Time (In Minutes) :	20 MINUTES		
Type of Product (Solvent) :	ARDROX 9PR5	Technique Sheet No :	NDIS PT TS E1
Removal Method :	SOLVENT MOISTENED CLOTH		
Type of Product (Developer) :	ARDROX 9D1B	Acceptance Criteria :	Record as per Tech Sheet
Dwell Time (In Minutes) :	10 MINUTES		

Remarks: Cloth > dry , clean & lint free

Item Ref / Weld Detail	INTERPRETATION - RESULTS	N Rec	Rec.
A & B	NO RECORDABLE INDICATIONS WERE DETECTED		✓

Technician Name	Supervisor / Evaluator Name	Client/Inspection Authority:
EMMANUEL AMOAKOHENE	EDWARD KUMI DIAWUO	
Date: 07 October 2020 Signature	Date: 07 October 2020 Signature	

Figure 4.11: Final NDT report

4.3 Parametric Analysis

The parameter readings recorded for the turbojet engine run test included;

i. Temperature of exhaust gas;
ii. Revolution Per Minute (RPM);
iii. Thrust.

4.3.1 Exhaust Gas Temperature

This parameter was obtained with the aid of a thermocouple during the turbojet engine test. The temperatures were taken every 120s by placing thermocouple at the rear of the exit nozzle. A maximum temperature of about 780^{O}C (1053.15K) was attained as compared to 701.85 ^{O}C (975K) recorded in the work of M Usman Butt, (2019).

The exhaust gas temperature was determined against time to properly determine the temperature profile at the exhaust nozzle. The data acquired during the engine run for a period of 840 seconds is presented in a graph in Figure 4.12.

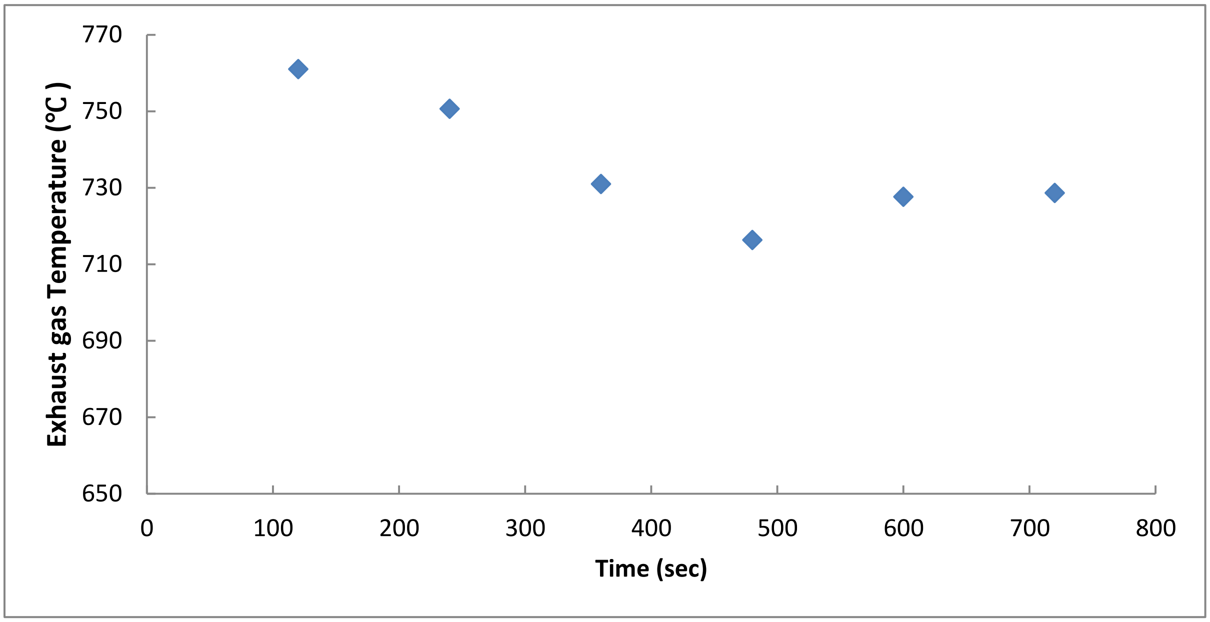

Figure 4.12: Exhaust gas Temperature (°C) against Time (sec)

The Exhaust gas Temperature against Time graph (Figure 4.12), describes time to be inversely proportional to temperature, characterized by the deeping of the graph around the 480th second. This was as a result of the increased drawing in of ambient air that eventually cools the inner tube and drops the temperature of the hot gas at the turbine right after the engine's initial ignition and combustion at an initial constant fuel flow rate. As the flow rate of fuel was increased after the 480th second, temperature began to rise.

4.3.2 Revolution Per Minute

This parameter was obtained with the aid of a tachometer during the testing section of the turbojet engine. The RPM readings were taken every 120s by directing the tachometer right on the turbine blades of the compressor. A maximum RPM of 100000 was attained as compared to 84000 RPM and 120000 RPM attained in the turbojet engine of M Usman Butt, (2019) and axial type turbojet engine of Nam Seo Goo et al., (2006) respectively.

The Revolution Per Minute was plotted against time to determine the turbojet engine Speed with respect to time. The revolution per minute is the main measure for the high performance rating of the engine. The data acquired during the engine run for a period of 840 seconds is presented in Figure 4.13.

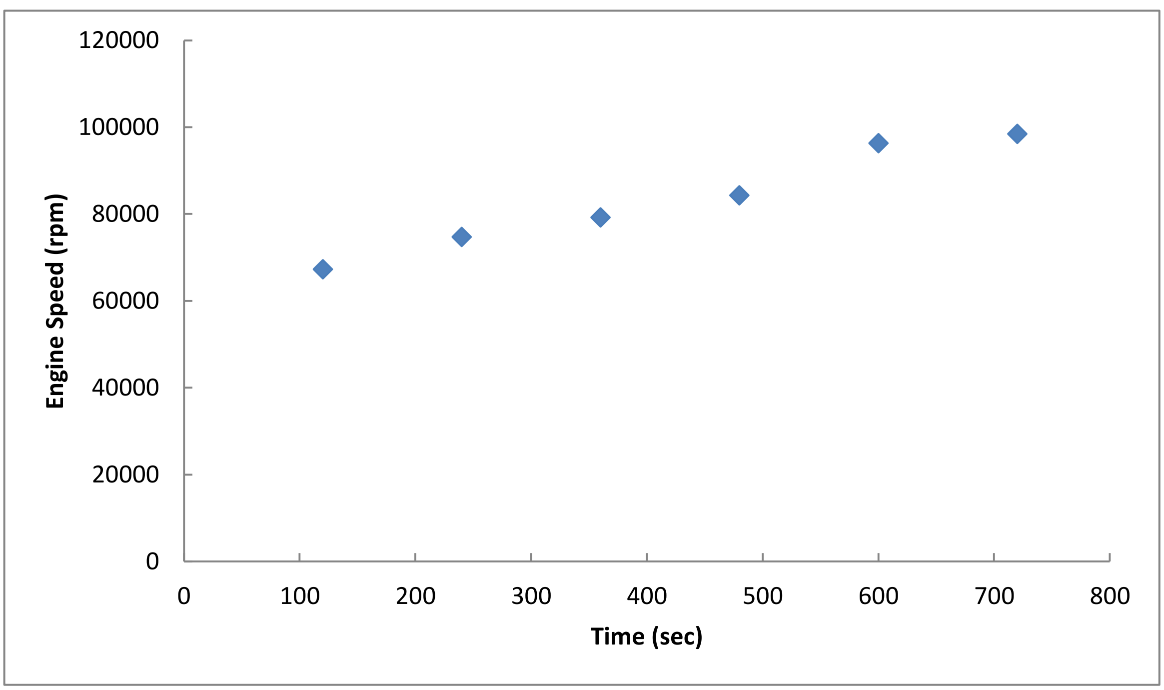

Figure 4.13: Engine Speed (rpm) against Time (sec)

Reference to the graph in Figure 4.13, Engine Speed (rpm) against Time (s) revealed a direct proportionality between the two parameters. Since the turbine and compressor blades are connected by a common shaft, the hot gases at high velocity and pressure exiting via the turbine blades increase the revolutionary speed of the blades at the turbine as well as increase the revolution at the compressor, this accounts to the direct proportionality between RPM and Time. As the flow rate of fuel was increased after the 480th second RPM increased significantly as these accounts for the increasing trend of points in Figure 4.13.

4.3.3 Thrust

This parameter was obtained with the aid of a spring balance. It was attached to a stationary point and then fixed to the engine. Readings were then taken as thrust is generated. Maximum thrust of 3.5N was achieved as compared to the 18.64N thrust in the axial turbojet engine developed by Nam Seo Goo et al., (2006) and 75N thrust attained in M Usman Butt, (2019). The

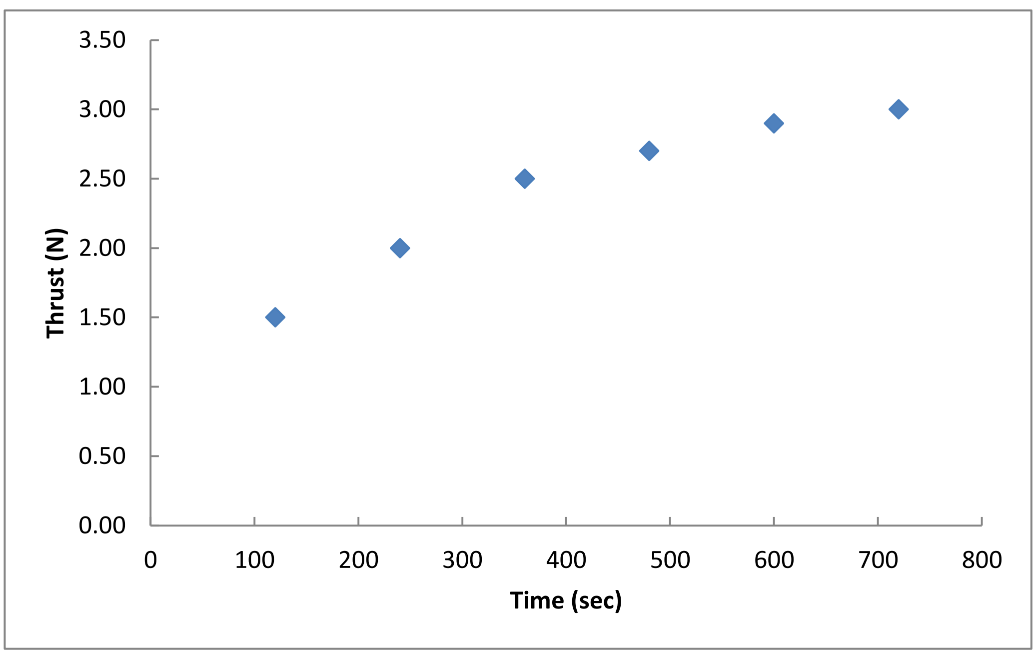

Figure 4.14: Thrust (N) against Time (sec)

Thrust was plotted against time to properly determine the force output produced by the engine.

The data obtained during the engine run for a period of 840 seconds is presented in Figure 4.14.

Thrust is dependent on Engine Speed (RPM), the higher the Engine Speed the higher the resultant force generated by hot gases exiting the turbine (exhaust nozzle). This accounts for the nature of the graph in Figure 4.14. As time increased thrust increased as well. This means thrust and time are directly proportional.

4.3.4 Exhaust Gas Temperature against Revolution Per Minute

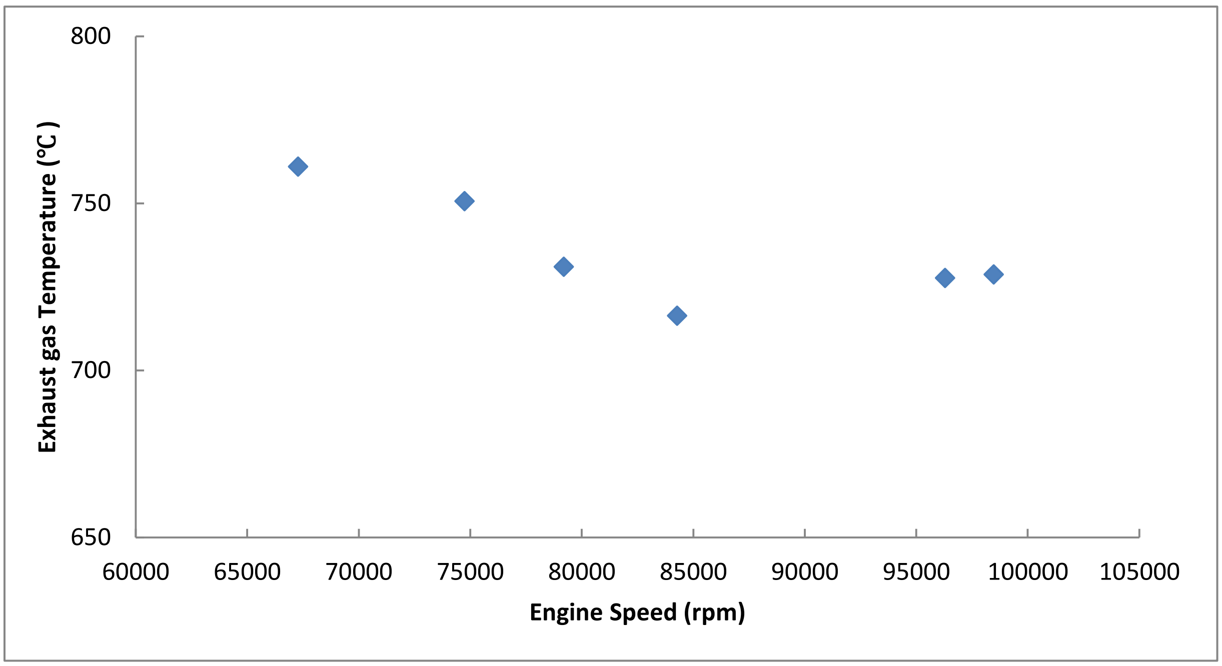

Figure 4.145: Exhaust gas Temperature (°C) against Engine Speed (rpm)

From the graph (Figure 4.15) as Engine Speed (RPM) increased Exhaust Gas Temperature dropped initially and began to level up as a result of the drop in temperature from the increase in compressor blade speed drawing in more ambient air into the chamber. As fuel flow rate increased midway of the test, temperature began to rise (Figure 4.15). The fifth data point jump in RPM as shown in the graph (Figure 4.15) was as a result of increase in the fuel flow rate after the 85000 rpm was recorded.

4.3.5 Exhaust gas Temperature against Thrust

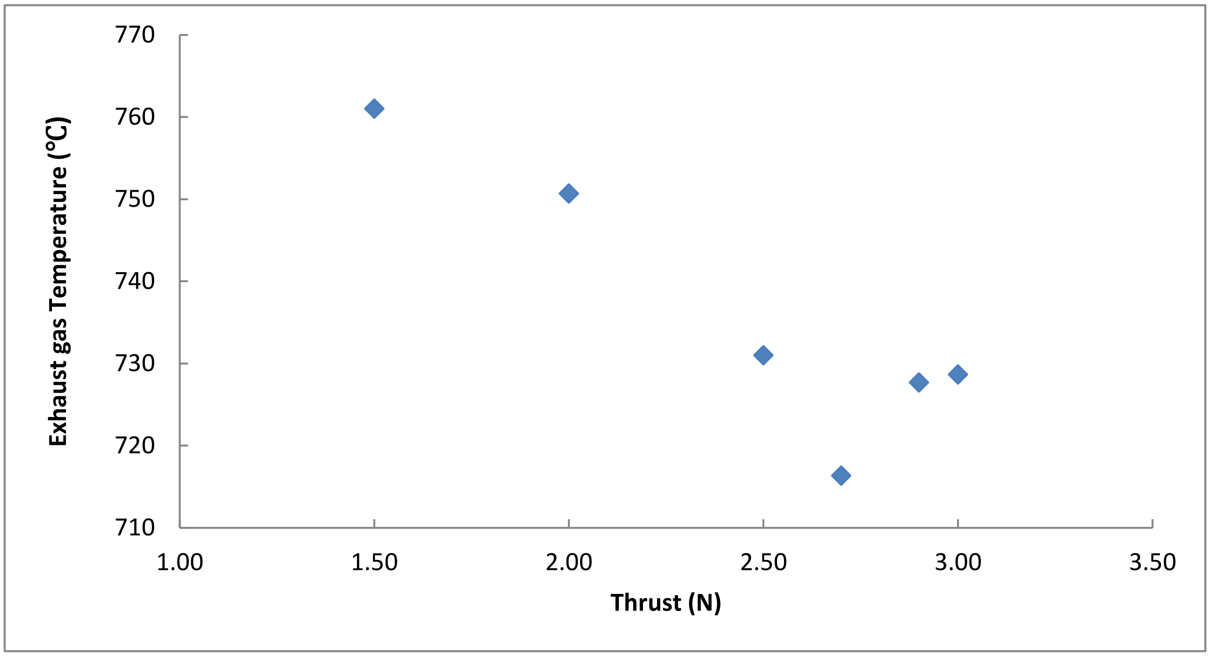

Figure 4.156: Exhaust gas Temperature (℃) against Thrust (N)

From the graph (Figure 4.16) as thrust increased temperature dropped initially and began to level up as a result of the drop in temperature from the increase in compressor blade speed drawing in more ambient air into the chamber, thereby increasing force output at the nozzle; the rise in temperature and thrust values from the graph (Figure 4.16) was as a result of the increase in fuel flow rate after the 2.60N and 3.10N thrust marks.

4.3.6 Engine speed Against Thrust

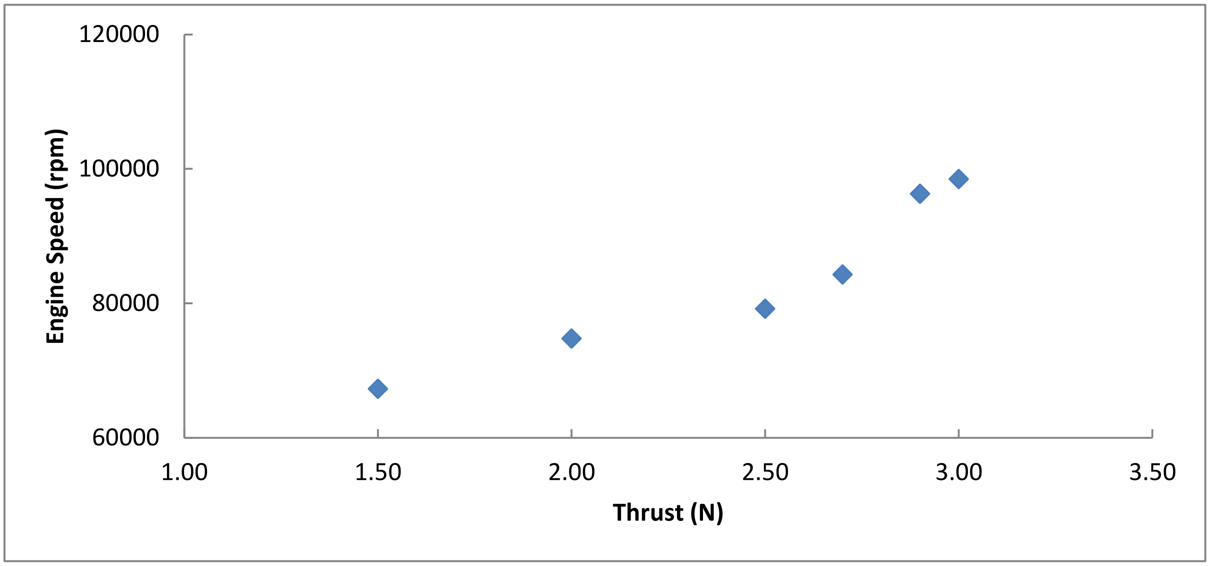

Figure 4.167: Engine Speed (rpm) vs Thrust (N)

The graph (Figure 4.17) confirms the fact that Engine Speed and Thrust are directly proportional to each other since there is an increasing trend on both axis. As fuel flow rate was increased after the 2.60N and 3.10N thrust marks, there was a jump in thrust values as reflected in the graph (Figure 4.17). This result is almost similar to the readings taken in Nam Seo Goo, et al. (2006).

4.4 Concluding Remarks

Chapter four exhibited respective outcomes as per the initial proposed objectives. The design of the turbojet engine using SOLIDWORKS was neatly developed, Production through metal works fabrication was accomplished. The parameters for Engine performance were also taken and their analysis reported a positive report on the turbojet engine performance.

CHAPTER 5

CONCLUSION AND RECOMMENDATION

This research sets out to design and produce a turbojet engine that runs at optimum conditions.

The design of the turbojet engine using a Computer Aided Design (CAD) known as SOLIDWORKS was accomplished.

The fabrication of the individual components and general engine assembly was a success. The engine was given a test run and its operation was satisfactory.

Readings for parameters including; Thrust, Engine speed (RPM) and Exhaust gas temperature were taken and the state of these parameters affected performance of the turbojet engine positively.

From the analysis of the parameters in Chapter four, it is evident that design and production of a working turbojet engine is possible. Moreover, the locally produced turbojet engine is capable of serving industrial energy demands that will generate economic benefit. It also opens door for more research work to be carried out in related areas.

4.5 Recommendations

The school of Nuclear and Allied Sciences could take up modeling and simulation of the turbojet engine for optimization purposes.

Further work can be done on the fabrication of exhaust to suit medium of energy transfer for varied applications. Additional work needs to be carried out on fuel delivery system, to make it universal for all kinds of fuel to be used and ease in swapping fuels.

It is recommended for further works to be carried out on oil types and oil pump compatibility for efficient pump operation.

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