A PROJECT REPORT ON

DESIGN AND CONNSTRUCTION OF JET ENGINE USING AUTOMOTIVE TURBOCHARGER

A DISSERTATION

SUBMITTED FOR THE PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE DEGREE OF

BACHELOR OF TECHNOLOGY

IN MECHANICAL ENGINEERING

SUBMITTED BY

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GUIDE

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DEPARTMENT OF MECHANICAL ENGINEERING

VEERMATA JIJABAI TECHNOLOGICAL INSTITUTE

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CERTIFICATE OF APPROVAL

By Examiners

This is to certify that the dissertation entitled “DESIGN AND CONSTRUCTION OF JET ENGINE USING DIESEL TRUCK TURBOCHARGER” is bonafied record of the dissertation work done by

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This dissertation is approved for the BACHELOR OF TECHNOLOGY, under the guidance of Prof. H. P. Khairnar, DEPARTMENT OF MECHANICAL ENGINEERING, V.J.T.I.

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Signature____________ Signature____________

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Summary of the project:

The project consists of Design, fabrication, assembly and testing of a Jet Engine, using a large diesel Truck turbocharger, on a small scale level. The turbocharger serves as an integrated compressor & turbine assembly which is suitably manipulated (carefully converted) in to an open cycle constant pressure gas turbine. The project mainly involves complex modeling, designing and analysis of combustion chamber using software packages like comsol, matlab, ANSYS and other related softwares like AutoCAD, soidworks etc; and then complete fabrication of the same completely by us.

Introduction:

The invention of the gas turbines around twentieth century during the era of Second World War led to a major breakthrough in the field of prime movers. The absence of the reciprocating and rubbing members, few balancing problems, exceptionally low lubricating oil consumption coupled with high power to weight ratio made gas turbines highly reliable. These inherent advantages of the gas turbines were realized when they were first used for aircraft propulsion around mid twentieth century; and ever since gas turbines have received a special attention by potential mass of engineers and scientists all around the globe. The gas turbines have been used as the source of power for variety of application most of which includes stationary power plant application, as propulsion device for marine, locomotives etc. but the vast portion of the application of gas turbines is found in aircraft industries. The introduction of the gas turbine as propulsion device in the airplanes have made air ways highly reliable source of transportation. It is not just the engineers and scientists who are thrilled by this new highly emerging and developing prime mover but it has also attracted the attention of the general public who are fascinated by its inherent advantages, simplicity of construction and high reliability.

Need of the study:

Fascinated by turbojet engine, we decided to learn all that we can about jet engines. We figured that the best way to explore the principles of a turbojet engine is to build one. Like us thrilled by the gas turbine propulsion, quite a few experimenters have gone to the extent of building their own custom gas turbine engines. The first military gas turbine engine was constructed by Garrett/ Aireseach on experimental basis using a simple turbocharger. It was built as a research project for US government. Many experimenters have uploaded their experimented gas turbine based projects on the internet. There is good amount of the information available on the subjects with all kinds of designs being employed. We want to use these ideas to study how actual gas turbines operate, what variables go into picture while designing a working gas turbine and what sort of difficulties are encountered while construction of an actual working gas turbine from a scrap turbocharger, this encouraged us to build our own turbocharger based turbojet engine that will be a research test bed for our project.

Objective of the project:

Our objective is to construct a working scaled model of a turbojet engine using diesel truck turbocharger which will be self sufficient and requiring no separate power sources to operate thus allowing the unit to be mobile. The turbojet engine project consists of Design, fabrication, assembly and testing of a Jet Engine, using a large diesel Truck turbocharger. This project is replica of actual working of the jet engine on a small scale level. The turbocharger serves as an integrated compressor & turbine assembly which is suitably manipulated (carefully converted) in to an open cycle constant pressure gas turbine. The project mainly involves complex modeling, designing and analysis of combustion chamber using software packages like comsol, mat lab, ANSYS and other related softwares like AutoCAD, soidworks etc; and then complete fabrication of the same completely by us.

SECTION 1: DESIGN OF JET ENGINE

Approach towards design:

The procedure that will be adopted in designing the turbojet engine is outlined below:

1. Define the system and its components.

2. Build up the physical/Block model describing all the components.
3. Obtain the equivalent diagrammatic representation of the block model.
4. Formulate the mathematical model and describe the assumptions made.
5. Write down the equations describing the model.
6. Solve the equations for desired output variables.
7. Examine the solution and variables.
8. Apply the necessary corrections to subvert the idealized corrections made in both the physical and the mathematical model.
9. Reanalyze and Redesign till the solutions obtained are compatible with the results expected of the actual system.
10. Detailed Design and selection of the various components based on the results obtained in the analyses of the mathematical model.

Definition of the system:

A Turbojet engine is an engine that accelerates a fluid into its surrounding environment to form a fast-moving jet. The reaction felt by the engine to this expulsion is the thrust force, which acts in the opposite direction to the jet. A Turbojet engine is an assemblage of five important components viz a Compressor coupled to a Turbine , Combustion chamber, Diffuser, Nozzle and Hydrostatic bearing. All the components when assembled together form what is called as a Turbojet engine.

Block Diagram of Turbojet Engine

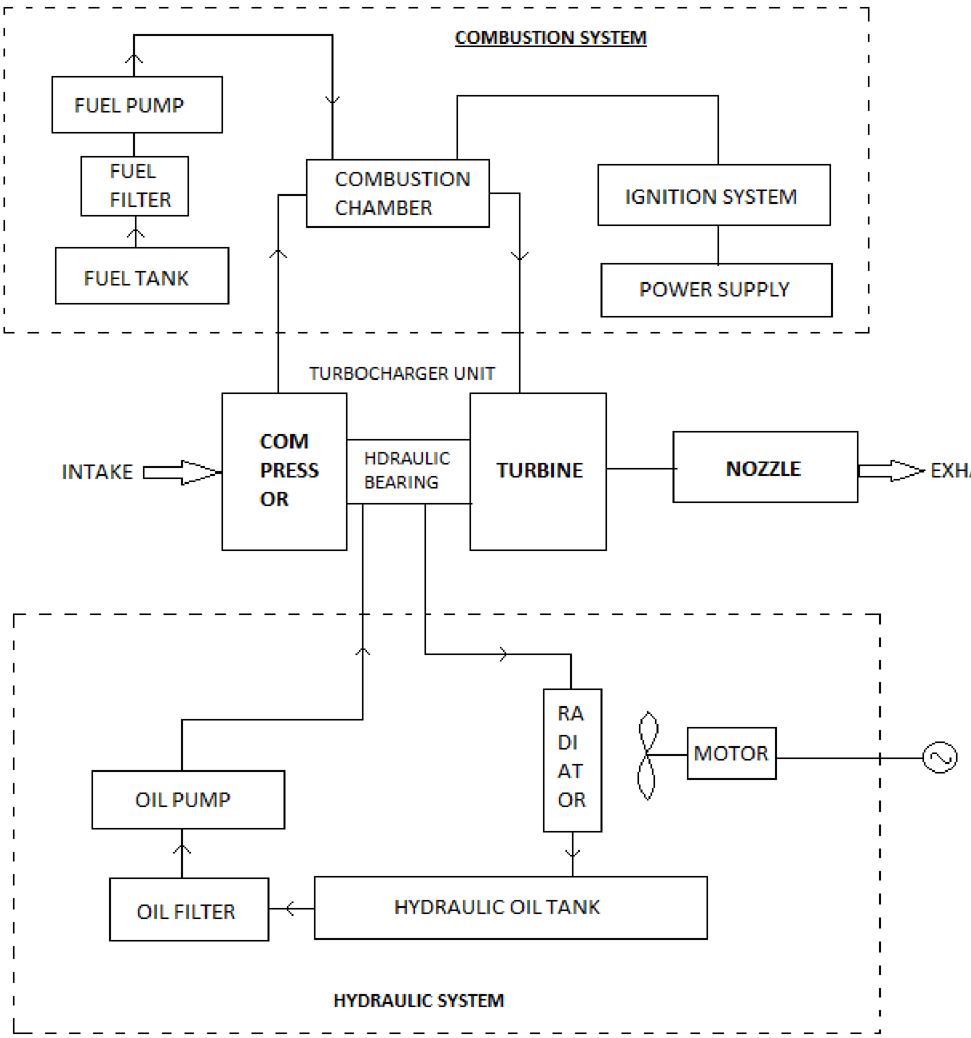


FIG: BLOCK DIAGRAM OF TURBOJET ENGINE

Description of the block diagram:

The entire block circuit of the engine has been divided into three major units for the sake of the simplicity of understanding. The three major sub units are listed below

1. The Turbocharger unit
2. The Hydrostatic lubrication unit and
3. The Combustion system

Each of these three units is further sub divided into sub units, brief description of which is given below:

The Turbocharger Unit:

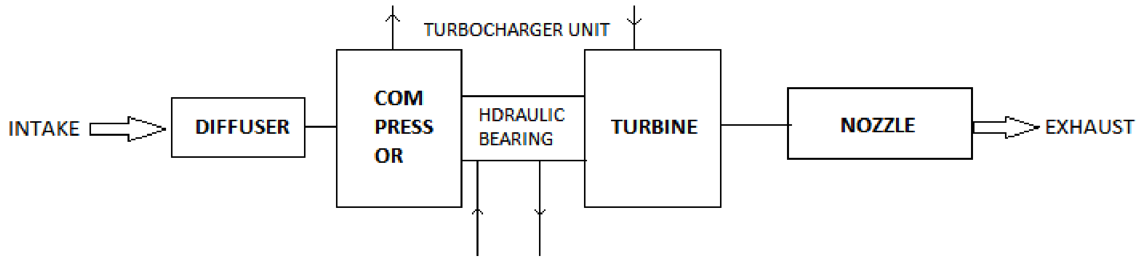


Fig: The Turbocharger unit

This unit is an assembly of an inlet diffuser, a huge diesel truck turbocharger and an exhaust nozzle.

Turbocharger

A turbocharger is a centrifugal compressor powered by a turbine that is driven by an engine's exhaust gases. A turbocharger's purpose is to compress the oxygen entering a car's engine, increasing the amount of oxygen that enters and thereby increasing the power output. The turbocharger is powered by the car's own exhaust gases. In other words, a turbocharger takes a by-product of the engine that would otherwise be useless, and uses it to increase the car's horsepower.

Turbocharger compressor: Turbocharger compressors are generally centrifugal compressors consisting of three essential components: compressor wheel, diffuser, and housing. With the rotational speed of the wheel, air is drawn in axially, accelerated to high velocity and then expelled in a radial direction.

Turbocharger turbine: The turbocharger turbine, which consists of a turbine wheel and turbine housing, converts the engine exhaust gas into mechanical energy to drive the compressor. The gas, which is restricted by the turbine's flow cross-sectional area, results in a pressure and temperature drop between the inlet and outlet. This pressure drop is converted by the turbine into kinetic energy to drive the turbine wheel.

Propelling Nozzle

The propelling nozzle is the key component of all jet engines as it creates the exhaust jet. Propelling nozzles turn pressurized, slow moving, hot gas, into lower pressure, fast moving colder gas by adiabatic expansion. Propelling nozzles can be subsonic, sonic, or supersonic, but in normal operation nozzles are usually sonic or supersonic. Nozzles operate to constrict the flow, and hence help raise the pressure in the engine, and physically the nozzles are very typically convergent, or convergent-divergent. Convergent-divergent nozzles can give supersonic jet velocity within the divergent section, whereas in a convergent nozzle the exhaust fluid cannot exceed the speed of sound of the gas within the nozzle. The nozzle shown in the figure is a convergent type nozzle.

The Hydrostatic unit:

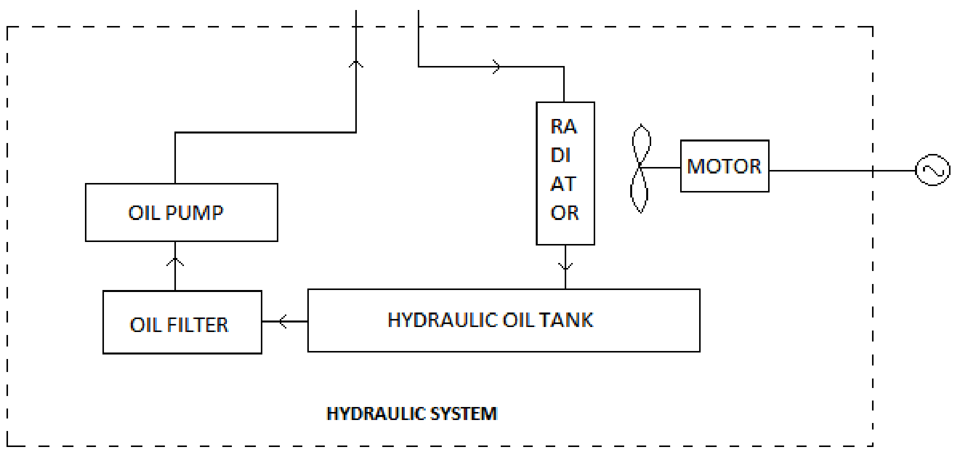


Fig: The hydraulic system

The hydraulic system consists of an oil pump, oil filter, oil storage tank and an air cooled radiator.

Hydraulic oil pump

An oil pumps function is to supply the oil to the turbocharger's hydrostatic bearing at considerable pressure. An external gear pump is most suitable for medium flows and pressures. An external gear pump consists of two meshing gears. The driver gear rotates the driven and while meshing low pressure zone is created and the downstream which sucks in the fluid. The fluid flows past the casing and the teeth surface and at the upstream the squeezing action produces high pressure.

Oil filter

An oil filter is a filter designed to remove contaminants from engine oil, transmission oil, lubricating oil, or hydraulic oil. Oil filters are used in different machinery. A chief use of the oil filter is in internal-combustion engines. Gas turbine engines, such as those on jet aircraft, require the use of oil filters. Oil filter consists of an element made of bulk material (such as cotton waste) or pleated Filter paper to entrap and sequester suspended contaminants. As material builds up on (or in) the filtration medium, oil flow is progressively restricted. This requires periodic replacement of the filter element

Oil storage tank

Gas turbines will have integral lubricating systems to prevent damage caused by excessive friction. Often a portion of the lubricating oil is used in the hydraulic oil systems for hydraulic control devices. Lubricating oil is typically stored in integral stainless steel and carbon steel tanks that are monitored for level

Radiator

Radiators are heat exchangers used to transfer the thermal energy from one medium to another for the purpose of cooling and heating. To cool down the engine, coolant heated from flowing through the engine is fed into the header of the radiator via the inlet and then cools down as it circulates through the tubes to the opposite header and cold coolant exits back into the engine via the outlet, and the cycle is repeated. As it circulates through the tubes, the coolant transfers its heat to the tubes which, in turn, transfer the heat to the fins that are lodged between each row of tubes. The fins then radiate the heat transferred by the tubes to the surrounding air, hence the term radiator

The combustion system:

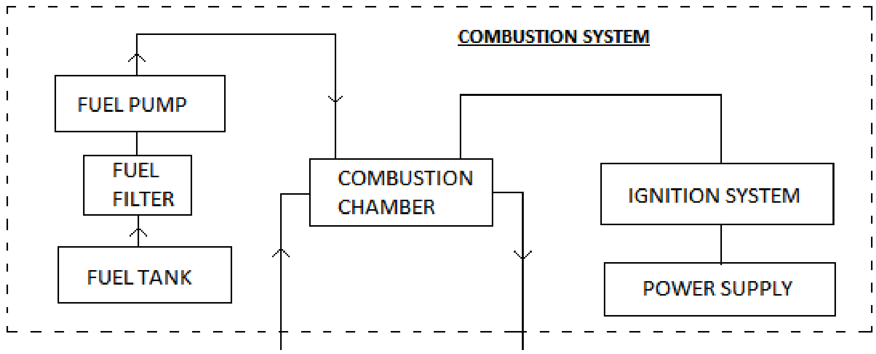


Fig: The combustion system

The combustion system consists of the combustion chamber, the ignition system, and the fuel pumping system which consists of fuel pump, fuel filter and fuel tank.

A gas turbine combustion chamber can be defined as a chamber which provides a space for formation of air fuel mixture, its combustion and thus formation of high temperature gases at highest combustion efficiency with minimum loss of chamber pressure.

The fig above is the cross-sectional view of the combustion chamber. It consists of the outer cylinder called casing and the inner cylinder called flame tube. The casing and the flame tube are both made up of the sheet metal. The flame tube is supported in the outer casing. The flame tube consists of the holes which are symmetrically drilled on the surface of the flame tube. The fuel nozzle situated at the center of the snout sprays the pressurized fuel into fine droplets. The flame tube is divided into three zones on the basis of the functionality of each zone. The three zones are primary, secondary and tertiary zones. These zones contain primary, secondary and tertiary holes respectively.

The combustor is a critical component since it has to operate at reliably high temperatures and provide suitable temperature distribution of hot gases at the entry to the turbine and create a minimum amount of pollutants over a long operating life. The operational requirement of a gas turbine combustion chamber is that even if the atmospheric conditions change, the combustor must deal with continuously varying fuel flow without allowing the engine to flame out or exceed temperature limits. The size and the design of the gas turbine combustion chamber are very critical for the efficient operation of the combustion chamber and it varies with the requirements.

Ignition system

The ignition system consists of 230V AC supply, an ignition coil, ignition coil driver circuit and a spark plug. The function of an ignition system is to produce high intensity spark at equal intervals of time. The 230V AC acts as a power source. 230V AC voltage is applied to the ignition coil which is transformer. The ignition coil transforms the 230V AC into 15,000V AC. This temporary surge of high voltage is enough to produce high intensity spark. The ignition coil driver circuit serves to break and make the circuit to obtain spark at equal intervals of time

Fuel pumping system

Fuel tank

A fuel tank is safe container for flammable fluids. Though any storage tank for fuel may be so called, the term is typically applied to part of an engine system in which the fuel is stored and propelled into an engine

Fuel filter

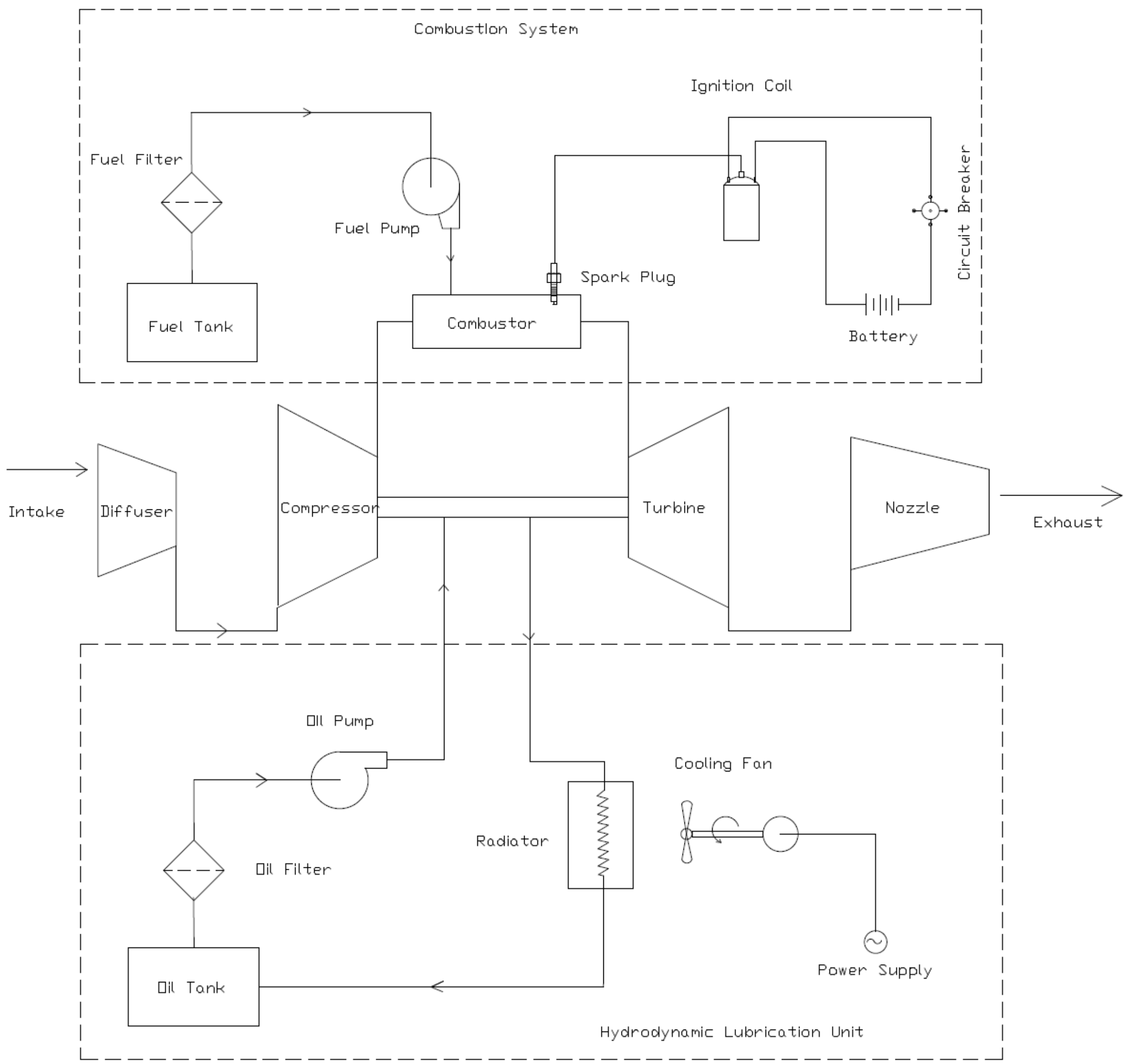
A fuel filter screens out dirt and rust particles from the fuel, normally made into cartridges containing a filter paper. They are found in most internal combustion engines. Unfiltered fuel may contain several kinds of contamination, for example paint chips and dirt that has been knocked into the tank while filling, or rust caused by moisture in a steel tank. If these substances are not removed before the fuel enters the system, they will cause rapid wear and failure of the fuel pump and injectors, due to the abrasive action of the particles on the high-precision components used in modern injection systems. Fuel filters also improve performance, as the fewer contaminants present in the fuel, the more efficiently it can be burnt.

Fuel pump

A fuel pump for jet engine is required to deliver fuel in small quantities at extremely high pressures to achieve the required atomization. An internal gear pump is most suitable for such application. An internal gear pump functions in the similar way as that of external gear pump except that the meshing gears are internal rather than external.

Equivalent Diagrammatic Representation of the physical model:

The equivalent diagrammatic representation of the physical model is nothing but representation with the blocks replaced by the equivalent symbols for each component. It helps in easy understanding of the circuit diagram. The main feature of the diagrammatic representation is the elimination of the need to label the components, once the symbols for each component is known no further aid is required for understanding the circuit diagram. The diagrammatic model for the above block model is constructed below.



Theoretical working of the model:

In order to understand the working of the jet engine model one has to know the principle of working of the gas turbine. A gas turbine consists of three basic units' viz. a compressor (radial/axial), a turbine (impulse/reaction) and a combustion chamber.

In order to produce an expansion through a turbine a pressure ratio must be provided and the first necessary step in the cycle of the gas turbine plant must therefore be compression of the working fluid. If after compression, the working fluid was to be expanded directly in the turbine and there were no losses in either of the component, the power developed by the turbine would just equal that absorbed by the compressor. Thus if the two were coupled together the combination would do no more than turn itself round. But the power developed by the turbine can be increased by addition of the energy to raise the temperature of the working fluid prior to expansion. Since the working fluid is air a very suitable means of doing this is by the combustion of the fuel in the air which has been compressed. Expansion of the hot working fluid then produces greater power output from the turbine, so that it is able to provide a useful output in addition to driving compressor. This represents the gas turbine or internal combustion turbine in its simplest form. The three components viz. compressor, turbine and the combustion chamber connected together are shown diagrammatically in fig below.

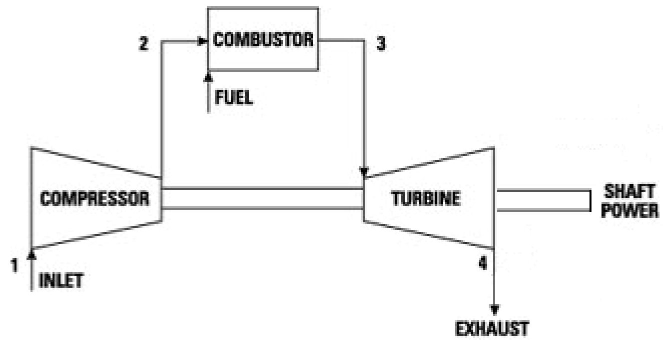


Fig: Simple gas turbine system

Having understood the working of a simple gas turbine, understanding the working of the jet engine project shouldn't be difficult because the working cycle of the model is same as that of simple gas turbine. For the sake of simplicity the working of the model is explained in three stages again on the basis of the functionality.

The Turbocharger unit:

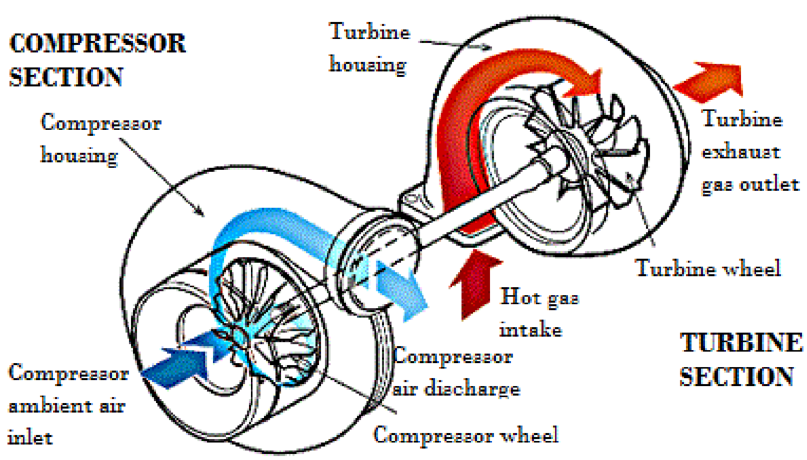


Fig: Working of Turbocharger

The turbojet engine project makes use of a large diesel truck turbocharger; this is simply because the turbocharger serves as an integrated compressor and turbine assembly. Thus eliminating to construct or separately search for the individual compressor and turbine units. This reduces a great deal of task as far as making of the project is concerned. The construction of the turbocharger has already been explained in the component description, it resembles very much like an actual gas turbine with centrifugal compressor coupled to the radial turbine, supported by a hydrodynamic bearing system. The combustion chamber is not present in turbocharger. The working cycle of the turbocharger matches with that of the simple gas turbine. Thus the functional working of the turbocharger atleast for this project is same as that of the simple gas turbine. The working of the turbocharger is explained below.

Working of turbocharger:

1. Through the air inlet the ambient air enters the compressor of the turbo.
2. The air is then compressed to increased density (mass/unit volume flow). Air enters the compressor at a temperature equivalent to atmosphere, but as compression causes the temperature to rise, it leaves the compressor at temperatures of 200 degrees C and more at high boost applications.
3. Sometimes a charge air cooler (intercooler) is employed after compressor unit that cools the compressed air to further increase its density and thus the amount of oxygen in same volume of air charge.
4. After passing through the outlet of the compressor, the air enters the combustion chamber where the air is mixed with the fuel to form a combustible air fuel mixture which is then burned.
5. After the air fuel mixture is burned in the combustion chamber it then flows into the turbine housing.
6. The high temperature gases then continue on to the radial turbine blades. The turbine rotates due to the impulse action of the high temperature high pressure gases.
7. A pressure and temperature drop occurs (heat expansion) across the turbine, which harnesses the exhaust gas energy to provide the power necessary to drive the compressor.
8. Not all the power produced by the turbocharger turbine is used to drive the compressor, part of the energy of the hot gases is used to drive the compressor and part is exhausted to the atmosphere.
9. In order to make some use of these exhausting hot gases which is otherwise wasted, we make use of an exhaust nozzle. The exhaust nozzle is a convergent nozzle which

adiabatically converts the pressure energy of the exhaust gases in to kinetic energy. This kinetic energy is used to get the useful thrust which can be suitably used for propulsive application.

The combustion system:

The working of the turbojet engine using a turbocharger is simply not possible without a combustion system. This makes combustion system extremely crucial in the overall functioning of the engine. The combustion system forms the heart of the engine; when this heart stops functioning, the functioning of all other related component ceases. The combustion system as said earlier consists of a combustion chamber, an ignition system and a fuel pumping system.

The combustion chamber forms the main mixing zone to achieve the stoichiometric air fuel ratio. In order to produce good stoichiometric air fuel mixture, right quantities of the fuel has to be mixed with the air continuously. Thus a fuel pumping system is the used here. The fuel pump produces sufficiently pressurized fuel which is then injected in to the combustion chamber by means of a spray nozzle. In order to produce good air fuel mixture the spray characteristics of the spray nozzle is to be given important consideration.

This stoichiometric mixture is then ignited by means of an ignition system. The ignition system consists of a high intensity spark plug producing a spark of high intensity. The energy for the spark is obtained from a 12V DC battery. The 12V DC is transformed into 10,000V AC by means of a transformer. Once the mixture is ignited and the turbine has reached the sufficient speed the ignition system is switched off.

Inside the combustion chamber the entire volume is divided in to three zones on basis of their functioning viz. the primary, secondary and the tertiary zone. The ignited mixture in the primary zone consists of partially burnt hydrocarbons/ fuel. In secondary zone these partially burnt HC's are converted into CO_2 and H_2O thus further releasing energy. The temperatures reached in the secondary zone can cross 1000 degrees Fahrenheit. Such high temperatures can cause hot streaks to appear on the turbine blades. In extreme cases the thermal stresses can even cause buckling of the blades, so to limit the temperature of the hot gases tertiary zone comes to the rescue. Inside the tertiary zone the high temperature hot gases are mixed with the cold air. The tertiary chamber functions in two ways viz. by bringing the temperature of the hot gases to the permissible limits and evenly distributing the heat flux throughout the chamber area. The even heat distribution helps in minimizing uneven thermal stresses on the turbine blades thus prolonging life of turbine blades.

The figure below shows the three zones of the combustion chamber with their functioning diagrammatically.

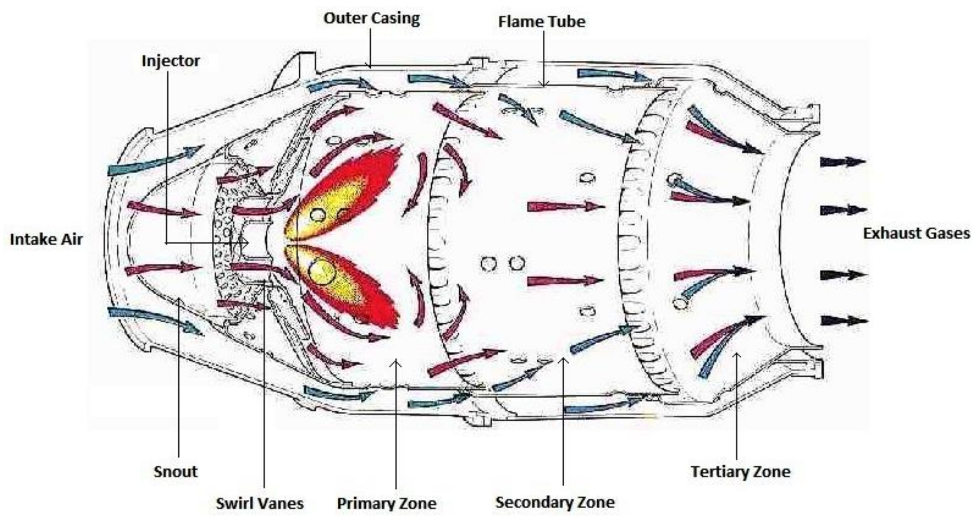
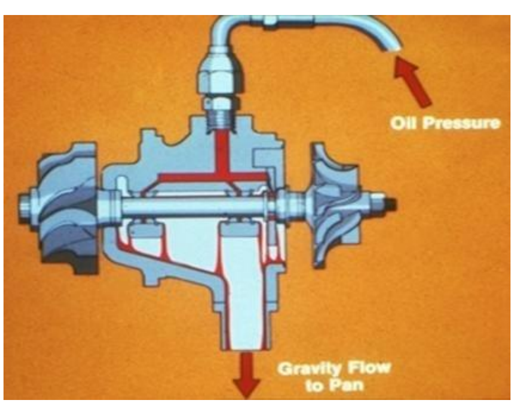


Fig: Combustion chamber of Jet engine

The hydrodynamic lubrication unit:

The hydrostatic lubrication system consists of an oil pump, oil filter, oil storage tank and an air cooled radiator. The hydrostatic lubrication unit is meant for the functioning of the turbocharger bearing. The turbocharger bearing requires continuous pumping of the clean lubricating oil for its operation. The lubrication oil from the oil pump is fed under pressure into the bearing housing, towards the journal bearings and the thrust bearing system. After passing through the bearing system oil flows out to the pan under gravity. The bearing system and the lubrication mechanism of the turbocharger have been briefly explained below.

The bearing system and lubrication mechanism:



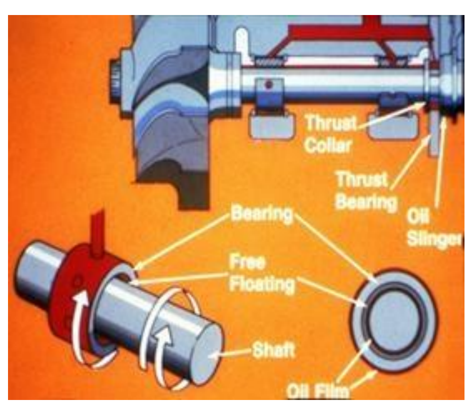


Fig: Lubrication mechanism Fig: Turbo bearing system

The bearing system used is called a hydro-dynamic bearing system. 2 rotating journal bearings rotate on the shaft and inside the bores in the bearing housing, to control the radial shaft movements and vibrations.

To control the axial rotor movements, a tapered land type thrust bearing has been positioned at the compressor end of the bearing housing. The thrust bearing is fixed and does not rotate. The lubrication system of the thrust bearing has been arranged with a steel thrust collar supporting the thrust bearing at the bottom side

The entire lubrication system works with a very thin film of oil. The result is, that the complete rotor is 'free floating' on a thin film of oil, both axial and radial

The oil flowing out of the bearing system of the turbocharger can be extremely hot. Most of the oils cannot withstand temperatures exceeding 150 degree Celsius hence to bring down the temperature the lubricating oil is allowed to pass through the air cooled radiator. The order in which the oil flows is from oil tank to oil filter to radiator to oil pump and from oil pump to the bearing system and finally from hydrodynamic bearing back to the oil tank.

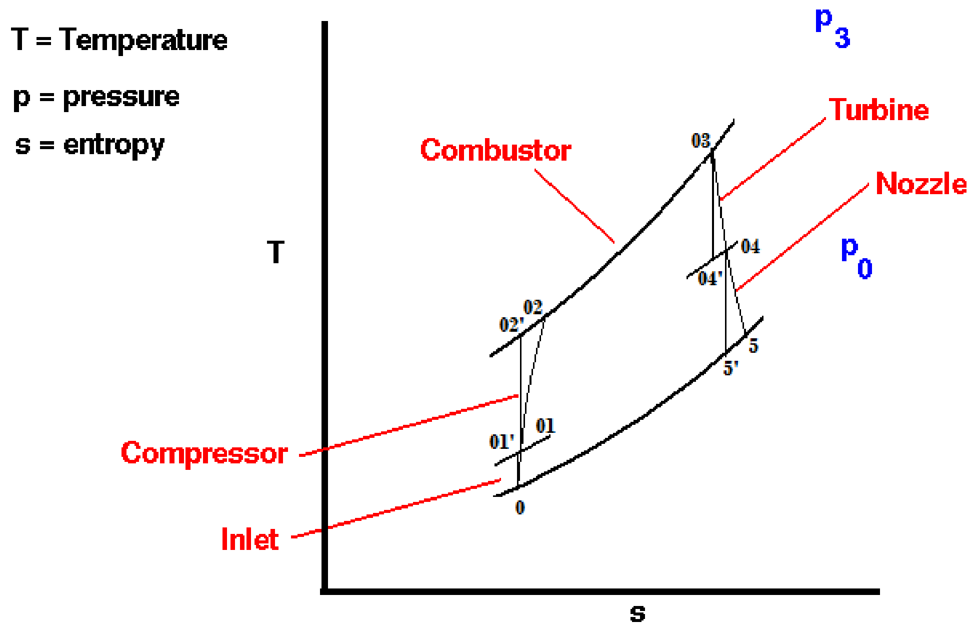
Mathematical model of Turbojet engine:

The mathematical model of turbojet engine is nothing but its thermodynamic model (cycle) and its complete analysis with all assumptions clearly stated.

The basic thermodynamic cycle of a turbojet engine of p-v and T-s diagrams is given in the figure below. This is Joule or Brayton cycle. In the analysis of turbojet cycles following assumptions are made.

1. As the fluid velocities are high in turbojet engine, the change in the kinetic energy between the inlet and the outlet of each component will be taken into account.
2. The compression and expansion processes are irreversible adiabatic involving increase in entropy.
3. Fluid friction results in pressure loss in combustion chamber.
4. The mass flow is assumed to be same in spite of addition of fuel.
5. The values of the Cp and γ of the working fluid vary throughout the cycle due to change of temperature and due to changes in the chemical composition of the working medium.

6. Slightly more work than that required for the compression process will be necessary to overcome bearing and windage friction in the transmission and to drive ancillary components.



Various processes occurring in the turbojet engine are depicted in the figure above. The energy equations for these processes are written below.

Inlet diffuser

Ambient air enters the diffuser at the pressure Po, temperature To and velocity Ci. The pressure rises to P1 at the diffuser exit where the velocity is reduced to Cj. There is no energy transfer; only energy transformation takes place here.

$$h_0 = h_{01}$$

$$\frac{T_{01'}}{T_0} = \left(\frac{P_{01'}}{P_0}\right)^{\frac{\gamma-1}{\gamma}}$$

Therefore pressure ratio,

$$\therefore \frac{P_{01'}}{P_0} = \left(\frac{T_{01'}}{T_0}\right)^{\frac{\gamma}{\gamma-1}}$$

Diffuser efficiency is given by;

$$\eta_d = \frac{P_{01} - P_0}{P_{01'} - P_0}$$

Therefore the static pressure rise in the diffuser is given by;

$$\frac{p_{01}}{p_0} = (1 + \eta_d \frac{\gamma - 1}{2} M^2)^{\frac{\gamma}{\gamma - 1}}$$

Compressor

Air enters the compressor at reduced velocity and Mach number. Its pressure and enthalpy is raised to P2 and h2 in the actual process (01-02). Both energy transformation and transfer occur in this process.

The actual work done by the compressor on the air is given by;

$$W_c = h_{02} - h_{01} = C_p \left(T_{02} - T_{01}\right)$$

Compressor pressure rise is given by;

$$\frac{P_{02'}}{P_{01}} = \left(\frac{T_{02'}}{T_{01}}\right)^{\frac{\gamma}{\gamma - 1}}$$

Now, the process of compression is not an ideal process so the performance of the compressor is given by compressor efficiency;

$$\eta_c = \frac{h_{02'} - h_{01}}{h_{02} - h_{01}}$$

Thus,

$$h_{02} - h_{01} = \frac{1}{\eta_c}(h_{02'} - h_{01}) = \frac{C_p}{\eta_c}(T_{02'} - T_{01})$$

$$W_c = h_{02} - h_{01} = C_p \left(T_{02} - T_{01}\right) = \frac{C_p T_{01}}{\eta_c}(\frac{T_{02'}}{T_{01}} - 1) = \frac{C_p T_{01}}{\eta_c}\left[\left(\frac{P_{02}}{P_{01}}\right)^{\frac{\gamma}{\gamma - 1}} - 1\right]$$

Combustion Chamber

Air enters the combustion chamber from the compressor at pressure P2, temperature T2. The combustion of the fuel increases the enthalpy of the air-fuel mixture. The mass of high temperature gases flowing from the combustion chamber to the turbine and the propelling nozzle is given by:

$$\dot{m}_j = \dot{m}_i + \dot{m}_f$$

$$\dot{m}_j = \dot{m}_i(1+f)$$

$$f = fuel\_ratio = \frac{\dot{m}_f}{\dot{m}_i}$$

Heat supplied in the combustion process is given by;

$$q = h_{03} - h_{02}$$

$$= C_p\left(T_{03} - T_{02}\right)$$

Again due to incomplete combustion the combustion process is inefficient the performance of the combustion chamber is given by;

$$\eta_{comb} = \frac{h_{03} - h_{02}}{f.Q_f}$$

Where Qf is the specific heat of the fuel.

Turbine

The products of the combustion from the combustion chamber enter the turbine at the pressure P3, temperature T3. Properties of these gases are different from those of the air flowing through the inlet diffuser and compressor. Expansion of the gases through the turbine and the nozzle is shown in the cycle. Both the energy transformation and transfer occur in this process.

Work done by turbine is given by,

$$W_T = h_{03} - h_{04} = C_p\left(T_{03} - T_{04}\right)$$

Pressure ratio of the turbine is given by;

$$\frac{P_{03}}{P_{04'}} = \left(\frac{T_{03}}{T_{04'}}\right)^{\frac{\gamma}{\gamma-1}}$$

Turbine efficiency is given by;

$$\eta_T = \frac{T_{03} - T_{04}}{T_{03} - T_{04'}}$$

Therefore;

$$TurbineWork = h_{03} - h_{04} = \eta_T C_p T_{03}\left[1 - \left(\frac{P_{04}}{P_{03}}\right)^{\frac{\gamma}{\gamma-1}}\right]$$

Also work done by the turbine is used to drive the compressor therefore;

$$h_{02} - h_{01} = h_{03} - h_{04}$$

$$i.e. \quad \frac{C_p T_{01}}{\eta_c}\left[\left(\frac{P_{02}}{P_{01}}\right)^{\frac{\gamma}{\gamma-1}} - 1\right] = \eta_T C_p T_{03}\left[1 - \left(\frac{P_{04}}{P_{03}}\right)^{\frac{\gamma}{\gamma-1}}\right]$$

Nozzle

Exhaust gases from the turbine enter the propelling nozzle at pressure P4, temperature T4. The gases expand adiabatically to the exit pressure P5. There is no energy transfer; only energy transformation occurs here.

$$h_{04} = h_{05'}$$

Nozzle pressure ratio is given by;

$$\frac{P_{04}}{P_{05'}} = \left(\frac{T_{04}}{T_{05'}}\right)^{\frac{\gamma}{\gamma-1}}$$

Nozzle efficiency is defined as the ratio of the actual and isentropic values of the enthalpy drop.

$$\eta_{noz} = \frac{h_{04} - h_5}{h_{04} - h_{5'}}$$

Now change in enthalpy in nozzle is given by;

$$h_{04} - h_5 = \eta_{noz} C_p T_{04} \left[1 - \left(\frac{P_5}{P_{04}} \right)^{\frac{\gamma}{\gamma-1}} \right]$$

Also;

$$h_{04} - h_5 = \frac{C_j^{\,2}}{2}$$

$$\therefore \quad \frac{c_j^{\,2}}{2} = \eta_{noz} C_p T_{04} \left[1 - \left(\frac{P_5}{P_{04}} \right)^{\frac{\gamma}{\gamma-1}} \right] \qquad or \qquad c_j = \sqrt{2\eta_{noz} C_p T_{04} \left[1 - \left(\frac{P_5}{P_{04}} \right)^{\frac{\gamma}{\gamma-1}} \right]}$$

Trust

The force which propels the object forward is called as trust or propulsive force. In case of the turbojet engine this propulsive force is developed by the jet at the exit of the propelling nozzle. Propulsive force developed by the nozzle is given by;

$$\therefore Thrust = \dot{m}_i \left[\left(1 + \dot{f} \right) c_j - c_i \right]$$

The thrust per Kg of the air flow is known as Specific thrust and is given by;

$$I_{SP} = \frac{F}{\dot{m}_a} = (c_j - c_i)$$

Now; The specific static thrust is given by;

$$c_i = 0 \qquad (I_{SP})_{St} = c_j \quad (I_{SP})_{St} = specific\_static\_thrust$$

Hence to develop a large specific thrust jet speed should be as large as possible.

Let $\Delta h_{\max}$ be the enthalpy drop in the nozzle corresponding to the velocity C_j, then jet speed is given by;

$$\frac{c_j^{\ 2}}{2} = \Delta h_{\max}$$

$$c_j = \sqrt{2C_p \Delta T}$$

Data Assumptions:

$\eta_c = 77\%$

$\eta_T = 78\%$

$\eta_{noz} = 85\%$

$\eta_{Tran} = 92\%$

$\eta_{comb} = 85\%$

$\gamma_a = 1.4$

$\gamma_g = 1.33$

$C_{pa} = 1.005\_KJ / Kg / K$

$C_{pg} = 1.147\_KJ / Kg / K$

$T_{amb} = T_0 = 293K$

$P_{amb} = P_0 = 0.98bar$

Compressor inlet temperature $T_{01} = 300K$

Turbine outlet temperature $T_{04} = 920K$

$\Delta P_{comb} = 0.2bar$

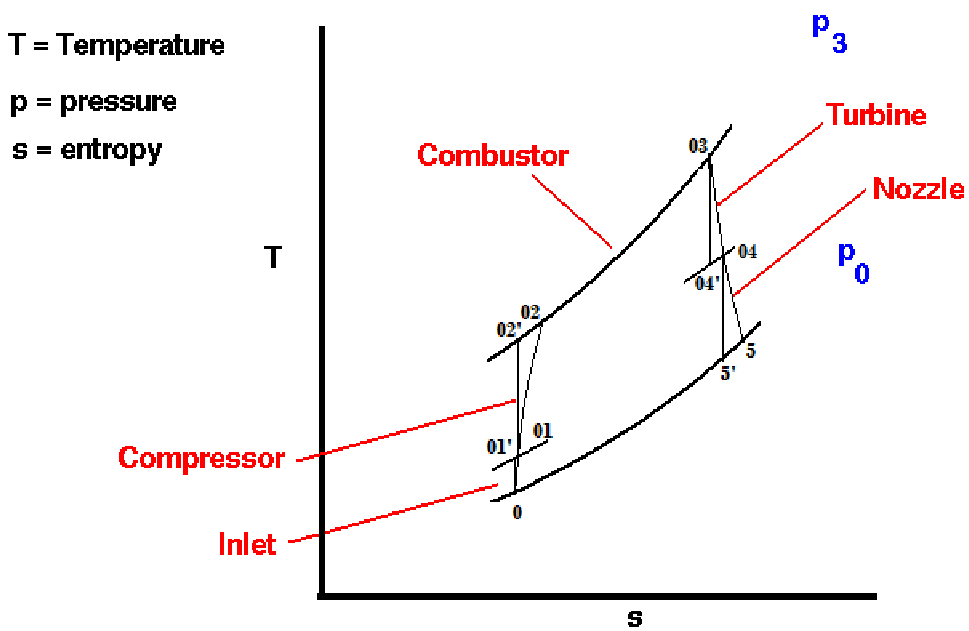
$Q_f = 43\_MJ$

$$Pressure\_Ratio = \frac{P_{02}}{P_{01}} = 2.5$$

Output Variables Required:

1. Compressor outlet temperature $T_{02} = ?$
2. Turbine inlet temperature $T_{03} = ?$
3. Turbine pressure ratio $\frac{P_{03}}{P_{04}} = ?$
4. Nozzle outlet temperature $T_{05} = ?$
5. Jet speed $C_5 = ?$
6. Intake air mass flow rate $\dot{m}_a = ?$
7. Air-fuel ratio $\frac{\dot{m}_a}{\dot{m}_f} = ?$
8. Fuel flow rate $\dot{m}_f = ?$
9. Exhaust gases mass flow rate $\dot{m}_g = ?$

Solution:



1. Diffuser
   Assume diffuser is absent in the turbocharger unit, hence there is no ramming therefore air directly enters the compressor eye at atmospheric pressure at temperature 300K

2. Compressor
   Air enters the compressor at temperature 300K and pressure 0.98 bar. Pressure ratio of the compressor is assumed to be 2.5

$$\frac{T_{02'}}{T_{01}} = \left(\frac{P_{02'}}{P_{01}}\right)^{\frac{\gamma_a - 1}{\gamma_a}}$$

$$T_{02'} = T_{01} \times \left(\frac{P_{02'}}{P_{01}}\right)^{\frac{\gamma_a - 1}{\gamma_a}}$$

$$= 293 \times 2.5^{0.286}$$

$$= 380.3K$$

$$\therefore T_{02'} = 380.3K$$

   Compressor efficiency

$$\eta_c = \frac{T_{02'} - T_{01}}{T_{02} - T_{01}}$$

$$T_{02} - T_{01} = \frac{T_{02'} - T_{01}}{\eta_c}$$

$$= \frac{380.3 - 293}{0.77}$$

$$= 114.15K$$

$$\underline{\therefore T_{02} = 407.15K}$$

3. Turbine
   All the work done by the turbine is used to drive the compressor therefore
   Work done by turbine=Work done on compressor

$$\eta_{Tran} \times C_{pg}\left(T_{03} - T_{04}\right) = C_{pa} \times \left(T_{02} - T_{01}\right)$$

$$T_{03} - T_{04} = \frac{C_{pa} \times \left(T_{02} - T_{01}\right)}{\eta_{Tran} \times C_{pg}}$$

$$= \frac{1.005 \times (114.15)}{0.92 \times 1.147}$$
$$= 108.7K$$

$$\therefore T_{03} - T_{04} = 108.7K$$

Now $T_{04} = 920K$

$$\therefore T_{03} = 1028.7K$$

Turbine efficiency

$$T_{03} - T_{04} = \eta_T \times T_{03} \times \left(1 - \frac{1}{r_t^{\frac{\gamma_g - 1}{\gamma_g}}} \right)$$

$$108.7 = 0.78 \times 1028.7 \times \left[1 - \frac{1}{r_t^{\frac{1.33-1}{1.33}}} \right]$$

$$\therefore r_t = 1.8$$

$$r_t = \frac{P_{03}}{P_{04}} = \frac{P_{02} - \Delta P_{comb}}{P_{04}}$$

$$\therefore P_{04} = \frac{P_{02} - \Delta P_{comb}}{r_t}$$
$$= \frac{2.5 - 0.2}{1.8}$$
$$= 1.278$$

$$\therefore P_{04} = 1.278$$

4. Nozzle

   Exhaust gases from turbine outlet enters the propelling nozzle at pressure P_{04} and temperature T_{04}.

$$\frac{T_{04}}{T_{5'}} = \left(\frac{P_{04}}{P_5}\right)^{\frac{\gamma_g - 1}{\gamma_g}}$$

$$= \left(\frac{1.278}{1}\right)^{\frac{1.33-1}{1.33}}$$

$$= 1.0628$$

$$\therefore T_{5'} = \frac{T_{04}}{1.0628} = \frac{920}{1.0628} = 865.57K$$

Nozzle efficiency

$$\eta_{noz} = \frac{T_{04} - T_{5'}}{T_{04} - T_5}$$

$$T_{04} - T_5 = \frac{T_{04} - T_{5'}}{\eta_{noz}}$$

$$= \frac{920 - 865.57}{0.85}$$

$$= 64.035$$

$$\underline{\therefore T_5 = 855.96K}$$

Jet speed

$$\frac{C_5^{\ 2}}{2C_{pg}} = T_{04} - T_5 = 64.035$$

$$C_5 = \sqrt{2 \times C_{pg} \times \Delta T}$$

$$= \sqrt{2 \times 1147 \times 64.035}$$

$$= 383.27 m/s$$

$$\underline{\therefore C_5 = 383.27 m/s}$$

Thrust

$$F = \dot{m}_a \times \left(C_j - C_i\right)$$

$C_i = 0$

$\therefore F = \dot{m}_a \times (C_j)$

$\dot{m}_a = \dfrac{F}{C_j} = \dfrac{150}{383.27} = 0.39$

$\underline{\dot{m}_a = 0.39kg / s}$

Air-Fuel ratio

$h_{03} - h_{02} = \eta_{comb} \times \dot{m}_f \times C.V$

$\dot{m}_a \times C_{pa} \times (T_{03} - T_{02}) = \eta_{comb} \times \dot{m}_f \times C.V$

$\dfrac{\dot{m}_f}{\dot{m}_a} = f = \dfrac{C_{pa} \times (T_{03} - T_{02})}{\eta_{comb} \times C.V}$ = Fuel: Air ratio

$= \dfrac{1.005 \times (1028.7 - 407.15)}{0.85 \times 43000}$

$= 0.017$

Therefore Air-Fuel ratio is given by $= 58.5:1$

Fuel flow rate

$\dot{m}_f = \dot{m}_a \times f$

$= 0.39 \times 0.017$

$= 6.63 \times 10^{-3}$

$= 0.4kg / \min$

$\underline{\therefore \dot{m}_f = 0.4kg / \min}$

Exhaust gases mass flow rate

$\dot{m}_g = \dot{m}_f + \dot{m}_a$

$= 0.39 + 0.00663$

$$= 0.4 kg / s$$

$$\therefore \dot{m} = 0.4 kg / s$$

Tabulated Results & its examination:

Sr. No.	Output Variable	Calculated Values	Expected Values	Comment on calculated Values	Status of acceptance
1	Compressor outlet temperature T_{02}	407.15K	425K	OK	Acceptable
2	Turbine inlet temperature T_{03}	1028.7K	1060K	OK	Acceptable
3	Turbine pressure ratio $\frac{P_{03}}{P_{04}}$	1.8	2	OK	Acceptable
4	Nozzle outlet temperature T_{05}	855.96K	850K	OK	Acceptable
5	Jet speed C_5	383.27m/s	416m/s	LESS	Acceptable
6	Intake air mass flow rate $\dot{m}_a$	0.39kg/s	0.85kg/s	LESS	Acceptable
7	Air-fuel ratio $\frac{\dot{m}_a}{\dot{m}_f}$	58.5:1	90:1	LESS	Acceptable
8	Fuel flow rate $\dot{m}_f$	0.4kg/min	0.56kg/min	OK	Acceptable
9	Exhaust gases mass flow rate $\dot{m}_g$	0.4kg/s	1.41kg/s	LESS	Acceptable

Inferences:

Based on the tabulated results of the above analysis following inferences can be deduced:

1. Due to personal error the results are deviated a little.

2. The assumptions are made merely on the basis of personal judgments and cannot be justified as such.
3. The assumptions can go wrong in certain cases.
4. The results obtained are within the permissible limits to be accepted
5. There is no further need to apply corrections and reanalyze the calculation at this stage.

Conclusion:

Thus on basis of the inferences made in the above section we have come to the conclusion that no correction is to be applied for the above calculation; the reanalysis of the design procedure is thus not required. It can be suitably stated that the design analysis carried out on the basis of the assumptions made is feasible and the results are within the range of acceptance.

Detailed Design and selection of components

The design and the selection of various components will be completely based on the results obtained in the analysis of the mathematical model of turbojet engine.

1. Turbocharger

There are a number of factors, such as turbo lag, boost threshold, heat, back-pressure, low-end torque, and top-end power, that must be taken into account when selecting a turbo. A large turbo will suffer from turbo lag and won't produce much low-end torque but it also won't put too much heat to the intake charge, won't have much back-pressure, and will produce loads of top-end power. A small turbo, on the other hand, won't have much turbo lag and will produce loads of low-end torque but will also have lots of back-pressure and will add lots of heat to the intake charge. The turbocharger selection based on the operating characteristics of the compressor and turbine is widely used for the selection of turbocharger for passenger cars. For the turbojet engine application the turbocharger is selected on the basis of the compressor and turbine maps which are explained in the section below.

Operating characteristics of Compressor:

The compressor operating behavior is generally defined by maps showing the relationship between pressure ratio and volume or mass flow rate. The useable section of the map relating to centrifugal compressor is limited by the surge and choke lines and the maximum permissible compressor speed.

Surge line

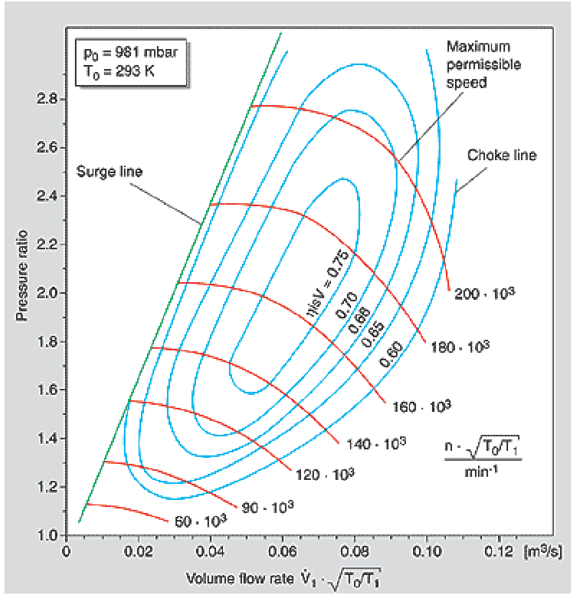


Fig: Compressor map of a turbocharger for passenger car applications

The map width is limited on the left by the surge line. This is basically "stalling" of the air flow at the compressor inlet. With too small a volume flow and too high a pressure ratio, the flow can no longer adhere to the suction side of the blades, with the result that the discharge process is interrupted. The air flow through the compressor is reversed until a stable pressure ratio with positive volume flow rate is reached, the pressure builds up again and the cycle repeats. This flow instability continues at a fixed frequency and the resultant noise is known as "surging".

Choke line

The maximum centrifugal compressor volume flow rate is normally limited by the cross-section at the compressor inlet. When the flow at the wheel inlet reaches sonic velocity, no further flow rate increase is possible. The choke line can be recognized by the steeply descending speed lines at the right on the compressor map.

Operating characteristics Turbine

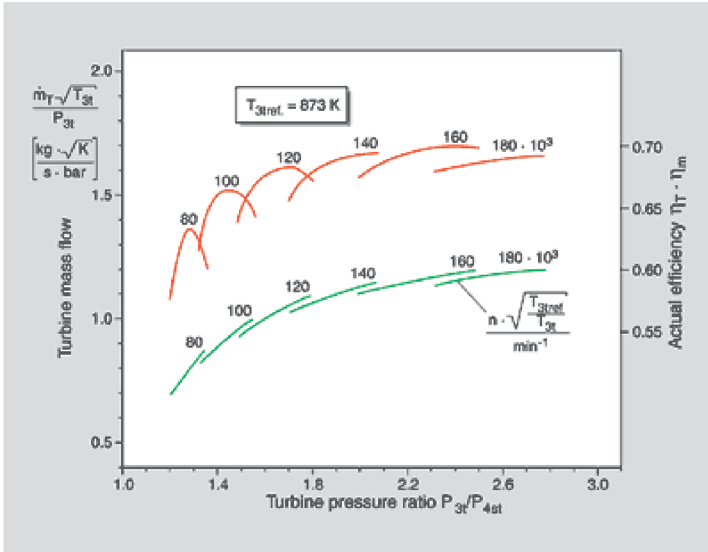


Fig: Turbocharger turbine map

The turbine's characteristic behavior is determined by the specific flow cross-section, the throat cross-section, in the transition area of the inlet channel to the volute. By reducing this throat cross-section, more exhaust gas is dammed upstream of the turbine and the turbine performance increases as a result of the higher pressure ratio. A smaller flow cross-section therefore results in higher boost pressures. The turbine's flow cross-sectional area can be easily varied by changing the turbine housing.

Besides the turbine housing flow cross-sectional area, the exit area at the wheel inlet also influences the turbine's mass flow capacity.

The operating characteristics of exhaust gas turbocharger turbines are described by maps showing the flow parameters plotted against the turbine pressure ratio. The turbine map shows the mass flow curves and the turbine efficiency for various speeds. To simplify the map, the mass flow curves, as well as the efficiency, can be shown by a mean curve

For high overall turbocharger efficiency, the co-ordination of compressor and turbine wheel diameters is of vital importance. The position of the operating point on the compressor map determines the turbocharger speed. The turbine wheel diameter has to be such that the turbine efficiency is maximized in this operating range.

Requirements of Turbocharger:

1. It should be a diesel truck turbocharger.
2. It should be sturdy and robust to withstand high speeds, stresses and forces.
3. Compressor pressure ratio should be around 2.5.
4. Operating speed of the turbocharger must be greater than 70,000 rpm.

5. Turbine pressure ratio/Boost pressure should be high around 2.
6. Individual efficiencies of the compressor and turbine should be high.
7. Turbocharger should be able to withstand high dynamic vibrations.
8. Turbo lag should be minimum
9. Back pressure should be minimum
10. Turbo bearing must be hydrodynamic bearing with forced lubrication mechanism.
11. The lubrication system should be simple and easy to maintain.
12. The turbo lubricant should be easily available and cheap.
13. Operating temperatures of turbine should be high around 1000 degree Celsius.
14. High reliability at top speeds.
15. Overall maintenance of the turbocharger should be easy; turbocharger parts should be easily available.

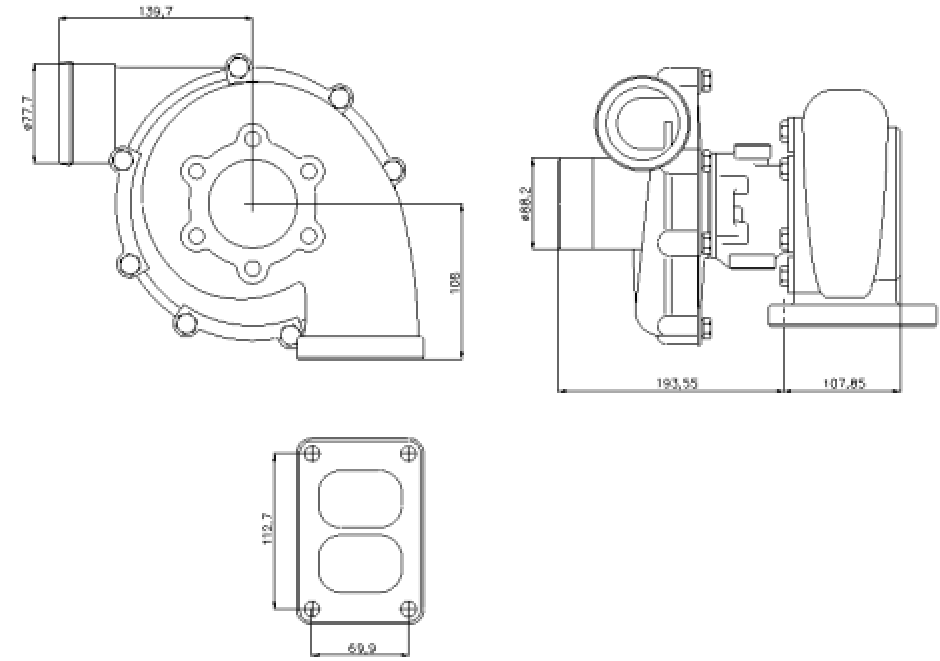
Selection of Turbocharger

There are many diesel truck turbochargers manufacturing industries in the world but based on our requirements of the turbocharger we select CZ STACONICE turbocharger, the details of the turbocharger is listed below.

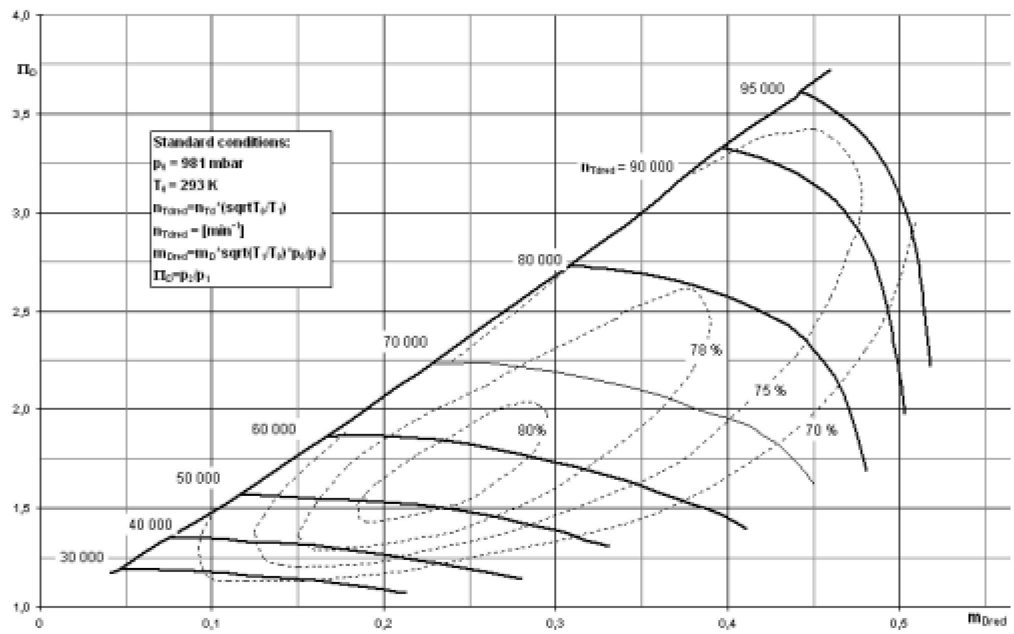
MANUFACTURER	:	CZ STRACONICE
COUNTRY	:	CZECH REPUBLIC
TYPE	:	K36 3566 2521
ASSY	:	K36 79 06
CUSI	:	TATRA
SERIAL	:	247134-97058
APPLICATION	:	LIAZ,TATRA
MOTOR OUTPUT	:	160 - 450 kW

TURBO-CHARGER K36 - 97

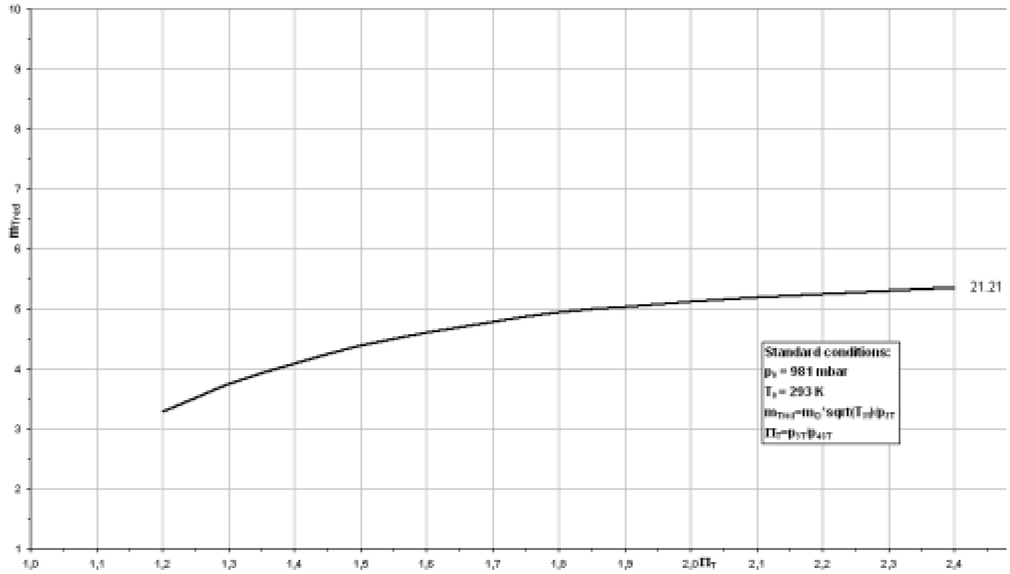
Construction drawing:



Graph 1: Compressor map



Graph 2: Turbine map



2. Combustion chamber

This section deals with the detailed design of the combustion chamber of the modeled turbojet engine. The design includes deciding the dimension of the combustion chamber, their particular shape, size, and areas of primary, secondary, tertiary zones, location of igniter, areas of the primary, secondary, tertiary holes and their respective location to achieve self-stabilizing flame. In the combustion chamber design, the major goals to be achieved are high combustion efficiency, reduction of visible smoke, reduction of oxides of nitrogen.

The size and shape of the combustion chamber vary with their requirements. A land-based gas turbine will have least restrictions as far as weight and size is concerned but aircraft application based gas turbines (Jet engine) will have more restriction on its size and weight. Since our gas turbine is meant for producing thrust similar to like jet engines of aircraft but on small scale; we will focus our attention on the combustion chamber of jet aircraft engine. Though it won’t matter much even if the design is based on the land-based gas turbines, but they are huge, complicated and too costly to suit our small scale turbojet engine.

Designing a combustion chamber is a complex process; many factors have to be simultaneously taken into consideration while designing. The shape and size will definitely affect these factors, like a too long combustor will involve more pressure loss and if the same combustor is too short it will lead to incomplete combustion. Even size matters, for a small turbocharger it is worth less to build a huge combustion chamber. All these precautions have been incorporated in the design procedure of this combustor.

Approach towards combustor design

1. Study of the existing jet aircraft combustion chamber.
2. Deriving empirical relations based of the study.
3. Manipulation of the empirical relations suited for our application.
4. Calculation of the combustor dimensions and other design details based on manipulated empirical relations.
5. Initial combustor model based on calculations.
6. Incorporation of necessary changes to the initial design to suit practicality and construction feasibility of the combustor.
7. Final model of combustor.

Some important factors affecting combustor design.

The main factors influencing the design of the combustion chamber for the gas turbines are.

1. The temperature of the gases after the combustion must be comparatively low to suit the highly stressed turbine materials.
2. At the end of the combustion chamber the temperature distribution must be of known form if the turbine blades are not to suffer from local overheating. In practice temperature increases with the radius from root to tip.
3. Combustion must be maintained in the stream of air moving with high velocity of 30-60 m/s and stable operation is required over a wide range of air/fuel ratio from full load to idling conditions. The air fuel ration might vary from about 60:1 to 120:1 for simple cycle gas turbines and from 100:1 to 200:1 if heat exchange is used. Considering that the Stoichiometric ratio is approximately 15:1 it is clear that high dilution is required to maintain the temperature level acceptable for turbine blades.
4. The formation of carbon deposits must be avoided, particularly the hard brittle variety. Small particles carried into the turbine in the high velocity gas stream can erode the blades and block cooling air passages; furthermore, aerodynamically excited vibration in the combustion chamber might cause sizable pieces of the carbon to break free, resulting in even worse damage to the turbine.
5. Avoidance of the smoke in the exhaust is of the major importance for all types of gas turbine.

6. Although gas turbine combustion systems operate at extremely high efficiencies, they produce pollutants such as oxides of nitrogen (NOX), carbon monoxide (CO) and unburned hydrocarbons (UHC) and these must be controlled at very low levels.

Analytical design of combustion chamber for the turbojet engine project:

Before starting the analytical design of the combustion chamber it is essential to keep in mind what requirements the combustion chamber needs to fulfill.

Requirements of the combustion chamber:
The main function of the combustion chamber for the turbojet engine project is to provide for the complete combustion of the fuel and air, the air being supplied by the compressor of the turbocharger and the products of the combustion being delivered to the turbine wheel of the turbocharger. In carrying out this function, the combustion chamber must fulfill following requirements.

1. Complete combustion of the fuel must be achieved.
2. The total pressure loss must be minimum
3. Carbon deposits must not be formed under any expected condition of operation
4. Ignition must be reliable and must be accomplished with ease over wide range of atmospheric conditions
5. Temperature and velocity distribution at the turbine inlet must be controlled
6. The volume and the weight of the combustor must be kept within the reasonable limits.
7. Reliability and endurance should be ascertained

The complete analytical design of the combustion chamber involves following steps.

1. Deciding size and shape of the entire combustion chamber
2. Division of three zones on the flame tube
3. Flame stabilization technique
4. Location of fuel spray nozzle
5. Calculation of total area of holes
6. Calculation of number of holes in each zone
7. Location of holes in each zone
8. Location of igniter
9. Final assembly of the combustion chamber with all details clearly depicted

1. Size and shape of the combustion chamber

This is extremely vital step in achieving an effectively functioning combustion chamber. The size & shape will definitely affect other factors like a too long combustion chamber will have a benefit of having a good mixing length and thus more chances of complete combustion but at the same time it will involve a more pressure loss and thus loss in efficiency. On the other hand a too short combustion chamber has an advantage of minimum loss of the pressure but at the same time it will lead to incomplete combustion thus a tradeoff has to be achieved between minimum loss of the combustor pressure and high combustion efficiency. Besides the technical aspect it is also essential to ascertain the feasibility consideration for example it is worthless to build a huge combustion chamber for a small size turbocharger. All these factors are taken into consideration in deciding size and shape of the combustion chamber.

Size of the combustion chamber

Deciding size of the combustion chamber involves deciding the length and the diameter of the flame tube and the outer air casing. The following empirical relation will help in deciding the above factors.

Empirical Relations:

Overall length of the outer casing = $6 \times$ Inducer diameter
Overall diameter of the outer casing = $2 \times$ Inducer diameter
Length of the flame tube = $6 \times$ Inducer diameter
Diameter of the flame tube = $2 \times$ Inducer diameter $-$ Air gap between outer casing &flame tube
Optimum air gap between outer casing and flame tube = 0.5 inch

Optimized dimensions of the combustion chamber
The empirical relation gives a basic idea of the size of the combustion chamber for starters. It is a crude judgmental approach for deciding the dimensions and needs to be optimized suited for our application. The following refinements have been made based on the feasibility and economical point of view.

Overall length of the outer casing:
Overall diameter of the outer casing:
Length of the flame tube:
Diameter of the flame tube:
Optimum air gap between outer casing and flame tube

Fig: Initial design depicting the dimensions

Shape of the combustion chamber

The shape of the combustion chamber is figured out based on three factors i.e. the compressor outlet, the turbine inlet and the arrangement of the combustion chamber on to the turbocharger.

The combustion chamber is arranged coaxially with the turbine inlet flange, i.e. the exhaust end or the exhaust flange of the combustion chamber is coaxial with the inlet flange of turbine. To do so it is essential to match the end dimensions of both the flanges thus the combustion chamber is provided with a taper at the exhaust end. The combustion chamber will lie vertically in line with the turbine flange and thus compressor end is connected to the combustion chamber via ducts with series of bends. Note that the shape of only outer casing has been refined the flame tube has not been touched. The basic shape is depicted in the fig below.

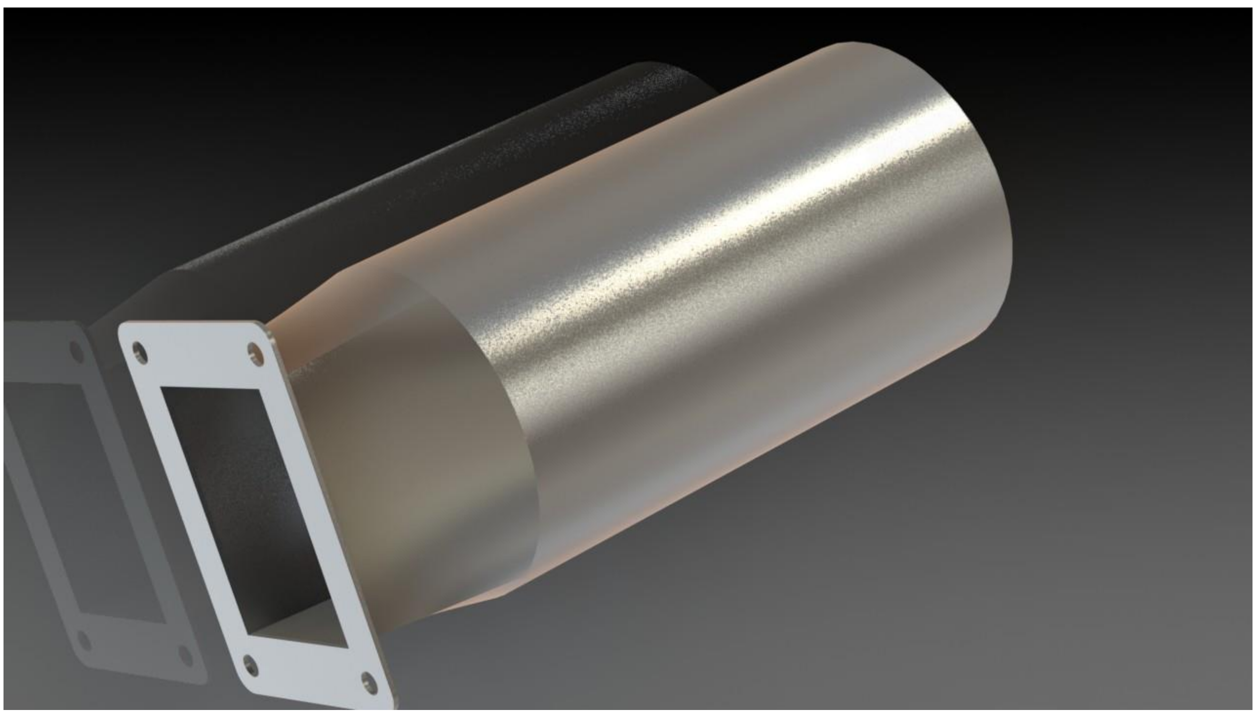


Fig: Initial design of combustor with taper at exhaust end and ducts at the compressor end.

The next step is mounting the flame tube in the outer casing. There are certain requirements to be fulfilled in designing the mounting system for the flame tube in the outer casing, the requirements are listed below.

i. The mounting should be strong enough to hold the flame tube in place.
ii. The mounting system should be capable to withstand high axial forces of combustion.
iii. It should be capable to withstand high temperatures of combustion.

iv. It should be simple in design.
v. It should assists in easy assembling and disassembling of flame tube for maintenance.

The three flange system for mounting the flame tube will be best suited for the application. The three flange system as the name suggest consists of three flanges. The first flange is welded to the flame tube, the second one is welded to the inside of the casing and the third one is welded to the front pipe. All the three flanges are bolted together to form a single assembly depicted in the figure below.

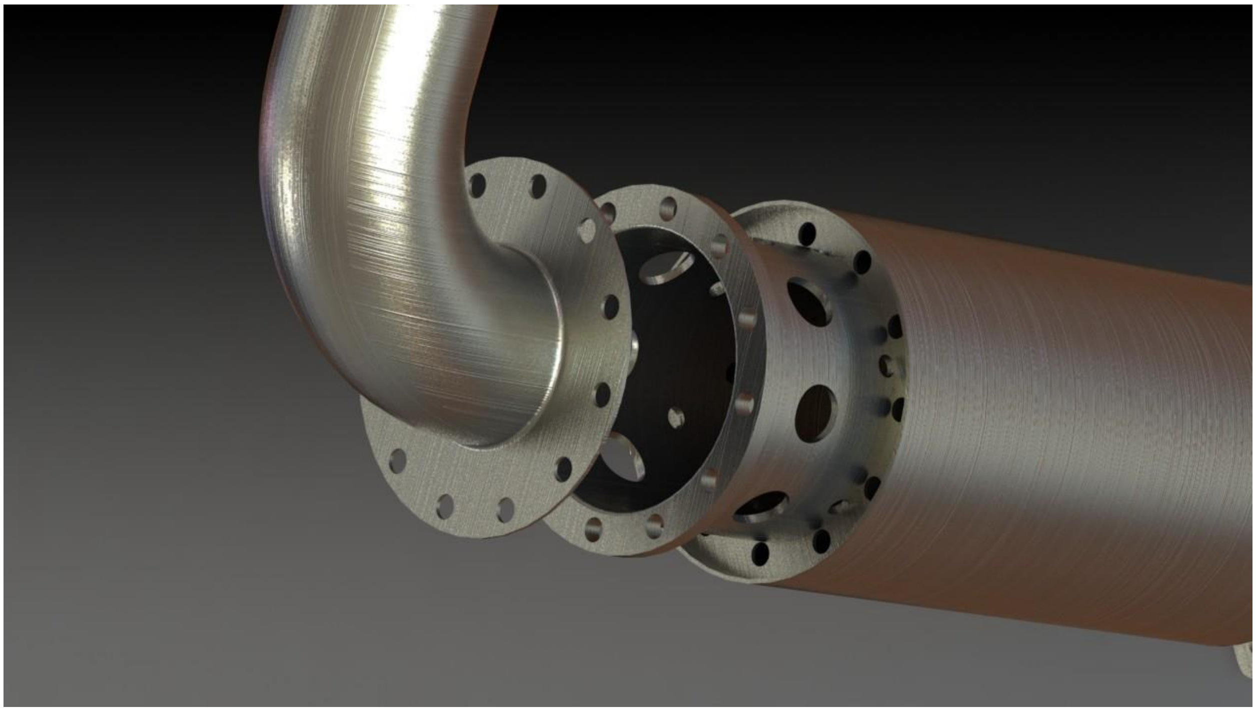


Fig: Initial design with the three flange mounting system.

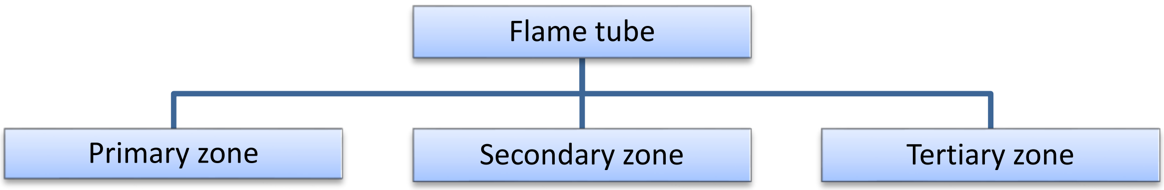
2. Division of zones on the flame tube

Since the overall air: fuel ratio is in the region of 100:1, while the stoichiometric ratio is approximately 15:1 the first essential feature is that the air should be introduced in stages. Three such stages can be distinguished.

1. Primary zone: It is also called the reaction zone; it develops the necessary high temperature for rapid reaction or rate of flame propagation. The primary zone must have flame stabilizers such as baffles to establish a recirculating zone. The flame stabilization is explained in detail in latter step.
2. Secondary zone: It is also called as mixing zone. It has a function in the combustion process in promoting mixing and ensuring adequate oxygen for the fuel for complete combustion downstream of the nominal reaction zone.

3. Tertiary zone: It is also called as dilution zone. It helps in bringing down the temperature of the products of combustion to the required level acceptable to the turbine blades.

Division of flame tube is shown in the figure below:



3. Flame stabilization

The zonal method of introducing the air cannot by itself give a self piloting flame in air stream which is moving in order of magnitude faster than flame speed in the burning mixture. The essential requirement is therefore to provide a recirculation zone which directs some of the burning mixture in the primary zone back into the incoming fuel and air. To achieve this the fuel is injected in the same direction as the air stream, and the primary air is introduced through the twisted radial vanes, known as *swirl vanes*, so that the resulting vortex motion will induce a region of low pressure along the axis of chamber. This vortex motion is enhanced by secondary sir through the short tangential chutes in the flame tube. The net result is that burning gases tend to flow towards the region of low pressure, and some portion of them is swept round towards the jet of the fuel.

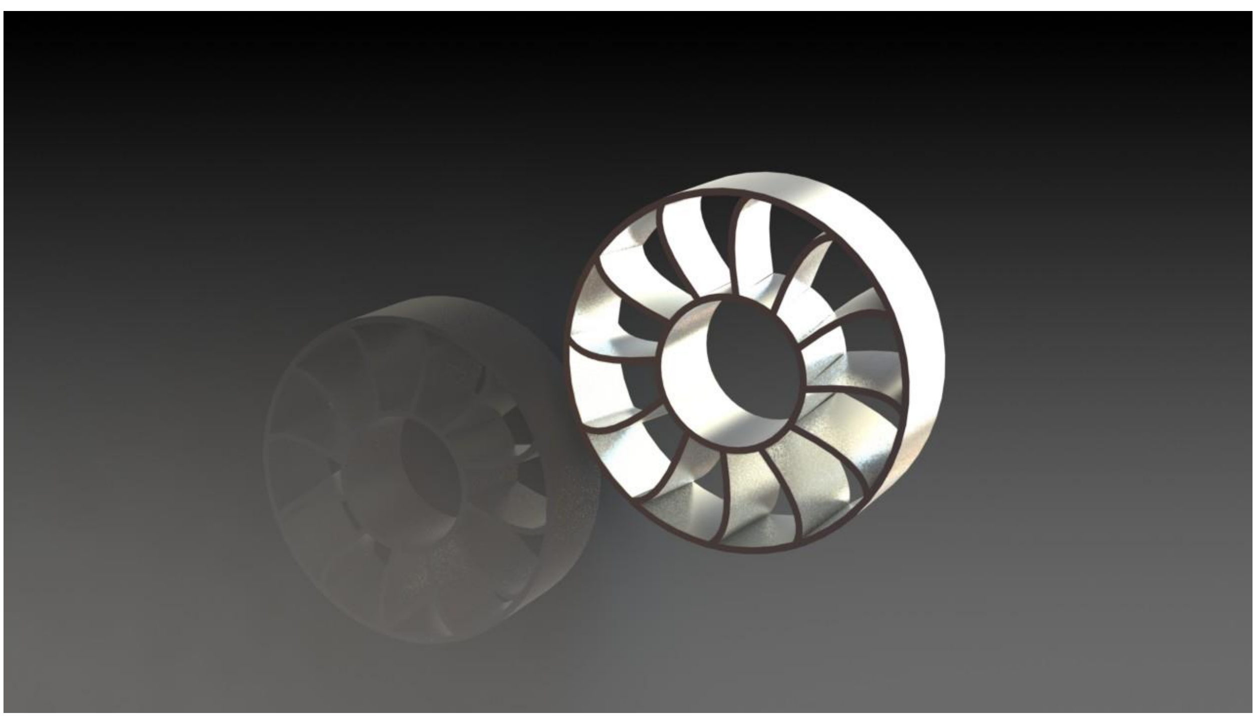


Fig: Swirl vanes

In order to incorporate the swirl vanes in the flame tube an arrangement has to be made in the primary zone to mount the swirl vanes and this is achieved by introducing the flare in the flame tube. The flare performs two functions i.e. it has an arrangements for mounting the swirl vanes and it also has tangential holes for introducing the short tangential chutes in the flame tube.

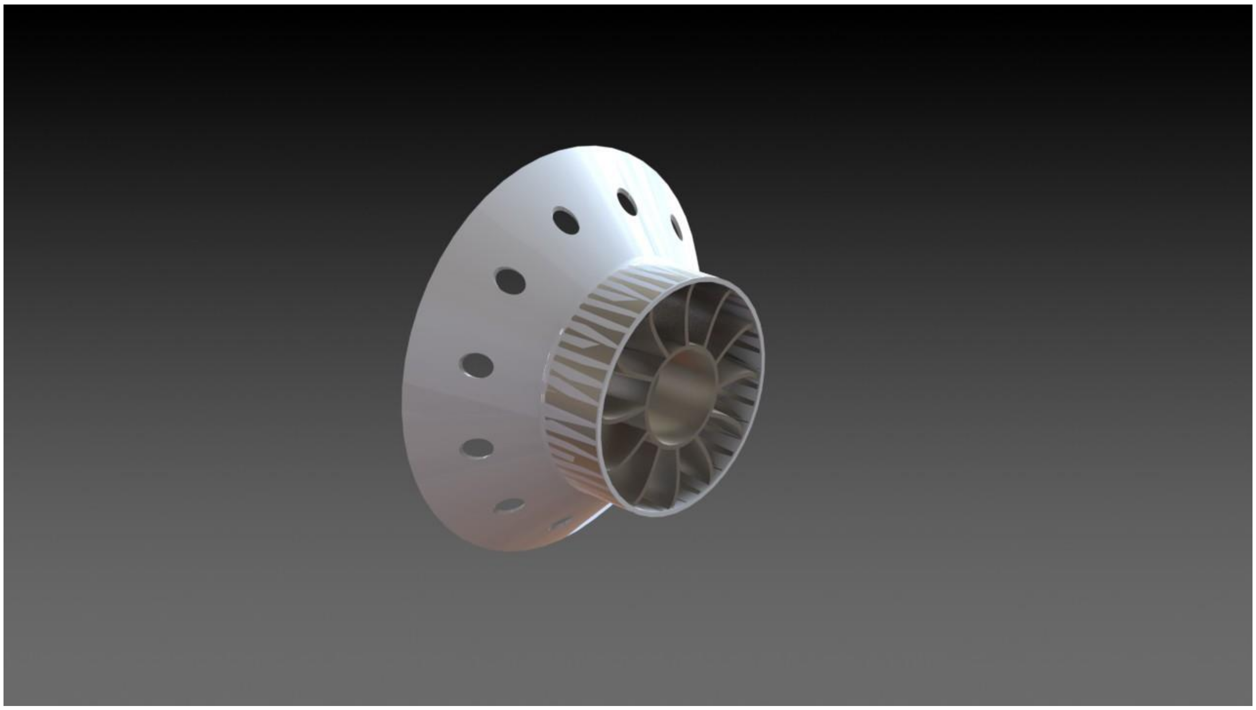
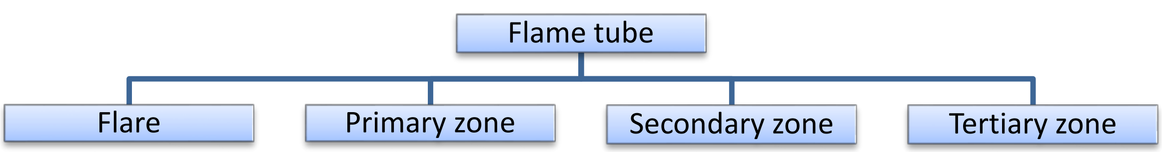


Fig: Flare with Swirl vanes

Thus flame tube should accommodate space for the flare other than three zones. The sub-division of the flame tube is shown in the fig below.



4. Location of fuel spray nozzle

The design of the flame tube demands that the fuel spray nozzle should be capable of spraying atomized fuel in the direction of the air i.e. along the axis of the flame tube, thus in order to stick to the design, fuel nozzle is arranged coaxially with the swirl vanes. The swirl vanes have a central blank hole for mounting the fuel nozzle.

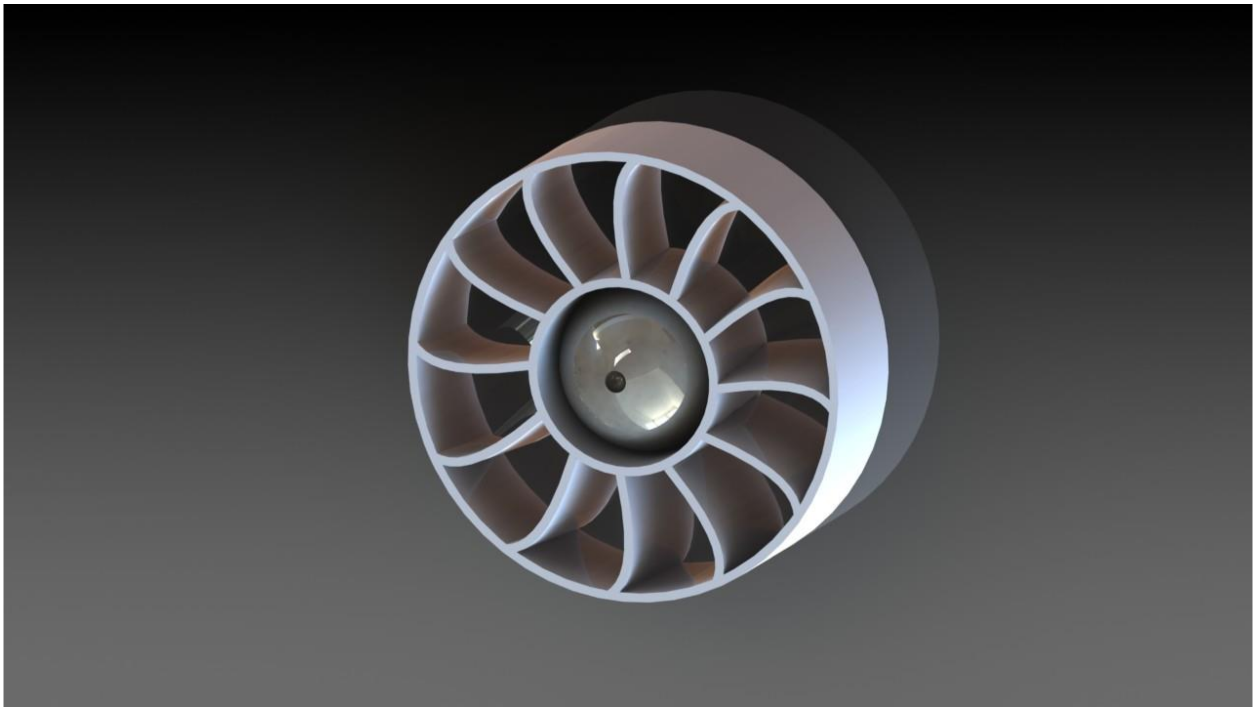


Fig: Swirl vanes with fuel spray nozzle at the centre.

5. Calculation of total area of holes on the flame tube

As discussed earlier the flame tube has been sub-divided into four zones, therefore air after entering the flame tube of the combustion chamber has to go through the four successive stages namely flare, primary zone, secondary zone and finally tertiary zone. All the zones including flare consist of holes of different areas. The size of the holes is of utter importance as effective functioning of the combustion chamber depends on the introduction of the right amount of the air at the right points. The total amount of the air entering the combustion chamber is roughly broken down below.

i. Around 15 to 20% of the air is introduced around the jet of the fuel through the primary holes in the primary zone to provide the necessary high temperature for rapid combustion.
ii. Some 30% of the total air is then introduced through secondary holes in the flame tube in the secondary zone to complete the combustion. For high combustion efficiency, this air must be introduced at the right points in the process, to avoid chilling of the flame locally and drastically reducing the reaction rate in that neighborhood, and finally
iii. In the tertiary or the dilution zone the remaining air through tertiary holes is mixed with the products of combustion to cool them down to the temperature required at the inlet to the turbine. Sufficient turbulence must be promoted so that the hot and the cold streams are thoroughly mixed to give the desired outlet temperature distribution, with no hot streaks which would damage the turbine blades

Empirical relations

Total area of the holes = Inducer area of turbocharger =i.e.

Primary holes + Secondary holes + Tertiary holes + Flare holes & Swirl vanes = 6083 mm^2.

Flare holes and Swirl vanes = 10-20% $\times$ (Total area of holes) =912.3 mm^2

Primary hole area = 15-20% $\times$ (Total area of holes) =1216.42 mm^2

Secondary hole area = 30% $\times$ (Total area of holes) =1824.6 mm^2

Tertiary hole area = Remaining % $\times$ (Total area of holes) =3041.6 mm^2

Calculation of the actual values by optimization:

The optimization is based on the vigorous trial and error technique and is finely tuned with the practicability from the construction and continuous operation point of view. Thus the optimization has no theoretical base as such; it is merely experimental and judgmental approach.

Flare holes and Swirl vanes = % $\times$ (Total area of holes) =1100 mm^2

Primary hole area = % $\times$ (Total area of holes) =1400 mm^2

Secondary hole area = % $\times$ (Total area of holes) =2000 mm^2

Tertiary hole area = % $\times$ (Total area of holes) =3200 mm^2

6. Calculation of size and number of holes in each zone:

This section of the design is again based on the experimental data and the judgmental methods supported by theory. The dimension and the number of holes in each zone are so decided so as to give maximum benefit from the combustion point of view. The description below will give an indication of the necessity of the precise size and the number of the holes in each zone.

Flare with Swirl vanes: Flare and Swirl vanes acts as flame stabilizers which help to establish a recirculation zone for formation of the sustaining flame. But in addition to stabilization vigorous mixing action must be provided in order to mix air and fuel and then to burn unburnt mixture with burnt gases. The stability parameter indicates that it is better to provide a small number of large baffles than a large number of small baffles.

Primary zone: As the primary zone is the main reaction zone the size and the number of the holes is very critical. Too large holes will introduce chunks of air leading to inappropriate air: fuel mixture thus leaving large number of unburnt hydrocarbons which is not only loss of combustion efficiency but also loss of fuel efficiency; on the other hand too small holes will lead to loss of combustor pressure due to skin friction and thus loss in efficiency again, hence a compromise has to be achieved between the two with a trial and error technique.

Secondary zone: The size of the secondary holes are next in the line to pose criticality because secondary zone functions in promoting mixing and adequate oxygen for the fuel for complete combustion downstream the nominal reaction zone. Thus for high combustion efficiency, the air through the secondary holes must be injected carefully at the right points in the process, to avoid chilling the flame locally and drastically reducing the reaction rate in that neighborhood.

Tertiary zone: The size and the number of dilution air holes is a compromise between a large number of small holes to give fine scale mixing and small number of large holes to give better penetration.

The complete details such as size of the hole, its area, number of holes in each of the four zones including the flare is given in the table below.

Zone	Size(dia in mm)	Area/hole	No. of holes	Total area
Primary	12	116	12	1400
Secondary	14	142	14	2000
Tertiary	20	355	9	3200
Flare	11	100	12	1200

7. Location of holes in each zone:

After having decided the size and the number of the holes in each of the four zones the next vital step is locating the holes on the flame tube. This can be extremely critical as the formation of the sustaining flame is dependent only on the size of the hole and its correct location. Obtaining the precise location of the holes which will yield in highest combustion efficiency is a tedious task. There can be n number of ways to arrange the holes on the flame tube. Lots of trial and error experiments have to be conducted to achieve the best possible location of holes. Using probability and certain degree of trial experimentation the following layout of the holes is obtained.

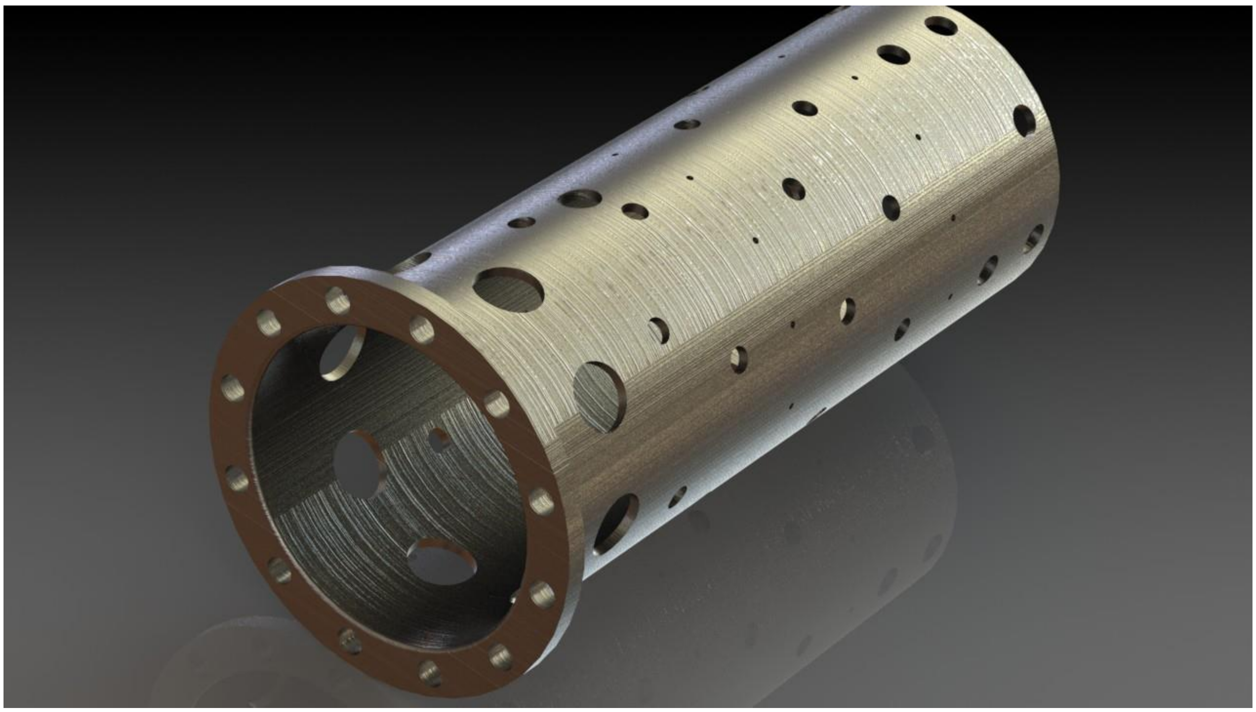


Fig: Layout of Holes on Flame tube

8. Location of igniter:

The igniter is used for the initiation of the ignition. Since the initiation of the ignition takes place in the main reaction zone or primary zone, the igniter should be essentially located in the primary zone. The igniter used for the turbojet engine is a simple standard automotive spark plug. The location of the spark plug is the most critical part of the design. The location of the spark plug both nearer and farther from the jet spray is unfavorable; this can be explained in the following way. The area near the spray nozzle is zone where the fuel and the air mixture formation just begins, since the mixture formation is not an instantaneous process it takes certain amount of time to achieve stoichiometric air: fuel mixture hence this area is unfavorable for locating the igniter as the combustion may never initiate in this area. As you go farther downstream of the combustion chamber the complications begin to start, if the ignition zone shifts downstream the length of the combustion process begins to decrease as a result combustion tends to remain incomplete in the combustion chamber. The completion of the combustion takes place in the turbine zone which increases the chances of turbine meltdown due to extreme temperatures. Thus again a precise compromise has to be reached here this time between probability of combustion initiation and possibility of turbine meltdown.

After vigorous trial and error the location of the spark plug is suitably achieved.

9. Final assembly of the combustion chamber

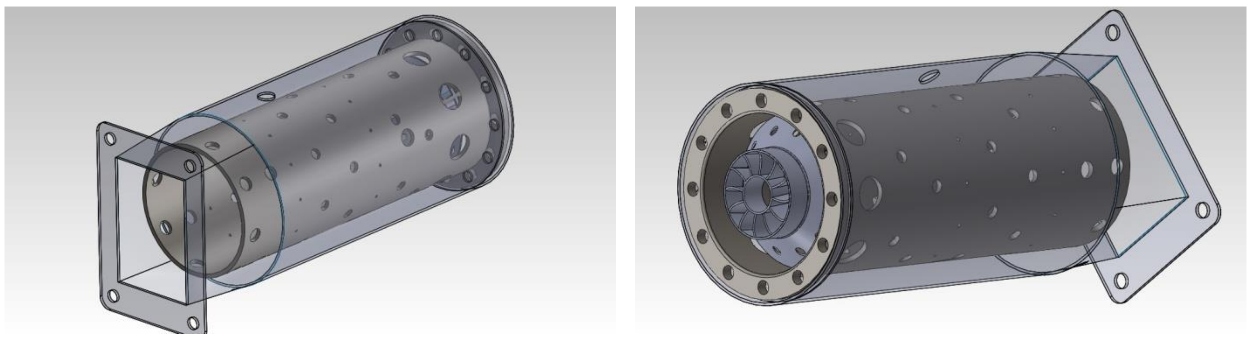


Fig: Final assembly of combustion chamber modeled in solidworks

The complete layout of the combustion chamber is given on the next page.

Nozzle

Analytical design of nozzle
Data:

$P_{04} = 1.278$

$P_{05} = P_a = 1$

$T_{05} = 855.96K$

$T_{04} = 920K$

$\eta_{nozzle} = 0.85$

$C_5 = 383.27m/s$

$\gamma = 1.333$

$\dot{m}_a = 0.39kg/s$

Now, we should check to compare the operating pressure ratio, $\frac{P_{05}}{P_{04}}$, of nozzle with the corresponding critical pressure ratio, $\frac{P_c}{P_{04}}$. If $\frac{P_{05}}{P_{04}}$ > then a simple convergent nozzle is sufficient to give full expansion of the gases, if it is smaller then a convergent-divergent nozzle would be necessary.

$$\frac{P_{05}}{P_{04}} = \frac{1}{1.278} = 0.7824$$

Critical pressure ratio is given by:

$$\frac{P_c}{P_{04}} = \left(\frac{2}{\gamma+1}\right)^{\frac{\gamma}{\gamma+1}}$$

$$\therefore \frac{P_c}{P_{04}} = \left(\frac{2}{1.33+1}\right)^{4.03} = 0.5404$$

$$\frac{P_{05}}{P_{04}} > \frac{P_c}{P_{04}}$$

Thus it can be seen that complete expansion of the gases is possible in convergent nozzle, hence no need of convergent-divergent nozzle.

Now,

$$p_5 v_5 = RT_5$$

Specific volume is given by:

$$\therefore v_5 = \frac{RT_5}{p_5}$$

Where $R = \frac{C_p(\gamma-1)}{\gamma} = \frac{1147 \times 0.33}{1.33} = 284.6 J/kgK$

$$\therefore v_5 = \frac{284.6 \times 855.6}{1 \times 10^5} = 2.436 m^3/kg$$

Let ‘A’ be the required throat area of the propelling nozzle then,

$C_5 \times A = \dot{m}_a \times v_5$

Area is given by:

$$A = \frac{\dot{m}_a \times v_5}{C_5}$$

$$\therefore A = \frac{0.39 \times 2.436}{383.27} = 24.787 \times 10^{-4} m^2$$

$$\therefore A = 24.787 cm^2$$

Let the cross-section of nozzle be circular for ease of manufacturing.

Thus throat diameter is given by:

$$\frac{\pi}{4} d^2 = 24.787$$

$$\therefore d = 5.6378 cm$$

Actual diameter has to slightly larger than this owing to the effect of the effect of the boundary layer at the nozzle outlet.

Let $d = 5.8 cm$

Let cone angle = θ

Importance of cone angle:

Cone angel of the propelling nozzle should be so selected that the back pressure on the turbocharger will be minimum. Smaller the cone angle larger is the back pressure and vice versa. Usual range of the cone angle is (8-12 degree).

Let $\theta = 8$ degree

From geometry of nozzle:

Taper length = $\dfrac{opposite\_length}{\tan(\theta)} = \dfrac{12}{\tan(8)} = 85 cm$

Overall length of nozzle:

Importance of straight length:

Back pressure on the turbocharger is partly affected by the straight length of the nozzle. Smaller the straight length larger is the back pressure and larger the straight length more is the friction loss, thus a compromise has to be reached between the less back pressure and less losses.

Let Straight length = 325 mm

∴ Overall length = 410 mm

Propelling Nozzle Dimensions:

Sr No	Dimension Parameter	Units (mm)
1	Nozzle tube diameter	82
2	Throat diameter	58
3	Cone angle	8 degrees
4	Cone length	85
5	Straight length	325
6	Overall length	410
7	Tube thickness	2

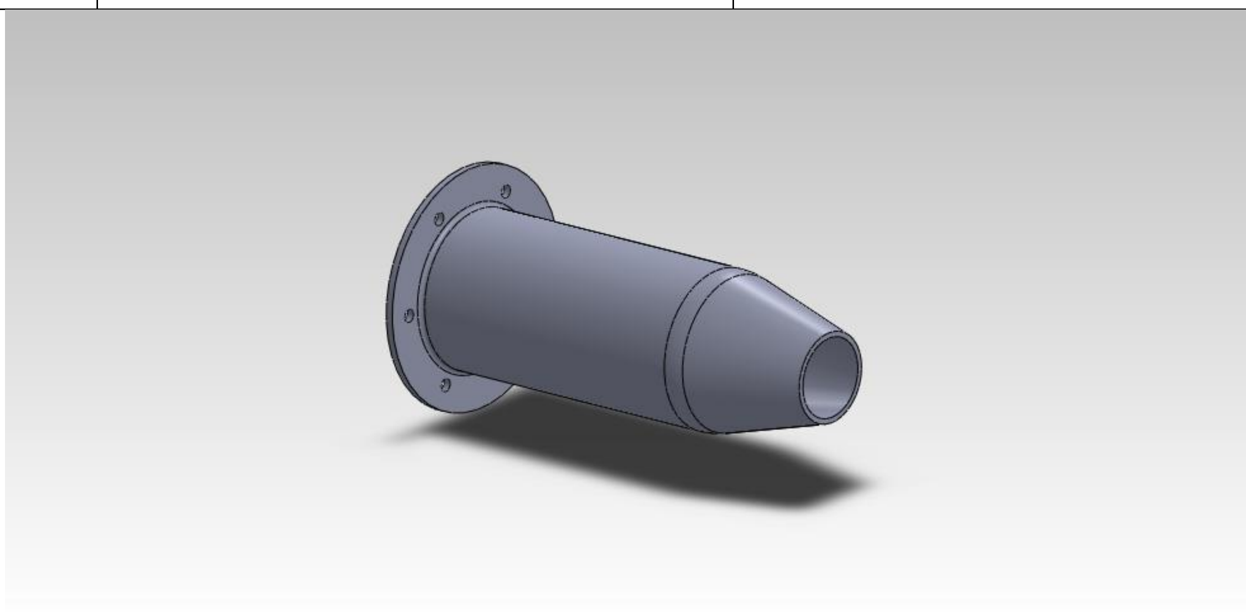


Fig: Nozzle

Gear pump

Selection of gear pump

General requirements of gear pumps for fuel pumping and lubrication:

- Robust and reliable operation
- High and low viscous products
- Smooth flow
- Simple design - only two moving parts
- Easy maintenance
- Reduced down time for service
- Wide range of materials
- High efficiency
- Conforms to API 676

TECHNICAL DATA SHEET (PUMP) EXTERNAL GEAR PUMP FOR LUBRICATION

TYPE	:	EXTERNAL SPUR GEAR PUMP
DUTY	:	CONTINUOUS
INSTALLATION (INDOOR/OUTDOOR)	:	OUTDOOR/INDOOR
LIQUID HANDLED	:	OIL (SAE 5W/50)
CAPACITY –	:	0-900 LPH (10 LPM)
OPERATING PRESSURE	:	10 Kg/Cm2
DISCHARGE PRESSURE	:	10 Kg/Cm2
HEAD (M)	:	0-10 MTR
ACCURACY	:	+/- 1%
MAXIMUM ALLOWABLE SPEED (SPM)	:	200 SPM
TYPE OF CONTROL (MANUAL/AUTOMATIC)	:	MANUAL
SUCTION PRESSURE	:	FLOODED
METHOD OF LUBRICATION	:	SUBMERGED TYPE
LUBRICANT RECOMMENDED	:	ENCLO/SA 460
TYPE OF GEAR	:	SPUR GEAR
PUMP HOUSING	:	CASTING
GLAND PACKING	:	PTFE

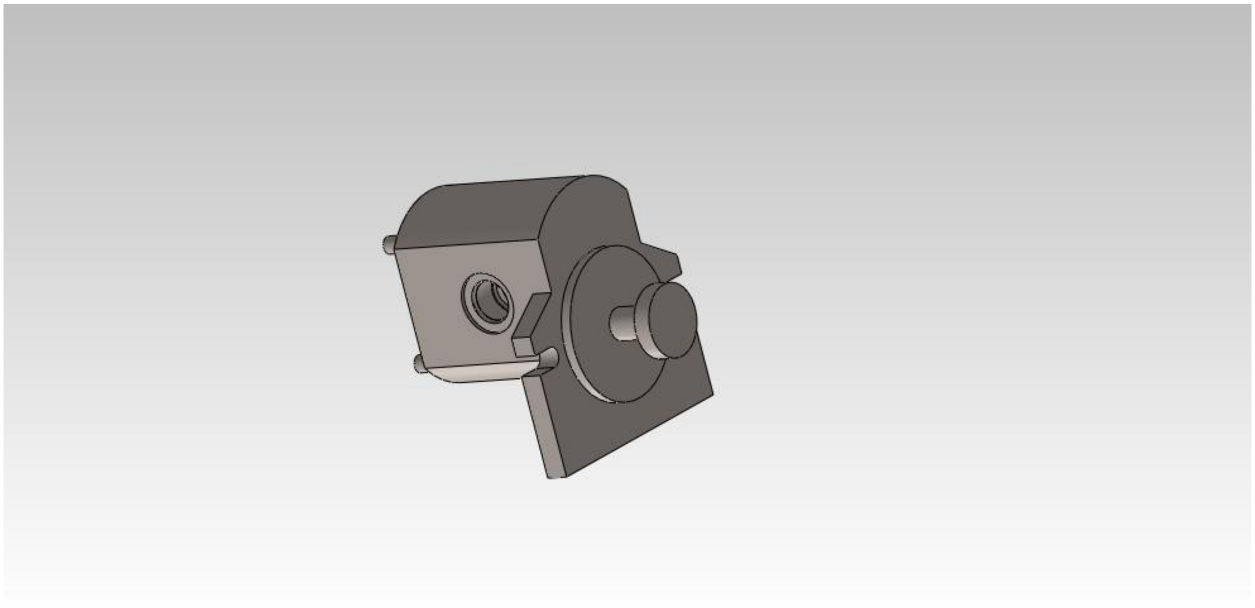


Fig: External gear pump

TECHNICAL DATA SHEET (PUMP) INTERNAL GEAR PUMP FOR FUEL PUMPING

TYPE	:	INTERNAL GEAR PUMP
DUTY	:	CONTINUOUS
INSTALLATION (INDOOR/OUTDOOR)	:	OUTDOOR/INDOOR
LIQUID HANDLED	:	PETROCHEMICAL -KEROSENE
CAPACITY –	:	0-900 LPH (5 LPM)
OPERATING PRESSURE	:	15 Kg/Cm2
DISCHARGE PRESSURE	:	20 Kg/Cm2
ACCURACY	:	+/- 1%
MAXIMUM ALLOWABLE SPEED (SPM)	:	200 SPM
TYPE OF CONTROL (MANUAL/AUTOMATIC)	:	MANUAL
SUCTION PRESSURE	:	FLOODED
METHOD OF LUBRICATION	:	SUBMERGED TYPE
LUBRICANT RECOMMENDED	:	ENCLO/SA 460
TYPE OF GEAR	:	SPUR GEAR
PUMP HOUSING	:	CAST STEEL
GLAND PACKING	:	PTFE
RELIEF VALVE	:	SPRING TYPE

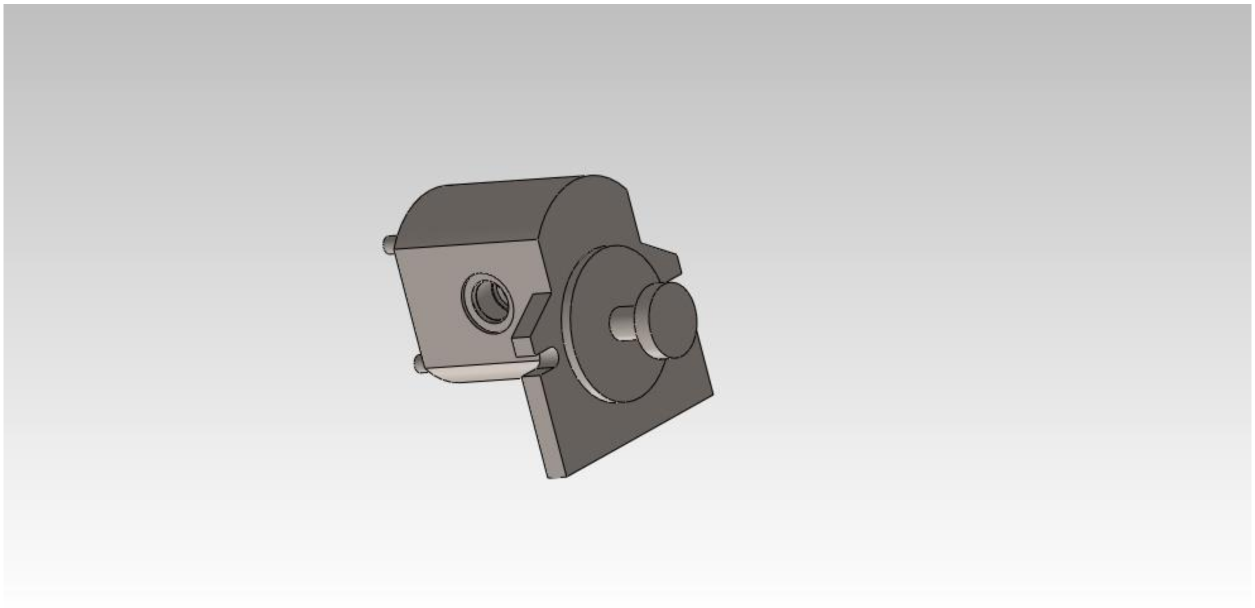


Fig: Internal gear pump

Motor

Selection of motor for internal gear pump:

Design power = $\frac{P \times Q}{\eta}$

$\therefore [P] = \frac{P \times Q}{\eta}$

$\therefore [P] = \frac{15 \times 10^{5} \times 8.333 \times 10^{-5}}{0.7}$

$\therefore [P] = 178.5W$

Std Motor available = 0.25 Kw

Std Motor to be selected = 0.75 Kw = 1hp

Selection of motor for external gear pump:

Design power = $\frac{P \times Q}{\eta}$

$\therefore [P] = \frac{P \times Q}{\eta}$

$$\therefore [P] = \frac{10 \times 10^5 \times 16.667 \times 10^{-5}}{0.7}$$

$$\therefore [P] = 238W$$

Std Motor available = 0.25 Kw

Std Motor to be selected = 0.75 Kw = 1hp

DATA SHEET FOR MOTOR

Type	:	Induction motor
HP	:	1
Kw	:	0.75
Voltage	:	415 V±10 %
No. of Phase	:	3 Ph.
Frequency	:	50 Hz ±5%
RPM	:	1440
Insulation Class	:	F
Duty	:	S 1 (Continuous)
Totally enclosed, fan cooled	:	TEFC
Degree of protection	:	IP 55
Type of Mounting	:	Foot & Flange Mounted

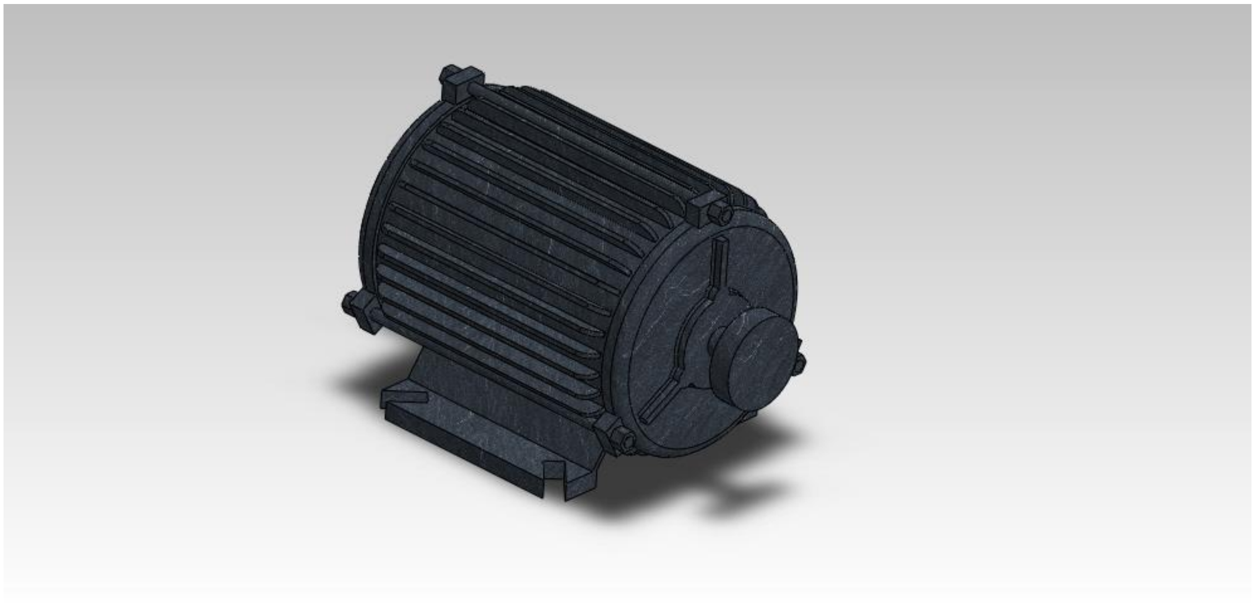


Fig: Induction Motor

Fuel tank

Requirements of fuel tank:

Robust
Light weight
Ease of Installation
High strength
Safety from fire
High Capacity

Dimensions of fuel tank
Length : 400 mm
Breadth : 120 mm
Height : 120 mm
Capacity : 5 liters

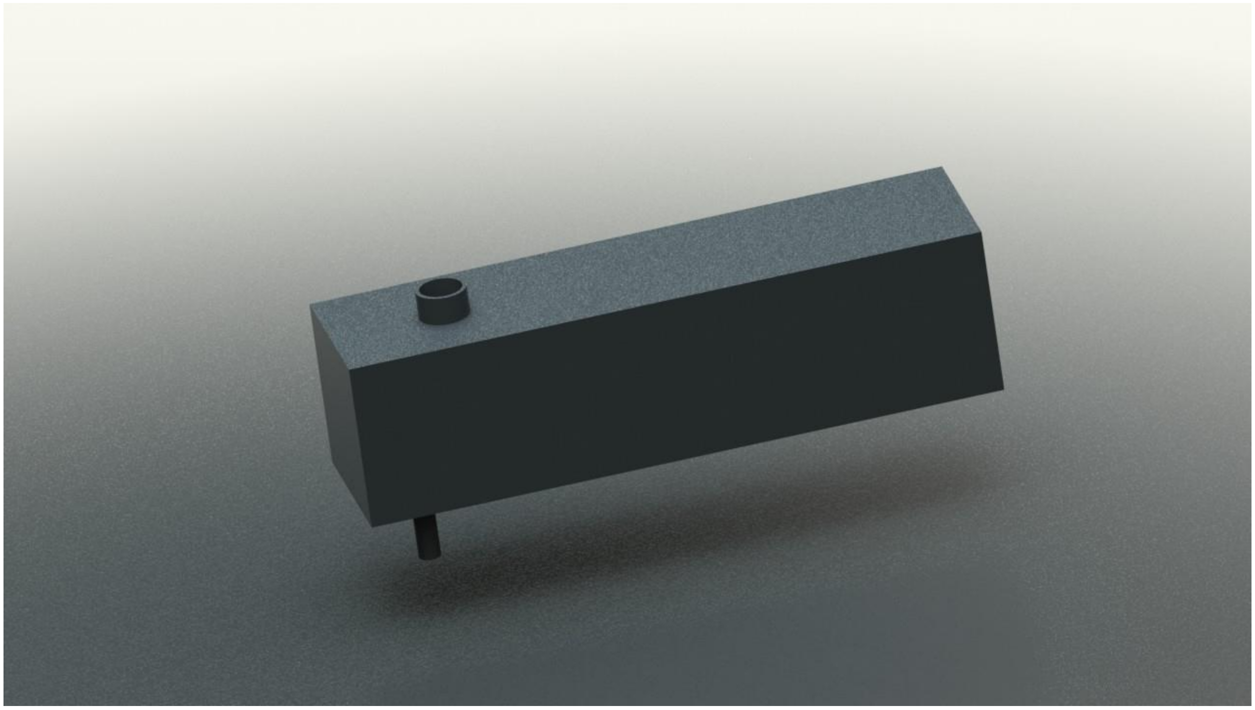


Fig: Fuel tank

Oil storage tank

Requirements of fuel tank:

Robust
Light weight
Ease of Installation
High strength
Safety from fire
High capacity

Dimensions of oil storage tank:
Length : 400 mm
Breadth : 120 mm
Height : 120 mm
Capacity : 5 liters

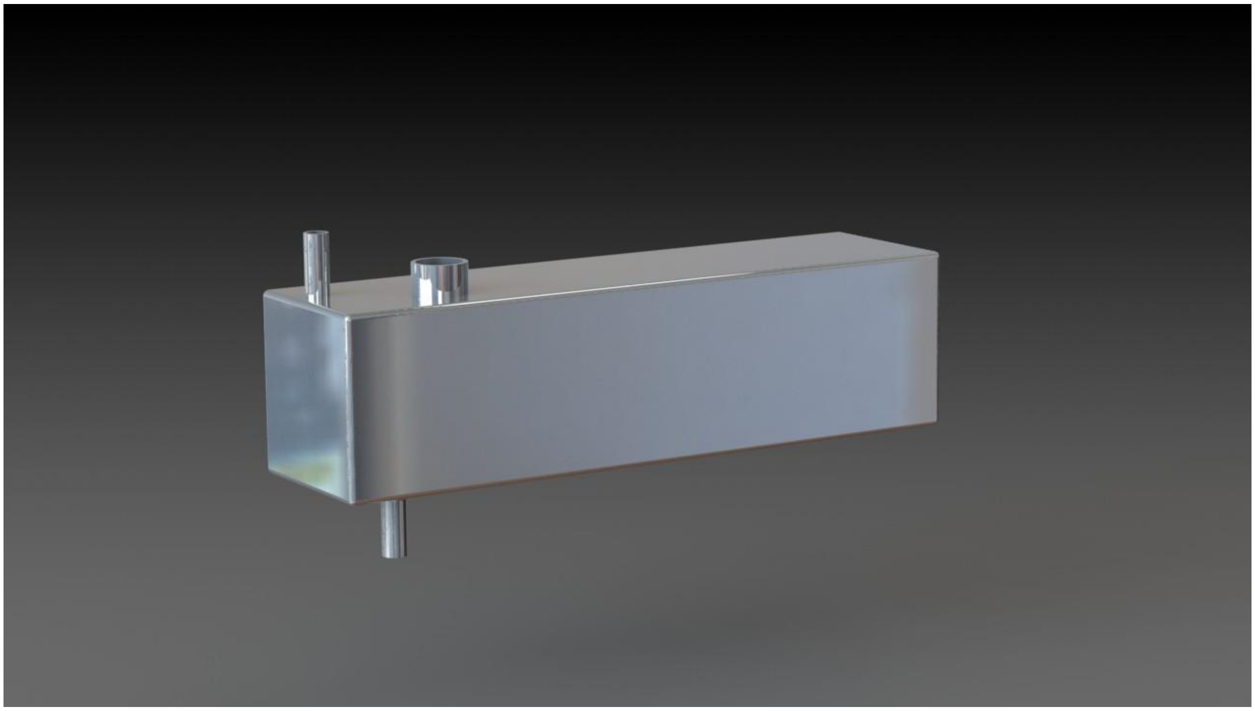


Fig: Oil tank

Oil Radiator

Requirements of oil radiator:

Robust
Light weight
Ease of Installation
High strength
Safety from fire
High cooling efficiency
High cooling rate

Final Assembly

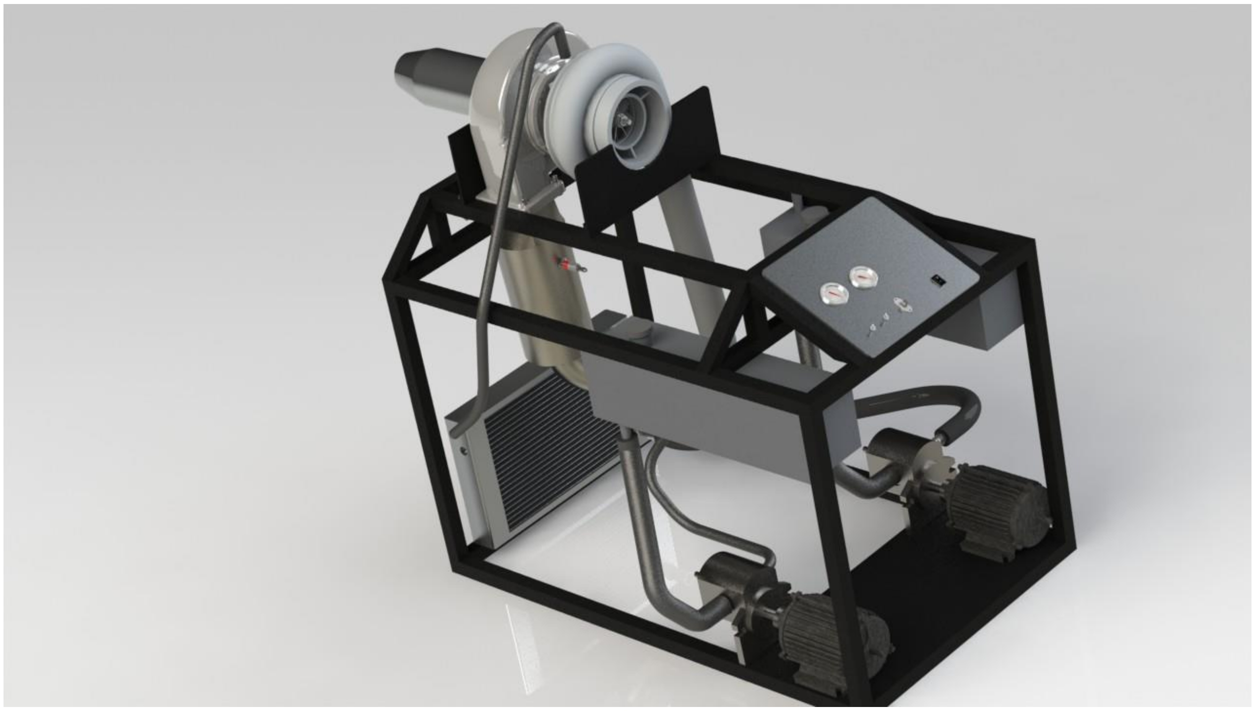


Fig: Final assembly model designed in solidworks

Construction of jet engine

Acquiring the parts of the engine:

The essential components needed for the construction of turbocharger based jet engine includes: A Turbocharger, battery and battery box, brass fittings, check valve, solenoid valve, rubber hoses and tubing, turbo flanges, pressure gauges, panel switches, oil reservoir, air filter, ignition coil, EGT pyrometer steel tubing for combustion chamber and steel for the engine frame. A complete list of the essential items necessary for the construction of working model of jet engine is given in the table below.

Note: All the components are acquired based on the design of the parts.

Sr.No	System	Component	Picture	Specifications	Use

1	Compression and expansion device	Turbocharger		Strakonice Czech Republic Model: K36 3566 2521	Compression and expansion device
2	Fuel System	Fuel pump		S. K. Industries Capacity: 5 Lpm Pressure: 20 bar	Pressurized pumping
3		Fuel Nozzle		Spartech India Ltd Capacity: 4 GPH Hollow cone spray	Fuel spraying device
4		Fuel Tank		Custom made Capacity: 5 Liters	Fuel storage
5	Fuel regulating circuit	Ball valve		S.K. Brass Fittings Std 0.5 inch brass ball valve	Fuel shut off valve (in case of disaster)
6		Hose and Fittings		S.K. Brass Fittings Std 0.5 inch brass connectors and fittings	Connecting components like oil tank to pump to hydraulic bearing

7		Pressure Gauge		Pressure solutions Range: 0-10 Psi	Fuel pressure monitoring
8	Lubrication System	Oil tank		Custom made Capacity: 5 Liters	Oil storage
9		Hydraulic Pump		S. K. Industries Capacity: 10 Lpm Pressure: 10 bar	Pressurized oil pumping for hydraulic bearing
10		Oil cooler			Cooling of lubrication oil
11		Turbine oil		Castrol Engine Oil Model: SAE DW50 Winter Oil	Lubrication on hydraulic bearing

12		Pressure gauge		Pressure solutions Range: 0-10 Psi	Oil pressure monitoring
13	Ignition System	Transformer		Model: Neon transformer Capacity: 10,000V	Converts normal supply voltage to high voltage
14		Spark Plug		Bosch spark plug	Creates high intensity spark
15	Control panel	Emergency stop switch, oil switch, ignition switch, fuel switch			For switching on/off of the engine system& controlling the combustion
16	Power source	Automotive Battery		Speed Batteries Capacity: 12V dc, 9 amps	Power source for other components
17	Engine starting device	Blower		Black and Decker High performance leaf Hog Blower Model No: LH 4500	For starting the engine

Examination of the turbocharger

Turbochargers, used on gasoline and diesel engines contain both a rotary air compressor and an exhaust gas driven turbine. The turbine is connected to the compressor by a drive shaft. Hot exhaust gasses from the engine drive the turbine wheel which, in turn, drives the compressor that forces the pressurized air in to the engine. By adding a turbocharger, the output of an internal combustion engine can be increased by 50%, or more.

Fig. 8 Turbocharger

Fig. 8 Shows a Garrett T-18A compressor with the housing removed. Notice the bent blades on the compressor near the center. These are the inducer vanes that draw air into the compressor inlet. Once air is drawn in, centrifugal force throws it to the outer edge where it is accelerated in the direction of rotation. It then moves to the outlet in the housing and passes on to the engine intake manifold.

Fig. 9 Compressor

Turbocharger compressor

The compressor on the turbocharger serves the same function as the compressor on the turbojet engine. It is used to compress a large amount of air into a small space and increase pressure. The compressor wheel turns at a very high speed; usually between 45,000 and 1,25,000 rpm. the larger truck turbochargers turn about 75,000 rpm. The compressor wheel is usually made from and aluminum alloy. It does not run at a high temperature so aluminum works fine. The compressed air exits the compressor into a diffuser. This is usually a casting that increases in area so that the air will be slowed down and the pressure will increase.

The compressor end contains the impeller. It is usually an investment casting of aluminum alloy. The blades neat the center are called the inducer vanes and are used to draw the air into the compressor where the radial blades accelerate it. The air then passes into the snail shaped housing called the diffuser.

Fig. 10
Turbine

The turbine

The turbine is located at the rear of the turbocharger inside a snail housing. The turbine is a radial inflow design. The snail housing is designed to increase the velocity of the inflowing air so that it strikes the turbine blades, at high velocity. The inflowing high speed air strikes the tips of the blades near the outlet and is designed to exhaust the hot gases to the rear. Gas temperature at this point is about 1800 deg. F. The turbine wheel is usually cast from hast alloy or some other nickel alloy.

Fig. 11
Bearing

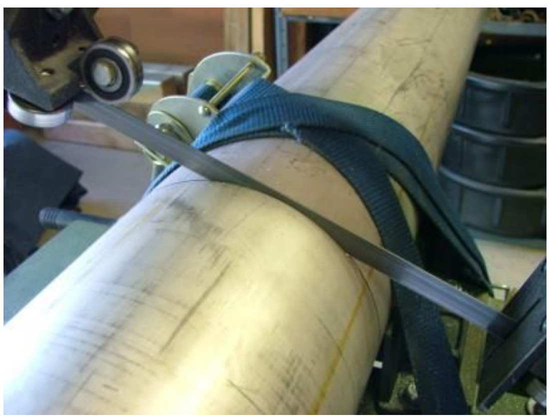
The Drive Shaft and Bearing
The turbine drives the compressor by means of a drive shaft, usually a very short, small diameter shaft that is friction welded to the turbine wheel and bolted to the compressor. The shaft runs through an aluminum bearing.
Most modern turbochargers use hydrodynamic bearings as shown in Fig. 11. This is an alloy sleeve bearing with design tolerances that allow a layer of oil between the shaft and the bearing. When the turbocharger is running, the oil supply is under pressure and the shaft rides on a layer of oil and does not touch the alloy bearing. The shaft is suspended on a layer of oil. The trust bearing on the turbine end rides on a layer of oil and is cooled by oil. The turbine end bearing runs extremely hot, usually about 1,800 deg. F. Large quantities of oil must be circulated to provide adequate cooling.

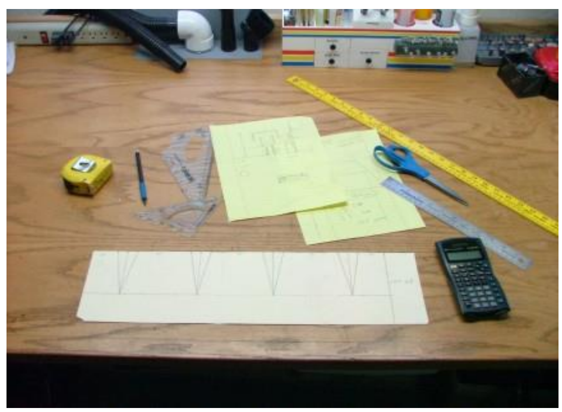
Construction of combustion chamber

Construction of the combustion chamber is the most time consuming and critical task because the working and the satisfactory performance of the jet engine is completely dependent on the working of the combustion chamber. Detailed discussion and lengthy design procedure has already been discussed a lot, now here attention is given on the manufacturing and the fabrication of the combustion chamber with necessary details and images for easy understanding.

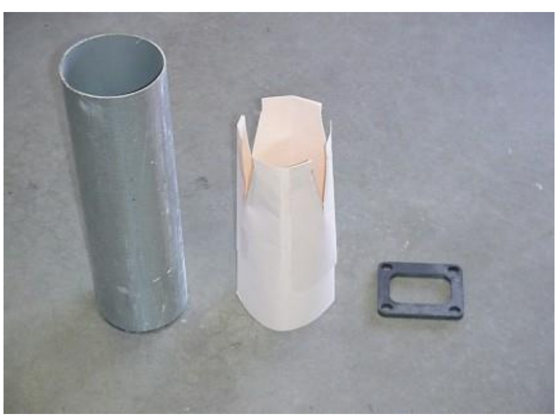
The combustion chamber is manufactured completely on the basis of the design layout discussed in the design of the combustor. Refer the final layout of the combustion chamber for details. The construction of the combustor consists of two main parts the outer casing and the flame tube with other parts added to their assembly.

The figure on the left shows the seamless tubing of SS308 which will be used for the construction of outer casing of the combustor. The tubing is cut to the required length. The casing consists of the taper at the end. In order to create a smooth taper some initial cuts are required to be made on the tubing. A paper template is made to give a best layout on the tubing for making these cuts. The figure on the right shows the paper template.





The tubing, flange and the paper template is shown in the figure below.



These are the preliminary cuts that will make the taper possible



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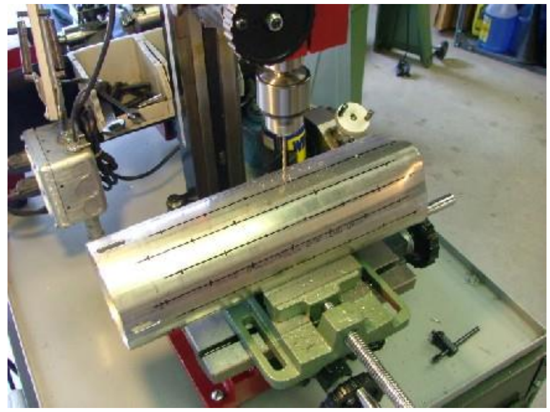
Using an angle grinder and an 80 grit flap disk a smooth taper is created.


This shows the completed combustor casing. Note the hole on the surface which is made for the mounting of the spark plug in the combustion liner.


Once the casing is over the next job is to construct the flame tube. The flame tube is that section of the combustion chamber where the actual combustion of the air-fuel mixture occurs thus the material of the liner needs to be of very high thermal resistance. SS310 seems to be a good option. The SS310 seamless tubing of 1.5mm thickness is cut to the required length. The image on the left shows the liner material being cut. The image on the right shows the drilling operation on the liner to make the holes of necessary dimensions as per the design.



The completed liner is shown in the images below. The figure on the right side shows the flange and the inner flare welded to the main liner.

All the necessary parts of the combustion chamber are depicted in the figure below. The image clearly shows the liner, outer casing and the 90 degree bend. Along with these parts the other parts are the swirl vanes, spray nozzle, spark plug and the copper pipe.

Assembling the Combustion Chamber:

The assembling procedure is self explanatory. Refer the sequence of the images below for easy understanding.

The image on the left is the swirl vanes with the nozzle being positioned in it.

The copper pipe is goes through the 90 degree bend. The swirl vanes are then inserted in the flare section.

This shows all the three flanges being bolted from outside.

The spark plug on the left is screwed in the liner from outside.

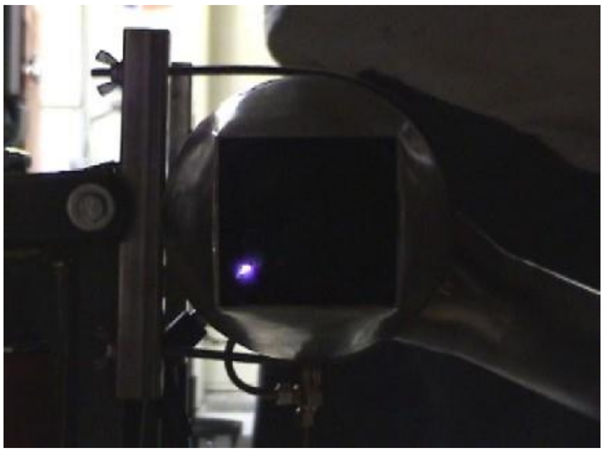
This shows the completed assembly of the combustion chamber. Note the copper tube coming out of the pipe. This will be the inlet for the fuel.

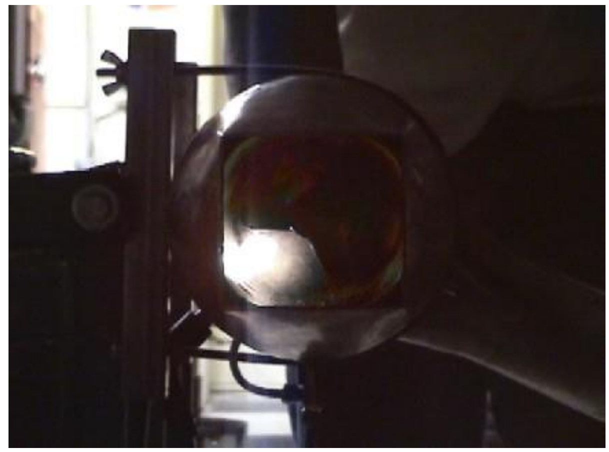
The figure on the left is the PVC pipe that is fitted on the 90 degree pipe of the combustor. The other end of this pipe will be press fitted to the compressor outlet.

The figure below shows the entire combustion chamber ready to be mounted directly on the turbocharger.

Testing of combustion chamber:

This is the crucial step as the working of the engine is guaranteed only by the working of the combustion chamber. Working of the combustion chamber means self sustaining combustion. The figures below depict the timely sequence of the combustion occurrence in the combustor. The image on the left shows the occurrence of the thick spark for initiating the combustion. While on the right shows the initiation of the combustion near the spark plug.





The image on the right shows fully developed flame propagating in forward direction.

The image on the right shows the flame out as soon as the air supply is lowered to a minimum value.

Installing the engine's subsystems

Jet engine test stand:

Turbojet engines operate at high temperatures and produce considerable thrust. A test stand must be constructed in such a manner that it can be fastened to a solid anchor of some sort. A welded Mild steel test stand of hollow square tube cross section of 0.5”×0.5” will support engine at a reasonable working height and support it while running.

Some method must be used to mount the turbocharger to the test stand. The turbocharger mounting is designed to take up the weight of the turbocharger and combustion chamber assembly as well as to withstand the thrust produced while the engine operation. The turbo must be secured so that it will not move when running.

For mounting the assembly two mounting straps are designed from mild steel plates see fig below, one at the compressor end and other at the turbine end. The mounting at the turbine end is secured by means of MS bolts and the other mounting is welded to the engine frame.

Mounting combustion chamber on Turbocharger

Having designed the combustion chamber based on the turbo flanges, mounting of the combustion chamber should not be difficult. The combustor assembly that was constructed earlier is simply positioned on the turbocharger. Below are the images of the turbocharger depicting the compressor outlet and the turbine inlet flange.

The image below shows the mounting of the entire combustor on the turbocharger. The image clearly illustrates the simplicity of the mounting procedure. The PVC pipe goes inside the compressor outlet; on the other hand combustor's flange is matched with the turbine flange, both the flanges are bolted together by means of SS 10mm bolts.

Below is the image showing the bolted assembly of the turbine and the combustor flanges.

Construction and fabrication of the exhaust nozzle:

The turbine exhaust nozzle is manufactured from SS308 2mm seamless tubing. The nozzle is manufactured completely on the design basis. Below is the image showing the step by step construction of the exhaust nozzle. On the left is the 4mm thick flange of MS and seamless tubing of SS308. Refer design of nozzle for detailed dimensions. The tapering section is constructed in the similar way as that of the combustor casing, the figure on the right shows the initial cuts made for the taper.

The figure on the right shows the required bend that is made by hammering out the cut taper. While the figure on the right shows the welding of the joints at the taper

The completed nozzle is shown in the figure below.

Mounting the exhaust nozzle on the turbocharger:

The mounting of the nozzle on the turbo is achieved by series of the bolts on the turbo. The turbo has 6 bolts of size 10mm symmetrically placed on the exhaust side. The nozzle flange manufactured accordingly to fit on the turbo exhaust. Refer the image below.

The images below depicts the complete engine assembly consisting of turbocharger, combustion chamber and the exhaust nozzle.

Mounting the Engine Assembly on the engine frame:

This is again a simple assembling step; the entire engine assembly show in the image above is mounted directly on the engine frame. Note the mountings in the image that were mentioned earlier while discussing the engine test stand.

Lubrication system

The oil pump, motor assembly can be seen in the fig below. The pump is an external gear pump. It is coupled directly to the 3 phase induction motor of 1 HP rating; refer the selection of the pump and the motor for details. Notice the mounting of the oil gear pump. The leveling of the gear pump and the motor should be accurate to ensure the there is no eccentricity between the pump and the motor, if there is any eccentricity there will be serious vibrations. Vibrations can damage the pump or the motor bearings. The leveling is thus a tedious procedure. The pump and the motor are connected by means of a standard coupling with 16mm bore drilled on it. The oil goes into the turbocharger bearings under about 45lbs pressure and returns by gravity.

The image below shows the mounting of the flanges for the turbocharger’s hydrostatic bearing. the figure on the right also shows the ball valve for controlling the oil flow to the turbocharger.

The figure on the left shows the hoses mounted on the brass fittings, the image on the right side depicts the oil tank, the oil hose from the turbo is connected to the oil tank without any interference so that the oil from the turbo flows directly to the tank under the influence of gravity.

Fuel pumping system

The fuel pump, motor assembly can be seen in the fig below. The pump is an internal gear pump. It is coupled directly to the 3 phase induction motor of 1 HP rating; refer the selection of the pump and the motor for details. This assembly is made in the similar way as that of the oil pump and the motor with the same leveling procedure. Note that the internal gear pump here has a different mounting than that of oil pump.

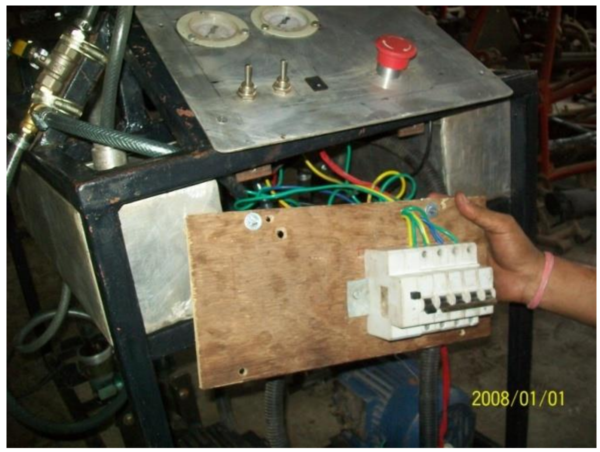
The image on the left shows the mounting of the fuel tank. The fuel tank is design to accommodate 1 gallon of fuel (kerosene). The image on the right side shows the connection of the fuel tank with the fuel pump inlet. The fuel from the fuel tank flows directly into the fuel pump without any interference.

The fuel hose tee connection is made from the tee brass fitting shown below. The fuel hoses are nylon impregnated fire resistant.

The left image shows the ball valve for controlling the fuel supply to the combustion chamber.

Mounting of the control panel

The control panel is made out of the aluminum sheet of 3 mm thickness. The panel has two pressure gauges. The oil gauge indicates the oil pressure entering the turbo and the fuel pressure gauge indicates the pressure of the fuel entering the combustor. The two switches on the left side of the control panel are for switching the fuel supply and oil supply. The red button is the emergency switch and is connected in such a way that when hit it shuts off the fuel supply to the combustion chamber. The engine comes to halt safely without combustion of fuel.



The image below shows the wiring taken out from MCB. The device on the left of the board is the ignition coil driver circuit.

Electrical connections

The image on the left is the three phase wiring connected to the motor. The right side image depicts the ignition coil


Final assembly:

The completed engine assembly is depicted below


Operational and startup procedure:

1. Start oil pump and confirm 45-psig- system pressure.
2. Start fuel pump and confirm 100-psig-sustem pressure.
3. Place blower into the inlet and allow turbine to accelerate (about 1 minute).
4. Turn the igniter on. Allow engine to accelerate until no further acceleration can be achieved with the blower.
5. Open ball valve to pre ignite cold engine. You will hear a rumbling sound like a furnace.

6. Turn fuel idle valve on (25 pounds nozzle pressure). Confirm fuel ignition. Do not remove blower yet.
7. If the turbine outlet temperature exceeds 1,100 deg. F. Shut fuel off immediately.
8. Allow engine to accelerate until it tries to pull the blower into the engine.
9. Remove blower from inlet turn igniter off.
10. Allow engine to accelerate to idle speed (approximately 25,000 rpm).
11. Open throttle to 80-100 psig for full power.
12. The engine can be accelerated, reduced, or idled with the fuel control. Combustion temperature should be around 850-875 deg. F.

Appendices

Combustion systems

1: Introduction

The design of the gas turbine combustion system is a complex process involving fluid dynamics, combustion and mechanical design. For many years the combustion system was much less amenable to theoretical treatment than any other components of the gas turbine, and any development programme required considerable amount of trial and error. With very high cycle temperatures of modern gas turbines, mechanical design remains difficult and that enabled a need for mechanical development programme. The rapidly increasing use of the computational fluid dynamics (CFD) in recent years has had a major impact on the design process which has increased the understanding of the complex flow and reducing the amount of trial and error required.

The main purpose of this chapter is to show what are the problems faced in the process of designing. The improvements made in one module of the design will have its effect on other modules, thus a compromise has to be made on the number of conflicting requirements, which will vary widely with different applications.

The most common fuels for the gas turbines are liquid petroleum distillates and natural gas and the attention will be focused on the combustion systems suitable for these fuels.

In the combustion chamber design, the major goals to be achieved are high combustion efficiency, reduction of visible smoke, reduction of oxides of nitrogen.

2: Operational requirements

The combustor is the critical component because it must operate reliably at extreme temperatures, should provide a suitable temperature distribution at entry to the turbine, and create minimum amount of pollutants over a long operating life.

A good design of the gas turbine will emphasize the importance of high component efficiency and high cycle temperature. For combustion system which is one of the components of the gas turbine, high component efficiency means high combustion efficiency and low pressure loss. For calculation purposes the combustion efficiency is considered to 99% and a pressure loss of 2-8% of compressor delivery pressures. Effect of these losses on the overall efficiency is not as pronounced as the inefficiencies in the turbo machinery.

Aircraft gas turbines face the problems associated with operating over a wide range of inlet pressure and temperature within the working conditions of Mach number and altitude. A typical sub-sonic aircraft will operate at a cruise altitude of 11000m, where the ambient pressure and temperature are 0.227 bar and216.8K respectively as compared with the sea level values of 1.013bar and 288.15k. thus the combustor has to operate at greatly reduced air intensity and mass flow at high altitudes, while using the same air/fuel ratio as at sea level to produce the appropriate value of the turbine inlet temperature. Atmospheric conditions may change but the combustor must deal with these changes by continuously varying fuel flow without allowing the engine to flameout or exceed the temperature limits.

Stationary land-based gas turbines have wider choice of fuels natural gas is the preferred fuel for applications such as pipeline compression, power generation etc. If natural gas is not available liquid fuels are most widely used. Gas turbines can also be designed for dual fuel operation, with normal operation on natural gas and an option to switch to the natural gas for short periods.

Advantages of liquid fuels over Gaseous fuels

1. Requires less space for storage.
2. Higher calorific value.
3. Easy control of consumption.
4. Absence of danger of spontaneous combustion.
5. Easy handling and transportation.

Disadvantages of Liquid fuels

1. Excess air needed for complete combustion.
2. Operating efficiency is less.
3. Requires complex fuel spray system and fuel pumping system which consumes power and also adds to the overall weight of the engine.
4. Heavy spark is required to ignite the air fuel mixture which in turn requires high voltage source for igniter.

Advantages of gaseous fuel over liquid fuels:

1. Better control of combustion.
2. Much less excess air is needed for complete combustion.
3. More efficiency of operation.
4. Cleanliness.
5. Gives economy of heat and higher temperature.
6. Does not require complex fuel spray a system, also use of the fuel pump is eliminated since gaseous fuels are stored in pressure tanks under pressure.
7. High intensity spark is not required since air-fuel mixture is homogenous and is evenly distributed throughout the combustion zone.

Disadvantages of gaseous fuels:

1. Requires the use of air tight containers for fuel storage.
2. Involves leakage problems.
3. Danger of spontaneous combustion.
4. Unavailability of natural gases.

3: Types of combustion systems

Combustion in a normal open-cycle gas turbine is a continuous process in which the fuel is burned in the air supplied by the compressor, an electric spark is required only for initiating the process and thereafter the flame must be self-sustaining. There can be wide variety of ways for choosing a combustor configuration according to different requirements of aircraft and ground-based units with respect to weight, volume and frontal area. This can result in widely different solutions.

Comparison of various gas turbines and jet engines gives that, at present, three arrangements of the combustion chambers are being practiced viz.

1. A large combustion chamber
2. Multiple chambers and
3. Annular chamber

A large single chamber is usually employed in the case of heavy industrial power plants where space and weight are of secondary importance. Since space is not so important, relatively low gas velocities can be used which tends towards higher combustion efficiency and low pressure loss; further heavy sections can be incorporated at the critical sections, which if properly designed gives long life and high operating temperatures without buckling.

The multiple chamber arrangement is of common practice for the aircraft applications as well as for few stationary power plants or marine engines. Its main advantage is the ease with which the desired total combustion chamber volume can be achieved.

The third type of the combustion chamber, the annular chamber consist of the annular passage connecting the compressor delivery with the turbine nozzle, permitting the formation of continuous sheet of the hot gases which flows from former to the latter. Inside this annular chamber is supported the inner flame tube which in this case is also annular. Fuel is injected into the inner annular chamber by series of nozzles located at the compressor end of the chamber.

4: Some important factors affecting combustor design

The main factors influencing the design of the combustion chamber for the gas turbines are.

7. The temperature of the gases after the combustion must be comparatively low to suit the highly stressed turbine materials.

8. At the end of the combustion chamber the temperature distribution must be of known form if the turbine blades are not to suffer from local overheating. In practice temperature increases with the radius from root to tip.
9. Combustion must be maintained in the stream of air moving with high velocity of 30-60 m/s and stable operation is required over a wide range of air/fuel ratio from full load to idling conditions. The air fuel ration might vary from about 60:1 to 120:1 for simple cycle gas turbines and from 100:1 to 200:1 if heat exchange is used. Considering that the Stoichiometric ratio is approximately 15:1 it is clear that high dilution is required to maintain the temperature level acceptable for turbine blades.
10. The formation of carbon deposits must be avoided, particularly the hard brittle variety. Small particles carried into the turbine in the high velocity gas stream can erode the blades and block cooling air passages; furthermore, aerodynamically excited vibration in the combustion chamber might cause sizable pieces of the carbon to break free, resulting in even worse damage to the turbine.
11. Avoidance of the smoke in the exhaust is of the major importance for all types of gas turbine.
12. Although gas turbine combustion systems operate at extremely high efficiencies, they produce pollutants such as oxides of nitrogen (NOX), carbon monoxide (CO) and unburned hydrocarbons (UHC) and these must be controlled at very low levels.

5: Combustion chamber geometry revisited

Combustion of the liquid fuel involves the following:

i. The mixing of a fine spray of droplets with air
ii. Vaporization of droplets
iii. The breaking down of heavy hydrocarbons into lighter fraction
iv. The intimate mixing of molecules of these HC with O2 molecules and finally
v. The chemical reaction themselves.

A high temperature, such as is provided by the combustion of an approximately stoichiometric mixture, is necessary if all these processes are to occur sufficiently rapidly for combustion in a moving air stream to be completed in a small space. Since the overall air: fuel ratio is in the region of 100:1, while the stoichiometric ratio is approximately 15:1 the first essential feature is that the air should be introduced in stages. Three such stages can be distinguished.

i. Around 15 to 20% of the air is introduced around the jet of the fuel through the primary holes in the primary zone to provide the necessary high temperature for rapid combustion. The primary zone must have flame stabilizers such as baffles to establish a recirculating zone. The flame stabilization is explained in detail in latter step.

ii. Some 30% of the total air is then introduced through secondary holes in the flame tube in the secondary zone to complete the combustion. For high combustion efficiency, this air must be introduced at the right points in the process, to avoid chilling of the flame locally and drastically reducing the reaction rate in that neighborhood, and finally

iii. In the tertiary or the dilution zone the remaining air through tertiary holes is mixed with the products of combustion to cool them down to the temperature required at the inlet to the turbine. Sufficient turbulence must be promoted so that the hot and the cold streams are thoroughly mixed to give the desired outlet temperature distribution, with no hot streaks which would damage the turbine blades.

The necessary outline structure of the combustion chamber then appears as in fig. below, yielding a typical annular form, with a central flame tube consisting of three zones surrounded by outer casing.

6: Incomplete combustion & pressure losses

Having described the way in which the combustion process is accomplished, it is now possible to see how incomplete combustion and pressure losses arise. This is simply due to the poor fuel injector design leading to the fuel droplets being carried along the flame tube wall. Incomplete combustion may be caused due to the local chilling of the flame at the points of the secondary air entry. This can easily reduce the reaction rate to the point where some of the products into which the fuel has decomposed are left in their partially burnt state, and the temperature at the downstream end of the chamber is normally below at which the burning of these products can be expected to take place. Since the lighter hydrocarbons in to which the fuel has decomposed has the higher ignition temperature than the original fuel it is clearly difficult to prevent some chilling from taking place, particularly if the space is limited and the and the secondary air cannot be introduced gradually enough. If devices are used to increase the large scale turbulence and so distribute the secondary air more uniformly throughout the burning gases, the combustion efficiency will be improved but at the expense of the increased pressure loss. A satisfactory compromise must somehow be reached.

Combustion chamber pressure is due to two distinct cases:

(1) Skin friction and turbulence &

(2) Rise in temperature due to combustion

The stagnation pressure loss associated with the latter often called the fundamental pressure loss, arises because an increase in temperature implies a decrease in density and consequently an increase in the velocity and the momentum of the stream. A pressure force ($\Delta p \times A$) must be present to impart the increase in the momentum.

The pressure loss due to friction is found to be of very much higher- of the order of 20 inlet dynamic heads, it is known as cold loss. Friction loss is so high due to the need of high scale turbulence, turbulence of this king is created by the devices used to stabilize the flame e.g. swirl vanes. In addition there is turbulence introduced by the jets in the secondary and the tertiary air. The need for the good mixing of the secondary air with the burning gases has been emphasized. Similarly good mixing of the dilution air to avoid the hot streaks in the turbine is essential. In general the more effective the mixing the higher is the pressure loss. Here again a compromise must be reached this time between the uniformity of the outlet temperature distribution and the low pressure loss.

7: Some practical problems

We will briefly describe some of the problems which have not been mentioned but which are none the less important. These are concerned with (1): flame tube cooling, (2): fuel injection, (3): starting and ignition.

1. Flame tube cooling:

One problem which has assumed greater importance as permissible turbine inlet temperatures have increased is that of cooling the flame tube. The tube receives energy by convection from the hot gases and by radiation from the flame. It losses energy by convection to the cooler air flowing along the outside surface and by radiation to the outer casing, but this loss is not sufficient to maintain the tube wall at a safe temperature. A common practice is to leave narrow annular gaps between overlapping sections of the flame tube, so that the film of the cooling air is swept along the inner surface.

2. Fuel injection:

Most combustion systems employ the high pressure fuel systems in which the fuel is forced through the small orifice to form a conical spray of the droplets in the primary zone. The fuel is said to be atomized and the burner is often referred to as an atomizer. There will be a certain minimum fuel pressure at which a fully developed spray will issue from the orifice. The spray will consist of the droplets having wide range of the diameter, and the degree of the atomization is often expressed in terms of mean droplet diameter. 50-100 microns is the order of magnitude used in practice. The higher the supply pressure the smaller is the mean diameter. If the droplets are too small they will not penetrate far enough into the air stream, and if they are too large the evaporation time may be too long. The effective minimum supply pressure is one that will provide the required degree of atomization.

3. Starting and Ignition:

Under normal operating conditions the gas turbine combustion is continuous and self-sustaining. An ignition system however is required for starting, and the ignition and the starting systems must be closely integrated. The first step in starting a gas turbine is to accelerate the compressor to the speed that gives airflow capable of sustaining combustion: during the period of acceleration the ignition system is switched on and the fuel is fed to the burners when the rotational speed reached about 15-20% of the normal. An igniter is situated in the primary zone of the flame tube. Once the flame is established the igniter is switched off. Engine shutdown normally requires the engine to be brought back to idle followed by shutting off the fuel; shutdowns from the full power be avoided because of the possibility of differential expansion/ contraction leading to seal rubs or seizure of the rotor.