DEVELOPMENT OF A COMPUTER CODE TO DESIGN AND ANALYZE A COMBINED GAS-VAPOR POWER PLANT

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ABSTRACT

Gas Turbines are widely used in power production industry due to their higher efficiency and cleaner energy production. However, the procurement process of gas turbine requires analysis of various thermodynamic equations to conclude a preferable model of Gas Turbine. This project streamlines the process by taking in just five inputs available in gas turbine brochures and calculates various factors like efficiencies of compressor and turbine, mass flow rate of fuel and inlet air, the effect of inlet ambient conditions and exhaust gases compositions. Similarly, the program also calculates the various outputs in Combined cycle configuration. The relationship between different parameters of gas turbine has also been studied. Turbofans with high bypass ratio can be used for power production in the industry. Necessary modifications are studied and shaft power in terms of electrical power has been calculated. The effect of turbine inlet temperature on various factors is also analyzed. Next, single, and double shaft configurations of CCPP have been compared and analyzed. The effect of these two configurations on efficiency, emissions, and reliability have been research and concluded with the advantages and disadvantages of each configuration. In the last, the program with Graphical User Interface has been described.

ACKNOWLEDGMENTS

We pay our utmost gratitude to Engr. Abdul Naeem Khan for being a supportive supervisor throughout our journey. During the elapsed duration of the project, he has provided us with critical and valuable feedback. His unflinching and straight forward remarks have improved our project and learning capabilities.

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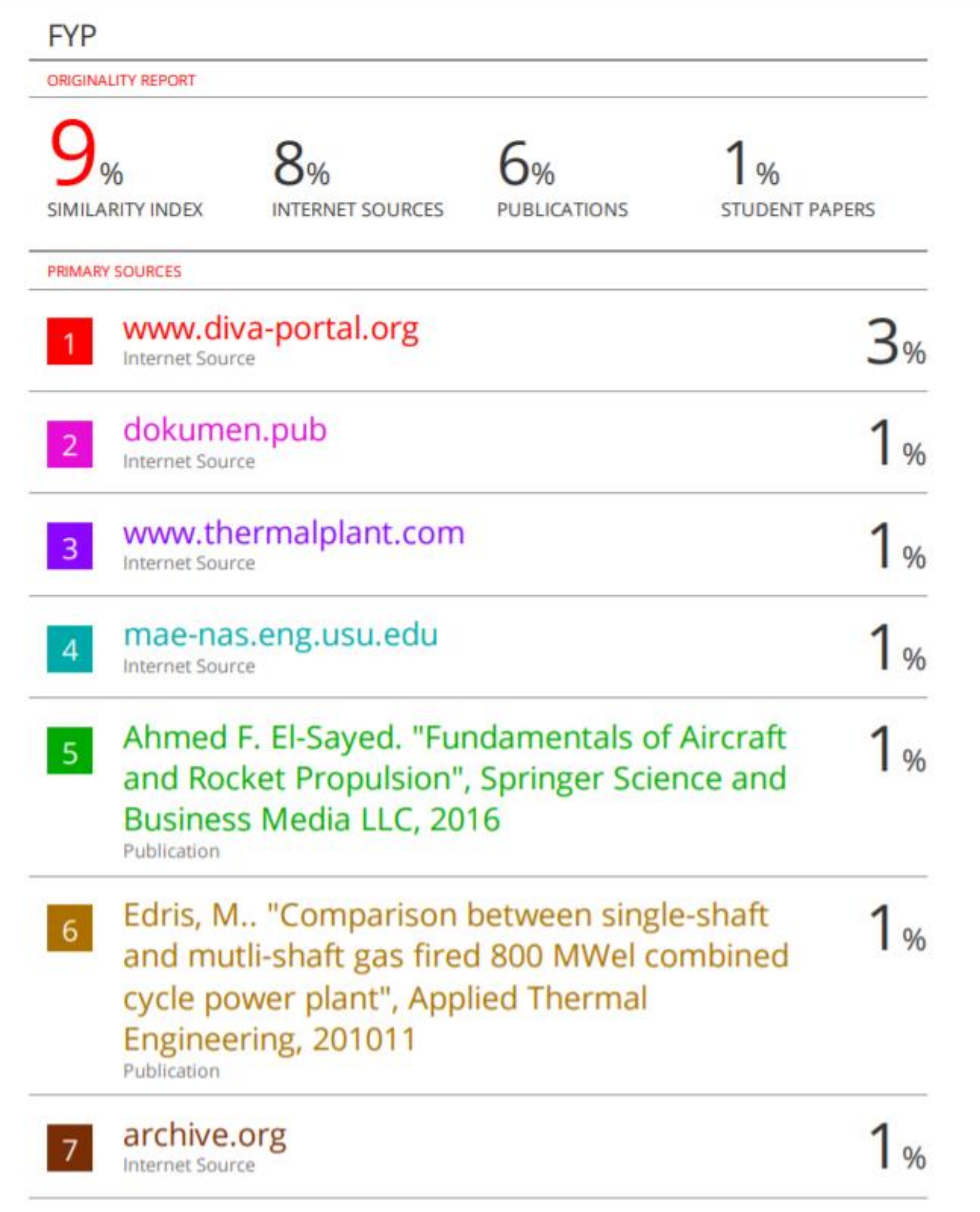

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ABBREVIATIONS

AFR	Air to Fuel Ratio
C	Velocity
CCPP	Combined Cycle Power Plant
K	Kelvin Constant
GUI	Graphical User Interface
HRSG	Heat Recovery Steam Generator
h	Specific Enthalpy
HBTE	High Bypass Turbofan Engine
ISO	International Organization for Standardization

NOMENCLATURE

Q	Heat Addition
W	Work Done
c_p	Conversion factor (optical efficiency of solar collector)
RH	Relative Humidity
LHV	Lower Heating Value
ρ	density (kg m–3)
φ	combustion efficiency
γ	specific heat ratio Conversion factor (optical efficiency of solar
η	Thermal efficiency (%)

CHAPTER 1: INTRODUCTION

Gas Turbines are at the forefront of energy production, with efficiencies reaching 40% in single cycle operations and 60% in combined cycle configuration. The production of energy from these gas turbines is not only much cheaper but also much cleaner than the traditional coal-powered or Heavy Furnace Oil powered powerplants. Thus, the electricity production using gas turbines is attributed to an economical, reliable, and cleaner method present.

Motivation:

The usage of gas turbines as a reliable source of production of energy is extensive. They have higher efficiencies and overall cleaner production as compared to coal power plants.

However, the procurement process can be tiresome. The catalogues for gas turbine models only provide limited data of five basic parameters. These parameters are not sufficient for engineers to make a conclusive decision. Thus, many calculations are performed on-site to get more data.

The software which is already present for this purpose is based on running simulations and complex mathematical equations. Thus, prior knowledge is required to solve these simulations.

One more area of interest is the use of aero-derivative turbine engines in the power production industry. Retired turbofan engines are available at discounted costs after their useful working life in aviation. The analysis of retired turbojets is instrumental in the feasibility of the economical application of these in power production.

Problem Statement:

To develop a program having Graphical User Interface (GUI), which is able to solve Gas Turbine in Single and Dual cycle configuration by taking minimum inputs from the users and displaying maximum outputs. The program should be able to compare different Gas Turbine Models. The program should also be able to predict the shaft power by using the Aviation Turbofan engine for power production. Finally, an analysis of the advantages and disadvantages of single and dual shaft configuration.

Objectives of the Project:

The main objectives of the project are:

- Developing a program having an intuitive Graphical User Interface that feeds in minimum parameters from the user.
- The Program should have in-built libraries for data required for the execution of calculations.
- Providing users with the optimum value by comparing results obtained from different sets of inputs.
- Research into the advantages and disadvantages of both single and twin shaft CCPP configurations and finding out which configuration is favorable for what conditions.
- To check the feasibility of using the Turbojet engine in the power production industry and suggesting modifications to make them compatible for power generation purposes.

CHAPTER 2: LITERATURE REVIEW

Combined Cycle Power Plant is one of the main driving components in the field of energy production. The combined gas power cycle uses a gas turbine combined with a steam cycle. Since 1900, gas turbines are under continuous development for electric power generation, and they can play a promising role in the growing energy demands. The size of gas turbines ranges from 500 kilowatts (kW) to 250 megawatts (MW). [1]. Gas turbines can either be used for power generation or combined heat with power generation. The normal efficiency of simple gas cycle power generation is around 40 per cent. The efficiency of a simple cycle gas turbine majorly depends on the lower heating value of the fuel. [2]. In gas turbines, the exhaust flow consists of hot gases and, in turn, has the potential to increase the generated output power. For this purpose, gas turbines are often used with steam cycles to maximize the potential of the exhaust flow of gas turbines. When a gas turbine is used in combination with a steam cycle, this is called combined cycle power generation. The normal thermal efficiency of the combined cycle power plant is around 60 to 65 per cent. This efficiency also depends on the lower heating value. [1]

The gas turbine operating in the fields is based on the Brayton Cycle. These turbines are deployed either in single cycle operations or combined-cycle operations.

Brayton Cycle:

The Brayton cycle forms the basis of the principles and operations of gas turbine engines. The cycle characterizes the gas turbines in which compression and expansion take place in rotary machines.

During the cycle, the parameters that get changed are Temperature(T), Entropy (s), Pressure(P), and Specific Volume(v).

For the characteristics of the fluid within the cycle, the ideal Brayton cycle is based on the following assumptions:

- Expansion and compression are reversible and adiabatic.

- The change of kinetic energy between intake and outlet is negligible.
- Pressure losses between inlet ducting, in the combustion chamber, across heat exchangers and exhaust and other ducts are negligible.
- The composition of working fluid remains the same throughout the cycle.
- The working fluid is considered to be perfect gas with constant specific heat.
- The mass flow of the working fluid remains unchanged.

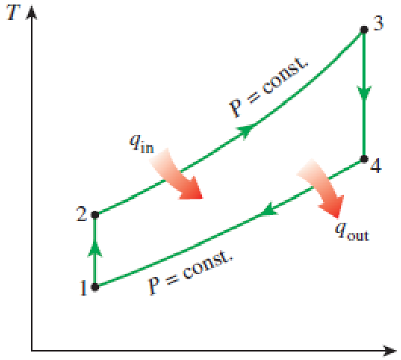


Figure 1 T-s diagram Ideal Brayton cycle [3]

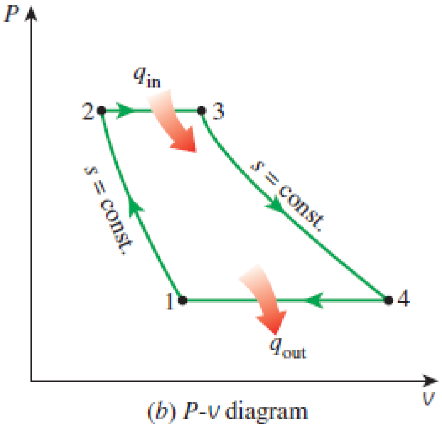


Figure 2 P-v diagram- Ideal Brayton cycle [3]

The ideal closed cycle takes place in the following steps:

From 1-2: Isentropic compression takes place. During this stage, the pressure of the gas is increased, and its column decreases. The temperature also rises.

From 2-3: Heat Addition at constant pressure. The temperature increases during this stage, and specific volume also increases.

From 3-4: Isentropic Expansion takes place, thus increasing the volume and decreasing the pressure—the temperature decreases during this stage.

From 4-1: Heat rejection at constant pressure takes place. The temperature is decreased, and specific volume is also decreased.

Energy Equation:

For the steady flow condition for the ideal Brayton Cycle, the following equation can be used.

$$q = w + (h_2 - h_1) + \frac{1}{2}(c_2^2 - c_1^2) \text{-------------------------------[1]}$$

Where q is the heat transfer per unit mass, w is the work done per unit mass, h is the enthalpy at a certain point, and c is the velocity of the air at a certain point.

Using the above equation, the energy exchange of different components can be calculated by applying it across different components.

From 1-2, the air is compressed in the compressor; the process involves no heat exchange thus, q = 0 and no change in kinetic energy thus $c_1 = c_2$.

$$w_{12} = -(h_2 - h_1) = c_p(T_2 - T_1) \text{ -------------------------------[2]}$$

From 2-3, the heat is added to the combustor chamber. This heat is added at constant pressure. The heat addition is given by:

$$q_{23} = (h_3 - h_2) = c_p(T_3 - T_2) \text{ --------------------------------[3]}$$

From 3-4, the expansion takes place in the turbine. This expansion produces work which is given by:

$$w_{34} = (h_3 - h_4) = c_p(T_3 - T_4) \text{ --------------------------------[4]}$$

The overall efficiency of the cycle can be calculated using net work divided by the heat supplied in the combustor chamber. This efficiency, η, is given by:

$$\eta = \frac{Net\ Work\ Output}{Heat\ Suplied}$$

$$\eta = \frac{c_p(T_3 - T_4) - c_p(T_2 - T_1)}{c_p(T_3 - T_2)} \text{------------------------[5]}$$

Gas Turbine Operation in Power Plants:

The basic gas turbine operation is based on the above-described gas cycle. The gas turbine consists of a compressor, a combustion chamber, and a turbine. The compressor and turbine are connected by the same shaft. The shaft is further extended to be connected to a generator for producing electricity.

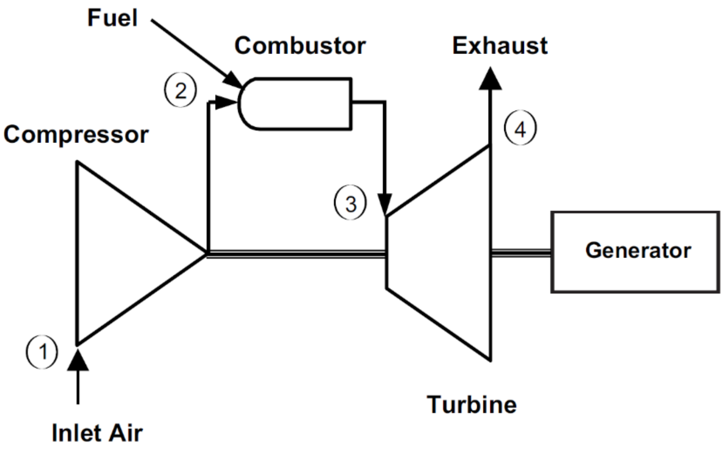


Figure 3 Open Cycle Gas Turbine [4]

The cycle is shown in the above depiction. The compressor takes in air from ambient conditions at point 1. This air is compressed to the desired pressure in the compressor. During this stage, the temperature of the air increases as a result of decreasing volume.

At point 2, this compressed air is passed to the combustion chamber. The heat is added to the combustion chamber by the burning of the fuel. The fuel can be gaseous or liquid. Gaseous fuels include natural gas, naphtha, or liquid hydrogen, while liquid fuels include a diesel or heavy fuel. The combusted fuel produces fuel gases. The temperature of the fuel gas mixture gets high and at released at point 3.

From point 3, this hot fuel gas mixture is passed to the turbine. The turbine expands the gases to the ambient pressure and releases them at point 4. The expansion takes place in two steps. In the first step, the gases are passed through nozzles which converts the thermal energy to kinetic energy. In the second step, the gasses are passed through the rotor of the turbine, thereby converting the kinetic energy to mechanical energy. The rotor of the turbine rotates, and the shaft also rotates. The rotation of the shaft operates the compressor, and the rest of the energy is used by the generator to produce the electricity. During this stage, the pressure of the gas decreases, and so does the temperature. However, the temperature of exhaust gases is still very high (usually 600^{o}C), having considerable amount of energy. This energy can be recovered using a heat recovery system generator, which produces high-pressure steam using the energy of exhaust gases from the gas turbine. This steam can be used to heat or generate energy via the steam cycle centrally.

Site Dependent Conditions:

There are ambient conditions that change with the change in location and time. The change in these ambient conditions changes the performance of the gas turbine. Hence all the testing of equipment is done at standard ambient conditions by the manufacturers. These standards are defined in ISO Standard 3977-2- Gas Turbine- Procurement-Part2: Standard Reference Conditions and Range. These standards define the air density at the inlet and mass flow rate. The three main parameters are:

Table 1 Standard ISO Ambient Conditions

Parameter	**Standard Condition**
Ambient Temperature	15^{o}C
Ambient Humidity	60%
Ambient Pressure	1.013bar

Ambient Temperature:

The temperature of the surrounding environment is called ambient temperature. This ambient temperature defines the air density of the surrounding. The increase in ambient temperature decreases the air density thus, decreasing the mass flow rate of the intake air.

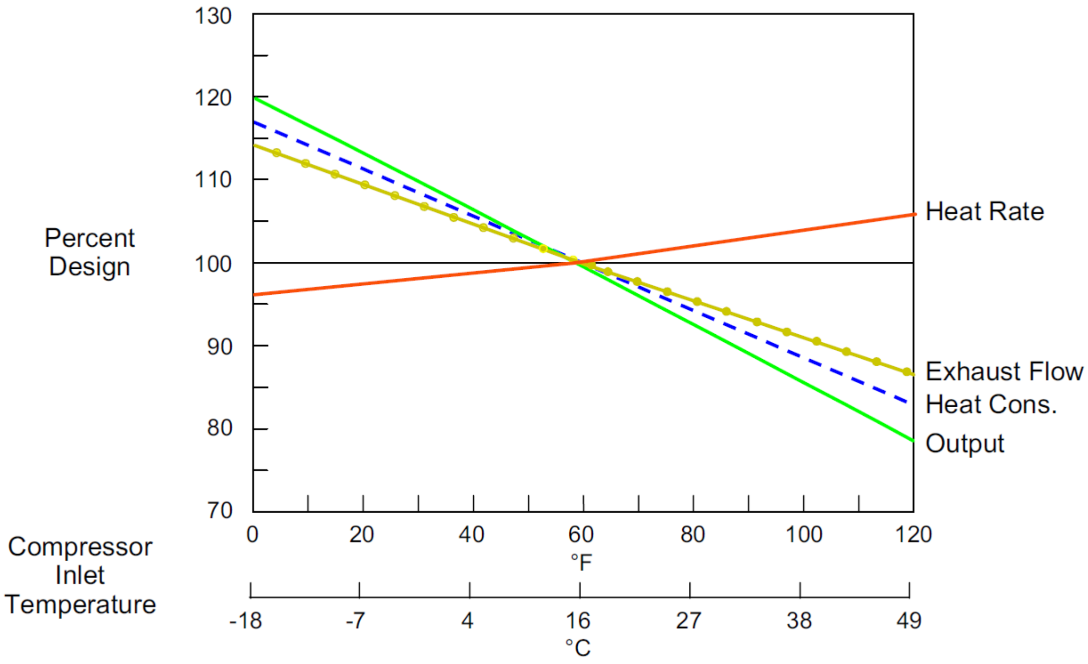


Figure 4 Effect of Ambient Temperature on Gas Turbine Performance [4]

Since mass flow relates to the power produced by the turbine, a decrease in mass flow rate decreases the power production. Similarly, the increase in temperature increases air volume, consequently increasing the work by the compressor to compress the intake air. More energy produced by the turbine would be used by the compressor.

Relative Humidity:

Relative humidity explains the content of water in the air. As the content of water increases in the air, the air density is reduced. This causes the power of the turbine to be reduced. The standard ambient relative humidity is taken to be 60%. This corresponds to 0.0064 kg of H_2O/kg of air.

The relationship between specific humidity and power output is depicted in the figure below. This graph shows that the power decreases with the increase in the specific humidity.

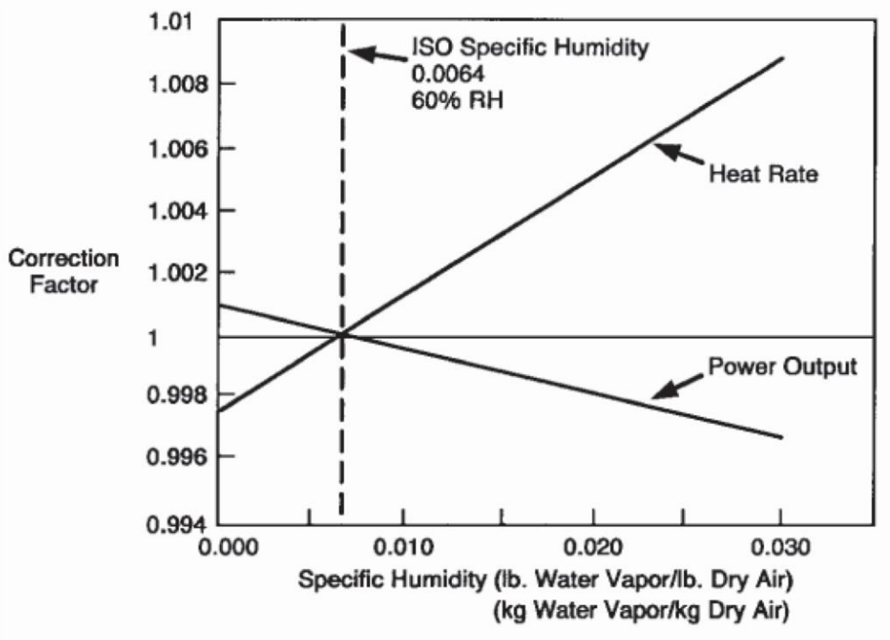


Figure 5 Effect of Humidity on Gas Turbine Performance [4]

The effect of relative humidity cannot be undermined. As the size of the gas turbine increases, the effect becomes significant.

Ambient Pressure:

This site related parameter is dependent upon air density and changes with the change in the elevation. The standard pressure for sea level elevation is 1.013bar. As the elevation rises, the air content decreases, thus decreasing the ambient pressure of the sit. The reduced pressure and reduced density of air contribute to the reduction of air mass flow in the turbine. The power output from the turbine is decreased resultantly.

The relationship among altitude, ambient pressure and power output is shown in the figure below.

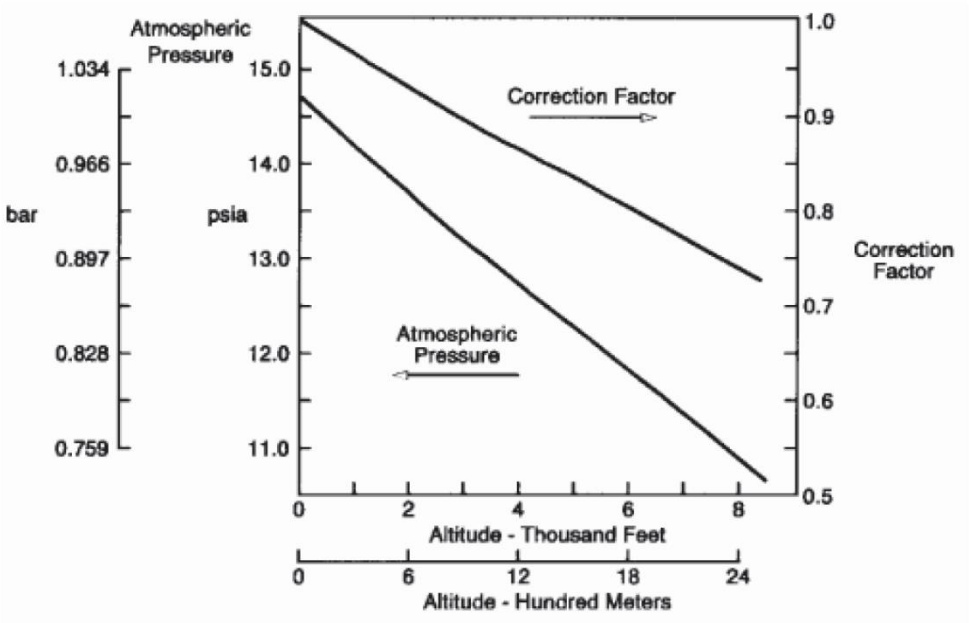


Figure 6 Effect of Pressure on Gas Turbine Performance [4]

The left axis of the graph shows the pressure plotted against elevation on the horizontal axis. The first graph shows that as the altitude increases, the atmospheric pressure decreases.

The right axis of the figure has power output plotted as a correction factor. As the atmospheric pressure decreases, the power output also decreases.

Turbine Inlet Temperature:

Turbine Inlet Temperature is the temperature of flue gases on the entry to the turbine. This temperature is the most important parameter in Gas turbine operations since it controls the work produced by the turbine and the thermal efficiency of the cycle.

As the turbine inlet temperature rises, the ability to produce more energy is increased since the thermal energy content of flue gases increases. The work of turbine is given by:

$$w_T = (h_3 - h_4) = c_p(T_3 - T_4) \text{ --------------------------------[6]}$$

Hence as T_3 increases, so does the work output of the turbine. The overall work output is given by:

$$w = c_p(T_3 - T_4) - c_p(T_2 - T_1) \text{ --------------------------------[7]}$$

Jet engine as Aeroderivative Engine:

Jet engines work on the Brayton cycle and are used for producing high-speed jet for producing thrust. Jet engines are the type of air-breathing engine with internal combustion. The main parts of jet engines are the compressor, combustion chamber, turbine, and propelling nozzle.

Jet engines have many different types based on their operating conditions and function. These types include turbojet, ramjet, and turbofan.

Turbojet uses thrust from the jet produced from the nozzle. The burnt gases are expanded in the propelling nozzle to produce a high-speed jet. Thus, turbojet is used for supersonic operations. They find their applications in the old aircraft.

In the modern-day, most aircraft's use turbofans due to higher efficiency at medium subsonic speeds. A turbofan uses a fan at the start of the compressor for increasing the airflow passing through the engine. The flow from the fan is divided into two streams: hot flow, which is passing through the combustion chamber and cold flow that is bypassing the combustion chamber and passing through the nacelle. The overall thrust is produced by the combination of this hot and cold flow. On the contrary, the fuel consumption is much lower as compared to turbojets at the same overall mass flow rates.

There are two configurations of turbofan based on their bypass ratio. The bypass ratio is the ratio of the mass flow rate of the bypass stream to the mass flow rate of the core.

$$\beta = \frac{\dot{m}_c}{\dot{m}_a} \text{-------------------------------} [8]$$

The bypass ratio is one of the main design parameters apart from pressure ratio, fan pressure ratio and turbine inlet temperature. The propulsive efficiency of the turbofan is dependent on the bypass ratio. A higher bypass ratio gives lower fuel consumption for the same thrust.

These configurations based on the bypass ratio are:

High Bypass Ratio Turbofan:

The high bypass ratio uses more fans thrust than the jet thrust is known as the high bypass ratio turbojet. These are the most common form of turbofans used in the aviation industry. Most of the jet engines today used in the aviation industry are High bypass turbofan engines (HBTE) because high bypass ratio turbofans are near as fuel-efficient as turboprops. Also, the fan is enclosed by the inlet and is composed of many blades. Thus it can operate efficiently at higher speeds than a simple propeller.

High bypass turbofan engines are also quieter than the simple turbojet engine because the thrust is developed by turning the fan using the turbine engine, which accelerates larger air quantity to a lower velocity as compared to simple turbojets. Thus, most jet engines retiring nowadays are High Bypass Turbofan Engines and are available easily.

Low Bypass Ratio Turbofan

These turbofans use more jet thrust than fan thrust. These are suitable for higher speeds than low bypass turbojet as used in the commercial aviation industry. These low bypass engines are used in modern military fighter engines.

Use of Retired HBTE in Power Industry:

The use of aviation turbofans in the power industry is on the rise. It is due to the advantages that turbofans provide, such as lower emissions and low weight-to-power ratio. These aero engines are efficient and suitable for mobile applications. These aero-derivative gas turbines are suitable for small power production operating on a simple gas cycle.

General Electric produces LM6000, an aero-derivative gas turbine derived from the CF6-80C2 engine for the purpose of power production. Other companies like Rolls Royce have WR-21 engine produced for marine applications derived from RR RB211 turbofan engine and GE LM2500 derived from high bypass turbofan CF6. CF56, manufactured by CFM, is used in modern aircrafts such as Boeing 737, Airbus A340-311, A340-211. These aircraft were launched about 30 years ago and are in the phase of retirement. This creates the opportunity for usage of their engines in the power production industry. The industrial derivative of CFM56 is not present in the industry.

Table 2 Design Point Inputs for CFM56-Turbofan

Parameter	**Design Point Inputs**
Mach Number	0
Mass Flow	465.8 kg/s
Fan Pressure Ratio	1.58
Low Pressure Compressor	2.0
High Pressure Compressor	9.96835
Overall Pressure Ratio	31.5
Bypass Ratio	6.6

The study evaluates different configurations and estimates the power production by the engine.

CHAPTER 3: METHODOLOGY

The project has been divided into four main stages. These stages are divided for the creation of a computer program and additional research.

Stage 1: Gas Turbine Operations

The operations of the gas turbine and different parameters at a different point in the gas turbine are calculated using the five basic parameters.

Inputs to the Program:

The input section of the program requires five inputs from the users. Other conditions are set to default and can be changed if the user wants them to change. These are taken as input from the user. These are:

- **The Overall Power Output**

It is the power output in MW obtained after the generator.

- **Overall Thermal Efficiency**

Thermal efficiency is the ratio of the net work done by the gas turbine to the heat supplied. For the simple cycle, the thermal efficiency is given by:

$$\eta_{gt} = \frac{c_{p_T}(T_3 - T_4) - c_{p_c}(T_2 - T_1)}{c_p(T_3 - T_2)} \quad \text{-------------------------}[9]$$

- **Exhaust Mass Flow Rate**

Exhaust mass flow rate is expressed in kg/s and indicates the mass of flue gases emitting from the turbine outlet per unit second.

- **Exhaust Temperature of Flue Gases**

Exhaust temperature, expressed in ^{o}C, is the temperature of the flue gases emitting from the outlet of the turbine.

- **The Pressure Ratio of The Compressor**

Pressure ratio is the ratio of the pressure of gases emerging out of the compressor to the pressure of the gases at the inlet.

In ideal cases, the pressure ratio of the turbine is equal to the compressor. However, it is considered nearly equal in the case of real gases.

Environmental Conditions:

The necessary environmental/site-dependent conditions required for the gas turbine are:

Table 3 Site Conditions for Turbofan

Parameter	**Standard Condition**
Ambient Temperature	30^{o}C
Ambient Humidity	60%
Ambient Pressure	1.013bar

These conditions are standardized for usage in documents by ISO Standard 3977-2-Gas Turbines- Procurement- Part 2: Standard Reference Conditions and Ratings. The manufacturers state their data calculated in these conditions. Thus, these values added by engineers for specific conditions must be considered, and data should be interpolated for these values.

Outputs of the Program:

Capturing this problem, we developed a program section that would take these easily available parameters from the user and process them to provide the important output parameters. The important parameters and their method of calculation are outlined here.

- **Isentropic Efficiency of Compressor:**

The isentropic efficiency of the compressor is the characterization of the blading properties of the compressor stage. This is taken to be 92% for the compressor. This is used and validated using iterations.

- **Compressor Outlet Temperature:**

The outlet conditions at the compressor outlet are found using the isentropic efficiency and pressure ratio of the compressor.

The compressor outlet pressure, P02, is calculated using pressure ratio P_{rc}:

$$P_{02} = P_{01} \times P_{rc} \qquad \text{-----------------------[10]}$$

The compressor outlet temperature in kelvin is found using the following relationship:

$$T_{02} = T_{01}\left[1 + \left(\frac{1}{\eta_c}\right) \times \left(P_{rc}^{\frac{\gamma-1}{\gamma}} - 1\right)\right] \text{--------[11]}$$

- **The Mass Flow rate of fuel**

The flow rate of the fuel is calculated using the heat flow rate and lower heating value of the fuel. The heat flow rate is calculated using the power output of the gas turbine and efficiency.

$$Heat\ flowrate = \frac{Power\ Output}{\eta_{thermal}} \times 100 \qquad \text{--------[12]}$$

$$m_f = \frac{Heat\ flowrate}{LHV} \qquad \text{-------------[13]}$$

The fuel-to-air ratio can be found using:

$$f = \frac{m_f}{m_a} \qquad \text{--------------------------------[14]}$$

- **The Mass Flow rate of Dry Air**

The mass flow rate of the dry air is calculated using the specific humidity content at the inlet of the compressor. Since from 60% relative humidity, the specific humidity of air is 0.0064 kg of water/kg of air, the water content of inlet air is calculated to be:

$$m_w = 0.0064 \times m_a \quad \text{--------------------------[15]}$$

The mass flow rate of dry air is then,

$$m_{dry.air} = m_a - m_w \text{ ---------------------------[16]}$$

When the temperature or relative humidity changes at the inlet, the included library in the program automatically updated the specific humidity for that temperature.

- **Power Consumed by Compressor**

The power consumed by the compressor is calculated using the mass flow rate of humid air, temperatures at inlet and outlet of compressor and cp value of humid air.

$$P_{comp} = \dot{m}_a \times c_{p_{comp}}(T_{02} - T_{01}) \text{ -----------------[17]}$$

- **Power Consumed by Turbine**

The power produced by the turbine can now be calculated using the difference of the given net power of the gas turbine and the power of the compressor calculated in the above equation.

$$P_{turbine} = P_{net} + P_{comp} \qquad \text{---------------------[18]}$$

- **Turbine Inlet Temperature**

The turbine inlet temperature can be calculated using the power of turbine and exhaust temperature, $T_{e_{gt}}$ And cp of exhaust gases.

$$TIT = \frac{P_{turbine}\ in\ kW}{m_e \times cp_{turbine}} + T_{e_{gt}} \quad \text{---------------------[19]}$$

- **Flue Gases Composition Analysis**

The composition of flue gases can be analyzed using combustion chamber analysis. This is done to find the greenhouse gases along with the calculation of cp of exhaust gas mixture.

The process is shown in the figure below. The incoming fuel reacts with the moles of the incoming air mixture to produce the exhaust gases mixture.

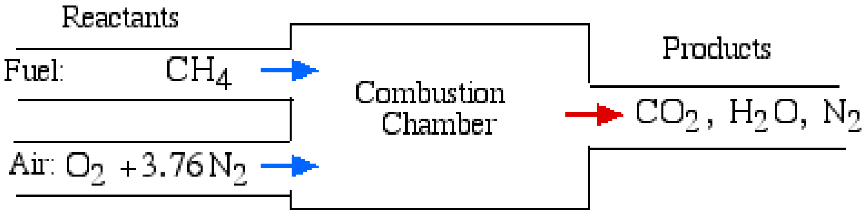


Figure 7 Combustion Chamber Analysis

For the analysis, complete combustion has been assumed. Furthermore, only natural gas has been considered with 100% methane quantity. The equation is given as:

$$\mathrm{CH_4 + N_{air}(O_2 + 3.76\ N_2) \rightarrow x.CO_2 + y.H_2O + z.O_2 + w.N_2}$$

The N_{air} depends on the air to fuel ratio. It is reciprocal of fuel to air ratio.

$$AFR = \frac{1}{f} \quad \text{------------------------[20]}$$

Moreover, the AFR is given by,

$$AFR = \frac{m_a}{m_{fuel}} = \frac{(NM)_{air}}{(NM)_c + (NM)_{H_2}} \text{--------[21]}$$

$$\frac{(NM)_{air}}{(NM)_c + (NM)_{H_2}} = \frac{N_{air} \times 29}{1 \times 12 + 2 \times 2} = AFR$$

From here, the N_{air} can be used to find x, y, z, w.

The moles of the gases are calculated using the comparison, which multiplied by the molar mass ratio gives the percentage of a particular gas in the exhaust gas.

Data for Calculations:

The calculations for the gas turbine are performed using the data from the gas turbine catalogue. The model of the gas turbine used is GE9HA.01. The input parameters are as follow:

Parameter	**Value**
Overall Power Output (MW)	538
Overall Thermal Efficiency %	42.8
Exhaust Mass Flow Rate (kg/s)	1020
Exhaust Temperature of Flue Gases (^{o}C)	621
The Pressure Ratio of the Compressor	26

The section related to values that have been set as default or changeable by user are:

Parameter	**Value**
Lower Heating Value (MJ/kg)	50
Pressure Loss at Inlet	1%
Mechanical Efficiency	99.6%

Electrical Efficiency	98.7%
Gamma in compressor	1.4
Efficiency of Compressor	92%

Stage 2: Combined Gas-Vapor Cycle Operations

The operations of the combined gas-vapor cycle are calculated using the following basic parameters.

Inputs to the Program:

- **Net Power Output of Combined Cycle**

This is the total output in MW from the combined cycle. This includes the sum of power output from the steam cycle and gas cycle. This is catalogue data and easily available from the validation study of combined cycle models.

$$P_{cc} = P_{gt} + P_{sc}$$

- **Net Power Output of Gas Cycle**

The net power output from the gas cycle is provided in the gas turbine catalogues. This is specific to TIT and other conditions. Stage 1 is integrated to find this for users.

- **The efficiency of Combined Cycle**

The combined cycle efficiency is given by the total work out by the two cycles divided by the input energy from the fuel. It is given by:

$$\eta_{cc} = \eta_{gt} + \eta_{st}(1 - \eta_{st})$$

- **The Efficiency of Gas Cycle**

The efficiency of the gas cycle is present in the catalogues and also can be calculated using the program in stage 1.

- **Mass Flow Rate and Temperature of Exhaust Gases from Gas Turbine**

The mass flow of exhaust gases can be found from the gas turbine cycle. The exhaust gas temperature is also given in the gas catalogues.

- **Pressure and Temperature at Steam Turbine Inlet**

The temperature and pressure at the inlet of the steam cycle provided in the catalogues for the combined cycle operations. These are the temperature and pressure required at the end of the Heat Recovery Steam Generator or HRSG.

Environmental Conditions:

The necessary environmental/site-dependent conditions required for the gas turbine are:

Parameter	**Standard Condition**
Ambient Temperature	15^{o}C
Ambient Humidity	60%
Ambient Pressure	1.013bar

These conditions are standardized for usage in documents by ISO Standard 3977-2-Gas Turbines- Procurement- Part 2: Standard Reference Conditions and Ratings. The manufacturers state their data calculated in these conditions. Thus, these values added by engineers for specific conditions must be considered, and data should be interpolated for these values.

Outputs of the Program:

The outputs from the steam cycle and their methods of calculation are described below:

- **The efficiency of Steam Cycle:**
  The efficiency of the steam cycle can be found using Equation 2.
- **Power of Steam Cycle**
  The power of the steam cycle can be found in the difference between the net power of the combined cycle and the power out of the gas turbine.
- **The Temperature of Exhaust of HRSG**

The temperature of exhaust gases after passing from the HRSG is given by the following equation:

$$Q_{in} = m_e . c_p (T_{exhaust_{exit}} - T_{exhaust_{inlet}}) \quad \text{------------[22]}$$

The Temperature of Outlet Water from Condenser:

The outlet temperature of cooling water from the condenser is calculated using Q_{out} and mass flow rate of cooling water. The inlet conditions are taken at ambient conditions.

$$Q_{out} = m_{cw} . c_p (Te_{cw} - Ti_{cw}) \quad \text{------------------[23]}$$

- **Power of Pump**

  The power of the pump is calculated using the condition of condensed steam at the inlet and outlet of the pump. The specific volume is considered to be constant for pump calculations.

$$P_{pump} = m_{steam} . v . (P_2 - P_1) \quad \text{------------------[24]}$$

- **Power of Steam Turbine**

  The power of the steam turbine is calculated using turbine efficiency and inlet and outlet conditions.

- **The Efficiency of Steam Turbine**

  The efficiency of the steam turbine shows how efficiently the turbine has expanded the steam.

Data for Calculations:

The calculations for the gas turbine are performed using the data from the gas turbine catalogue. The model of the gas turbine used is GE9HA.01. The input parameters are as follow:

Parameter	**Value**
Overall Power Output (MW)	470

Overall Thermal Efficiency (%)	41
Exhaust Mass Flow Rate (kg/s)	980
Exhaust Temperature of Flue Gases (^oC)	619
The Pressure Ratio of the Compressor	21.8

The section related to values that have been set as default or changeable by user are:

Parameter	**Value**
Lower Heating Value (MJ/kg)	50
Pressure Loss at Inlet	1%
Mechanical Efficiency	99.6%
Electrical Efficiency	98.7%

Stage 3: Turbofan for Ground Operations:

The use of retired turbofan for power generation is performed in this section. This has been done in many ways. Some of these ways are following:

Two Spools with Free Power Turbine

The use of a two-spool with a free turbine model includes a low-pressure shaft and a high-pressure shaft. In this configuration, the fan is removed. The High-pressure turbine drives the High-pressure compressor while the High-pressure turbine core is kept the same. The Low-pressure compressor is driven by a low-pressure turbine. An additional free turbine is added.

Two Spools with Integrated Power Turbine On LPS:

the two shafts are retained, and the free turbine is removed. Instead of the free turbine, LPT is used to expand the flow to atmospheric pressure producing power by rotating a low-pressure shaft. The shaft is connected with a generator and kept at a constant speed to maintain the frequency of 50 or 60Hz.

Single Spool with Free Power Turbine:

In this configuration, the free turbine is mounted downstream of the high-pressure turbine to expand the flow to atmospheric pressure and to extract the remaining energy.

The modifications for the engine are performed by keeping the following in mind:

- The modifications should be minimal.
- The redesigning should be reduced to improve the supply chain and cost of transformation.
- The power should be generated the highest.

Keeping the above-mentioned criteria, the model with two spools and free turbine has been selected since it provides the maximum output power and efficiency.

Inputs to the Program:

The input section of the program requires five inputs from the users. Other conditions are set to default and can be changed if the user wants them to change. These are taken as input from the user. These are:

- **The Mass Flow Rate of Core Air**

The mass flow rate of the core air is taken as input. It is considered dry air.

- **Turbine Inlet Temperature**

The turbine inlet temperature is the temperature at the inlet of the turbine. This is taken as input.

- **The Overall Pressure Ratio of Compressors**

Pressure ratio is the ratio of the pressure of gases emerging out of the compressor to the pressure of the gases at the inlet.

In ideal cases, the pressure ratio of the turbine is equal to the compressor. However, it is considered nearly equal in the case of real gases.

Environmental Conditions:

The necessary environmental/site-dependent conditions required for the gas turbine are:

Parameter	**Standard Conditions**
Ambient Temperature	25^oC

Ambient Humidity	60%
Ambient Pressure	1.013bar

Default Assumptions:

These parameters are already included in the program, and users are also given the option to modify them. Their value is derived from research. These are:

Parameter	**Value**
Lower Heating Value (MJ/kg)	50
Isentropic Efficiency of Compressor	88%
The efficiency of Combustion Chamber	99%
Efficiency of Turbine	92%
Mechanical Efficiency	99.6%
Electrical Efficiency	98.7%
Gamma in Compressor	1.4
Pressure Loss at Inlet	1%

Outputs of the Program:

Capturing this problem, we developed a program section that would take these easily available parameters from the user and process them to provide the important output parameters. The important parameters and their method of calculation are outlined here.

- **Compressor Outlet Temperature:**

The outlet conditions at the compressor outlet are found using the isentropic efficiency and pressure ratio of the compressor.

The compressor outlet pressure, P02, is calculated using pressure ratio P_{rc}:

$$P_{02} = P_{01} \times P_{rc} \qquad \text{------------------[25]}$$

The compressor outlet temperature in kelvin is found using the following relationship:

$$T_{02} = T_{01}[1 + \left(\frac{1}{\eta_c}\right) \times \left(P_{rc}^{\frac{\gamma-1}{\gamma}} - 1\right)] \qquad \text{------------------[26]}$$

- **Power Consumed by Compressor**

The power consumed by the compressor is calculated using the mass flow rate of humid air, temperatures at inlet and outlet of compressor and cp value of humid air.

$$P_{comp} = \dot{m}_a \times c_{p_{comp}}(T_{02} - T_{01}) \qquad \text{------------------[27]}$$

- **The Mass Flow rate of fuel**

The flow rate of the fuel is calculated using the heat flow rate and lower heating value of the fuel. The heat flow rate is calculated using the power output of the gas turbine and efficiency.

$$Heat\ flowrate = \frac{Power\ Output}{\eta_{thermal}} \times 100 \qquad \text{------------------[28]}$$

$$m_f = \frac{Heat\ flowrate}{LHV} \qquad \text{------------------[29]}$$

The fuel-to-air ratio can be found using:

$$f = \frac{m_f}{m_a} \qquad \text{------------------[30]}$$

- **Exhaust Temperature of Flue Gases**

Exhaust temperature, expressed in °C, is the temperature of the flue gases emitting from the outlet of the turbine. This is also called turbine outlet temperature.

$$T_{04} = TIT \times [1 - \{\eta_{turb} * \left(1 - \left(\frac{1}{P_{rc}}\right)^{\gamma - \frac{1}{\gamma}}\right)\}] \qquad \text{------------------[31]}$$

- **Power Consumed by Turbine**

The power produced by the turbine can now be calculated using the difference of the given net power of the gas turbine and the power of the compressor calculated in the above equation.

$$P_{turbine} = \dot{m}_a \times c_{p_{turb}}(T_{04} - T_{03}) \qquad \text{------------------[32]}$$

- **Exhaust Mass Flow Rate**

Exhaust mass flow rate is expressed in kg/s and indicates the mass of flue gases emitting from the turbine outlet per unit second. It includes the mass flow rate of fuel and inlet air.

$$m_{exhaust} = m_a + m_f \qquad \text{------------------[33]}$$

- **The Overall Power Output**

It is the power output in MW obtained after the generator.

$$P_{net} = P_{turbine} - P_{comp} \qquad \text{------------------[34]}$$

- **Overall Thermal Efficiency**

Thermal efficiency is the ratio of the net work done by the gas turbine to the heat supplied. For the simple cycle, the thermal efficiency is given by:

$$\eta_{gt} = \frac{c_{p_T}(T_3 - T_4) - c_{p_c}(T_2 - T_1)}{c_p(T_3 - T_2)} \qquad \text{------------------[35]}$$

- **Specific Fuel Consumption**

It is the fuel consumed per unit of power produced.

$$\mathrm{sfc} = \frac{\mathrm{m_f}}{P_{net}} \qquad \text{------------------[36]}$$

Stage 4: Single Vs. Multi-Shaft CCPP:

Combined cycle power plants combine cycle power plant have two major configurations. One is a single-shaft layout, and the other is a multi-shaft layout. A single shaft combines cycle power plant has both steam turbine and gas turbine mounted on one single shaft. In a multi-shaft combine cycle power plant, the steam turbine and gas turbine have separate shafts. Both layouts of the combined cycle power plant have benefits and drawbacks, which are explained in this paper. This paper aims to provide a clear comparison between single-shaft and multi-shaft configurations of a combined cycle power plants.

A literature review was carried out using keywords on reputable ISI journal databases. Keywords used are shown below:

- CCPP
- CCPP and layout
- CCPP and single shaft
- CCPP and shaft
- CCPP and performance
- CCPP and efficiency

The search engines used for the research were science direct, google scholar and Scopus. A total of ten research papers were studied, and their information was compiled.

CHAPTER 4: RESULTS AND DISCUSSIONS

Stage 1: Gas Turbine Operations

The dataset for the gas cycle operation has been taken from (Wettstein, 2020) and the results are validated. Calculations have been done on these input parameters, and there are some default parameters which include ambient conditions, compressor efficiency, etc. The gas cycle was tested against the following input data from the original engine manufacturers (OEM).

Overall, the errors are below 5%. This shows that the values have been implemented with the right strategy. The difference in compressor power is due to the usage of CDRA in the original paper, which supplies better estimation. However, the error of 1.16% justifies the usage for the simple polytropic efficiency usage.

Sr. no	**Gas Cycle Outputs**	**Value**	**Values from Research Paper**	**Error**
1	Gas turbine power (MW)	1052.00	1044	1%
2	Compressor power (MW)	505.75	497	2%
3	Gas cycle power (MW)	547.28	547	0%
4	Temp. at comp. outlet (°C)	496.30	492.1	1%
5	Turbine inlet temp. (°C)	1553.00	1588	-2%
6	Fuel-air ratio	0.0253	0.0253	0%
7	Mass flow rate of fuel (kg/s)	25.14	25.14	0%
8	Pressure at comp. inlet (bar)	1.03	1.033515	0%
9	Pressure at comp outlet (bar)	26.87	26.87	0%
10	Pressure at turbine inlet (bar)	25.12	24.98	1%
11	Pressure at turbine outlet (bar)	1.05	1.05	0%
12	O_2 Emissions (%)	12.85	12.6	2%
13	CO_2 Emissions (%)	6.815	6.5	5%

Stage 2: Combined Cycle Operations

The dataset for the combined cycle operation has been taken from (Wettstein, 2020) and the results are validated. Calculations have been done on the same input parameters as in single cycle operations withsteam cycle inputs added. There are some default parameters which include ambient conditions, compressor efficiency, etc. The gas cycle was tested against the following input data from the original engine manufacturers (OEM).

Sr. no	Gas Cycle Outputs	Value	Values from Research Paper	Error (%)
1	Gas Turbine power (MW)	1050.00	1044	0.57
2	Compressor power (MW)	502.75	497	1.16
3	Gas cycle power (MW)	547.28	547	0.05
4	Temp. at comp. outlet (°C)	496.30	492.1	0.85
5	Turbine inlet temp. (°C)	1553.00	1588	2.72
6	Fuel-air ratio	0.0253	0.03	0.67
7	Mass flow rate of fuel (kg/s)	25.14	25.14	0
8	Pressure at comp. inlet (bar)	1.03	1.033515	0.00
9	Pressure at comp outlet (bar)	26.87	26.87	0.01
10	Pressure at turbine inlet (bar)	25.12	24.98	0.58

11	Pressure at turbine outlet (bar)	1.05	1.05	0.29
12	O_2 Emissions (%)	10.82	12.6	14.11
13	CO_2 Emissions (%)	8.11	8	1.40

Results for Steam Cycle

Parameters	**Values**	**Results from Research Papers**	**Errors (%)**
Steam cycle power (MW)	163.00	156	4.48
Steam cycle efficiency (%)	31.82	33	3.58
HRSG exit temperature (°C)	209.60	(Extra Parameter)	
Cooling water exit temp. (°C)	39.90	-	
The temperature at the HRSG inlet (°C)	156.46	-	
Steam turbine outlet temperature (°C)	181.04	-	
Pump power (MW)	5.45	-	
Steam turbine power (MW)	157.6	156.3	0.80
Steam turbine efficiency (%)	33.45	34.1	1.90

Overall, the errors are below 5%. This indicates that the values have been implemented with the right strategy. The difference in compressor power is due to the usage of CDRA in the original paper, which provides better estimation. However, the error of 1.16% justifies the usage for the simple polytropic efficiency usage.

Trends:

The trends for different parameters have also been analyzed.

Inlet Air Conditions Vs. Compressor Power

In order to study the effect of inlet air conditions on the compressor work, compressor power at different inlet air temperature ranging from 5 to 45 degree Celsius have been plotted.

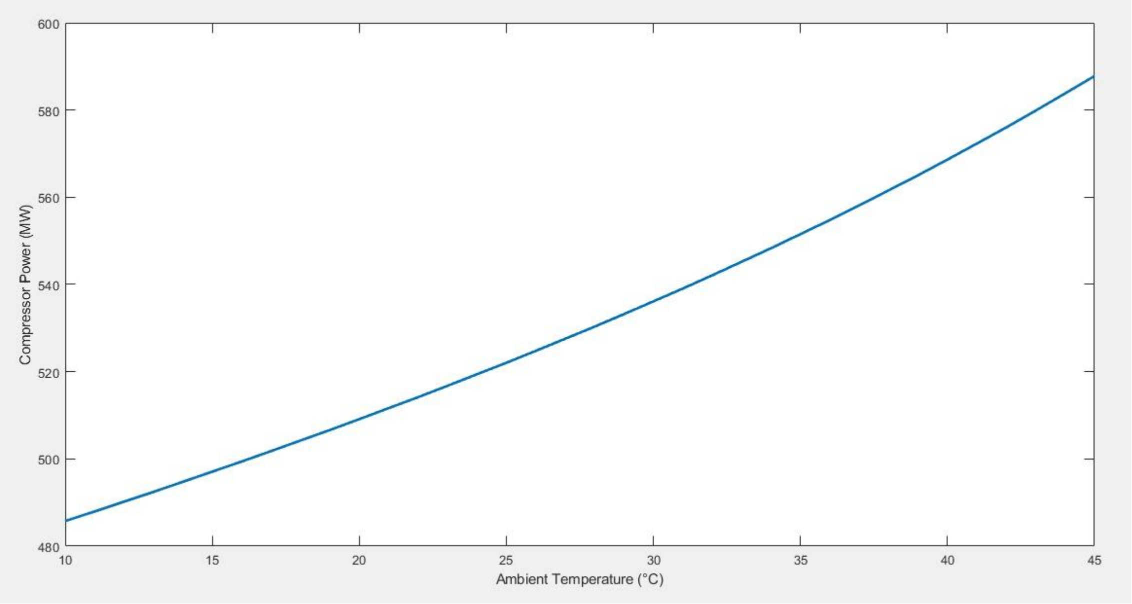


Figure 8 Gas Turbine-Inlet Air Temp. Vs. Compressor Power

The power consumed by the compressor increases as the ambient temperature increase. The power increases by 2MW by an increase of 1 degree Celsius.

From an increase of temperature from 5 to 45 degrees, the power consumption increases from 482MW to 597.2 MW, an increase of 115MW.

Steam Cycle Efficiency vs. Gas Turbine Exhaust Temperature:

The interdependence of the gas cycle and the steam cycle is shown by plotting the graph between gas turbine exhaust temperature and steam cycle efficiency. Since the steam cycle is operated using the energy from the flue gases, the relationship highlights the values for obtaining the efficiency from the steam cycle on changing the exhaust temperature of flue gases.

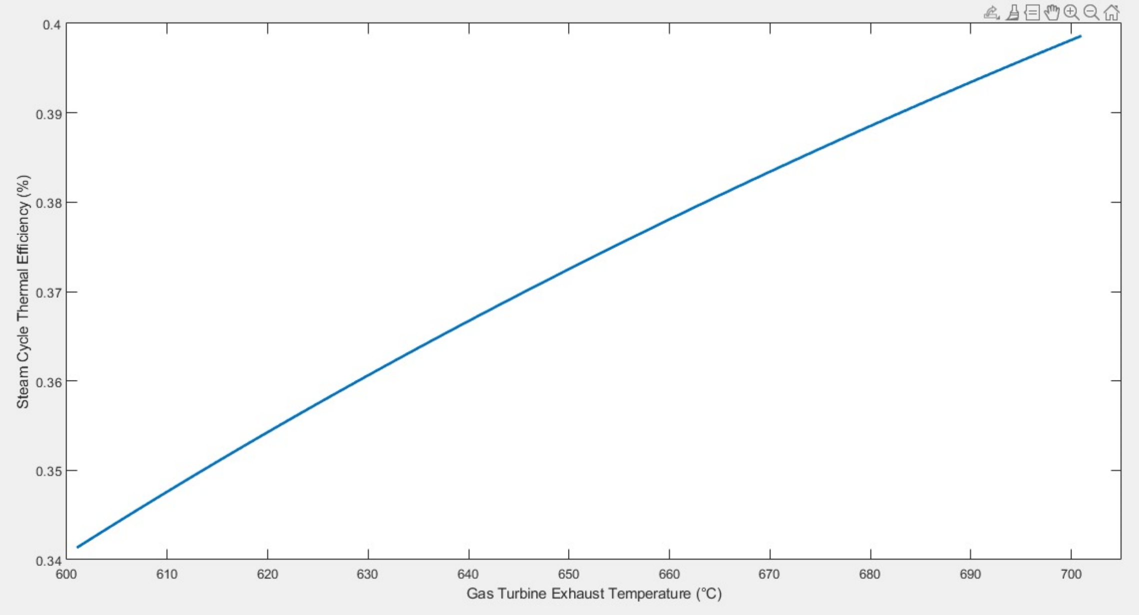


Figure 9 Gas Turbine- Steam Cycle Efficiency Vs. Exhaust Temperature

The graph shows that as the Gas Turbine Exhaust Temperature increases, the steam cycle efficiency also increases.

The temperature increases from 600 to 700 degree Celsius increases the steam cycle efficiency from 34.2% to 40%, an increase of 0.06% per degree increase in temperature of exhaust gases.

Fuel Mass Flow Rate VS. Gas Cycle Power Output

The relationship between fuel mass flow rate and gas cycle power output is shown in the figure below. As the gas cycle power is increased, this increase demands a linear increase in the mass flow rate of fuel.

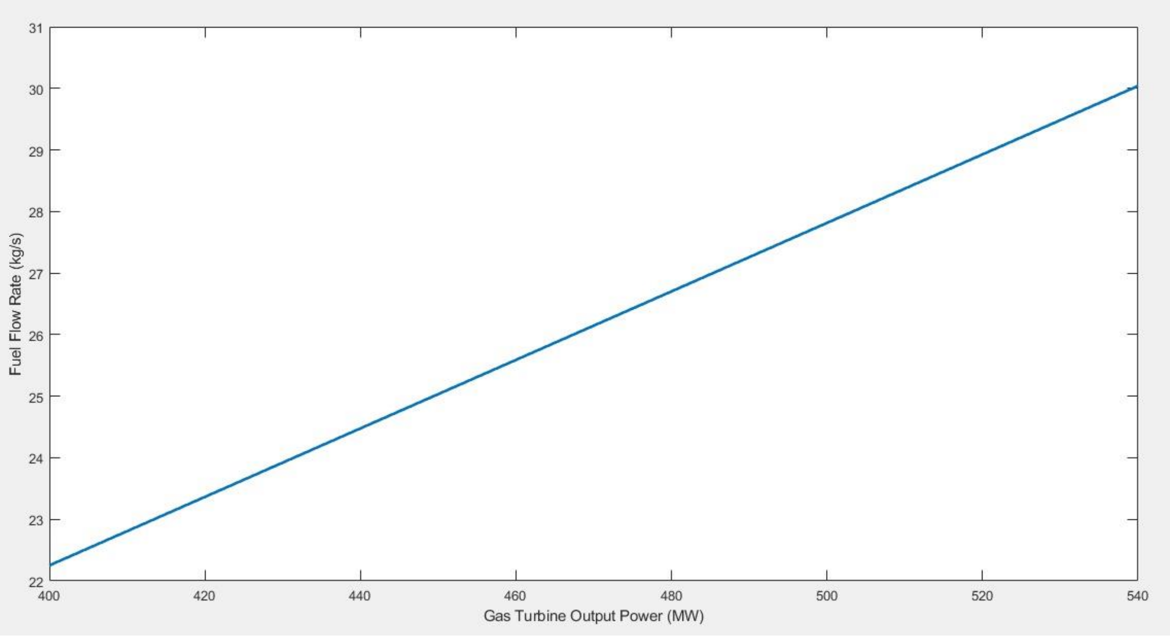


Figure 10 Gas Turbine- Fuel Flowrate Vs. Gas Cycle Power Output

The fuel flow rate is increased from 22.3 kg/s to 29.8 kg/s for an increase of power from 400MW to 540MW. This indicates a 0.054kg/s per MW increase in power.

Stage 3: Turbofan for Ground Applications:

The turbofan for the ground applications has been validated against the simulated results in various research papers. The calculations have been done on the design Combustion Chamber Outlet Temperature of 1343.5K.

With Inlet Fan Attached:

Initially, the fan has been retained due to simplicity and the aim of little modifications. The results have been calculated at design conditions and tabulated below:

Parameters	**Values**
Input Parameters	
COT (K)	1343.5
Total mass flow rate (kg/s)	61.29
Pressure Ratio of Fan	1.58
Pressure Ratio of Compressor	19.9367
Lower heating value (MJ/kg)	50
Pressure drops across diffuser (%)	2%
Turbine Efficiency	92%
Fan efficiency (%)	89%
Compressor efficiency (%)	88
Mechanical efficiency (%)	99.6
Electrical efficiency (%)	98.7

Combustor Chamber Efficiency (%)	99
Ambient pressure (bar)	1.01325
Ambient Temperature (°C)	25
Relative humidity (%)	60

Table 4 Results for Turbofan- With Fan

Validated Parameters

Parameters	**Results**	**Results from Research Papers**	**% Errors**
Exhaust mass flow rate (kg/s)	61.29	61.29	0.00%
Gas cycle efficiency (%)	40.86	39	4.77%
Gas turbine exhaust temp. (°C)	369.66	391.15	5.49%
Gas cycle power (MW)	10.31	10.67	3.37%
Mass flow rate of fuel (kg/s)	0.689	0.66	4.39%
Specific Fuel Consumption (µg/N. s)	66.8	64	4.38%

Other Parameters

Fan Power (MW)	3.0959
Gas turbine power (MW)	51.616

Compressor power (MW)	38.2014
Temp. at comp. outlet (°C)	602.132
Temperature at fan outlet (°C)	71.77
Fuel-air ratio	0.0112
Pressure at comp. inlet (bar)	1.0335
Pressure at comp outlet (bar)	32.6378
Pressure at turbine inlet (bar)	20.51
Pressure at turbine outlet (bar)	1.047

With Fan Removed

In the second iteration, the fan has been removed since it uses up to 3MW of energy and serves no purpose. In this stage, the results at standard conditions are:

Parameters	**Values**
Input Parameters	
COT (K)	1343.5
Total mass flow rate (kg/s)	61.29
Pressure Ratio of Compressor	19.9367
Lower heating value (MJ/kg)	50
Default Parameters	
Pressure drops across diffuser (%)	2%
Turbine Efficiency	92%
Fan efficiency (%)	89%
Compressor efficiency (%)	88
Mechanical efficiency (%)	99.6
Electrical efficiency (%)	98.7
Combustor Chamber Efficiency (%)	99
Ambient pressure (bar)	1.01325
Ambient Temperature (°C)	25
Relative humidity (%)	60

Table 5 Results for Turbofan- Without Fan

Validated Parameters			
Parameters	**Results w/o fan**	**Results with Fan**	**% Change**
Exhaust mass flow rate (kg/s)	62.18	61.29	1.43%
Gas cycle efficiency (%)	43.57	40.86	6.22%
Gas turbine exhaust temp. (°C)	440.9	369.66	16.16%
Gas cycle power (MW)	18.14	10.31	43.16%
Mass flow rate of fuel (kg/s)	0.8943	0.689	22.96%
Specific Fuel Consumption (µg/N. s)	49.57	66.8	-34.76%

Other Parameters		
Parameters	**Results w/o fan**	**Results with Fan**
Fan Power (MW)	0	3.0959
Gas turbine power (MW)	47.75	51.616
Compressor power (MW)	29.61	38.2014
Temp. at comp. outlet (°C)	478.3	602.132
Temperature at the fan outlet (°C)	n/a	71.77
Fuel-air ratio	0.0146	0.0112

Pressure at the comp. inlet (bar)	1.0335	1.0335
Pressure at comp outlet (bar)	20.6	32.6378
Pressure at turbine inlet (bar)	19.31	19.33
Pressure at turbine outlet (bar)	1.047	1.047

Trends:

The trend among different parameters has been studied. These parameters are affected by the Combustion Chamber Inlet Temperature. This is equivalent to the turbine inlet temperature.

Power Vs. Combustion Chamber Inlet Temperature:

In order to analyze the relationship between the power produced by the free turbine at different combustion chamber outlet temperatures, the graph is plotted. The power output from the turbofan is gained as shaft power.

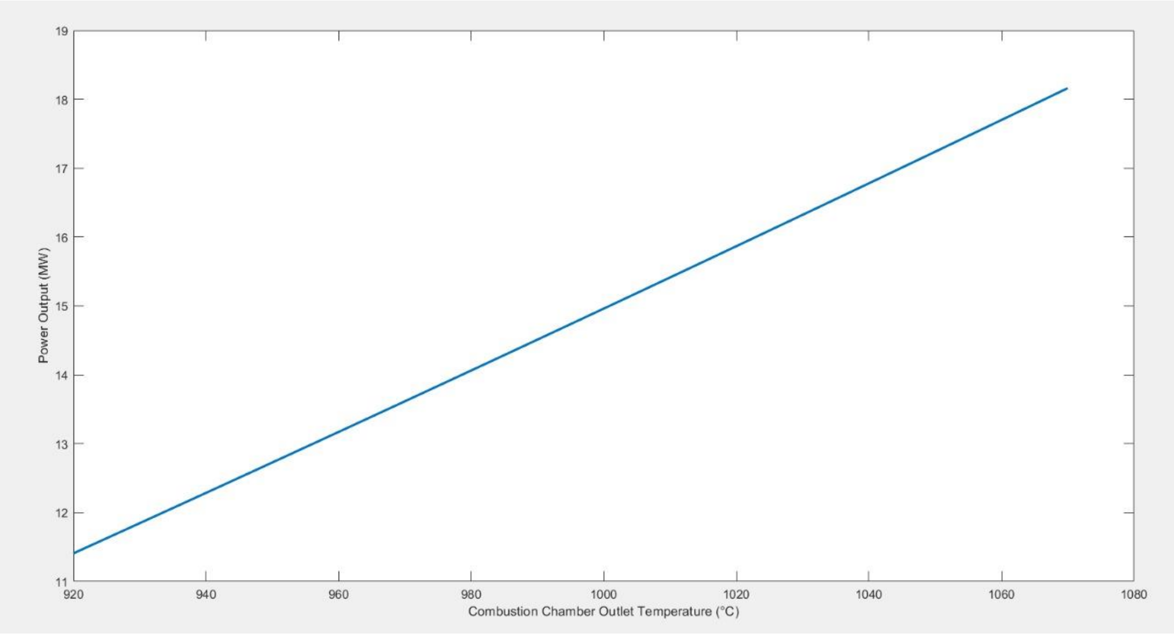


Figure 11 Turbofan- Power Vs. Combustion Chamber Inlet Temperature

The power has a direct relationship with the COT. As COT increases, the power output is increased correspondingly.

For an increase of temperature from 920 to 1070 degrees, the power is increased from 11.4 to 17.9MW.

This indicates the change of 0.043MW for each degree change in temperature.

<u>Thermal Efficiency and COT:</u>

Thermal efficiency has a direct relationship with the COT. The increase in COT increases the thermal efficiency. However, this increase is limited by the maximum value of COT that can be sustained by the turbine blades and materials.

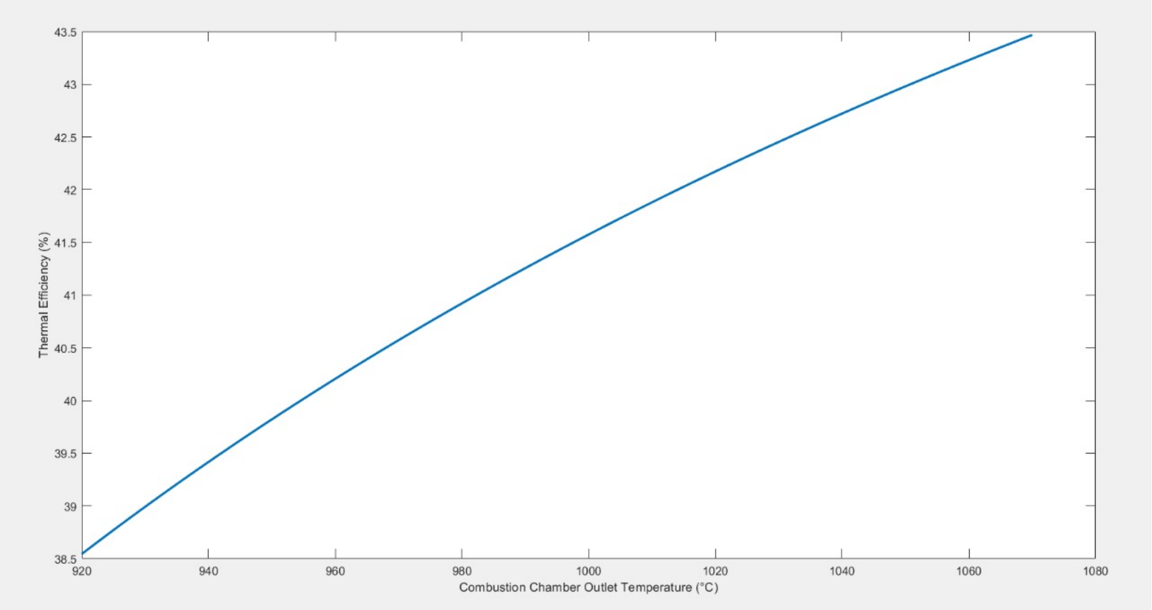


Figure 12 Turbofan- Thermal Efficiency Vs. COT

The thermal efficiency is increased from 38.7 to 43.5% from an increase of combustion chamber temperature from 920 to 1070 degrees. This indicates a 0.032% increase with each degree increase in the COT.

<u>Specific Fuel Consumption vs. COT:</u>

The specific fuel consumption indicates the mass flow rate of fuel required to produce one megawatt of power from the powerplant. The Specific Fuel Consumption has an inverse relationship with the COT. This is due to the reason that elevated temperatures produce more power by using lower amounts of fuel.

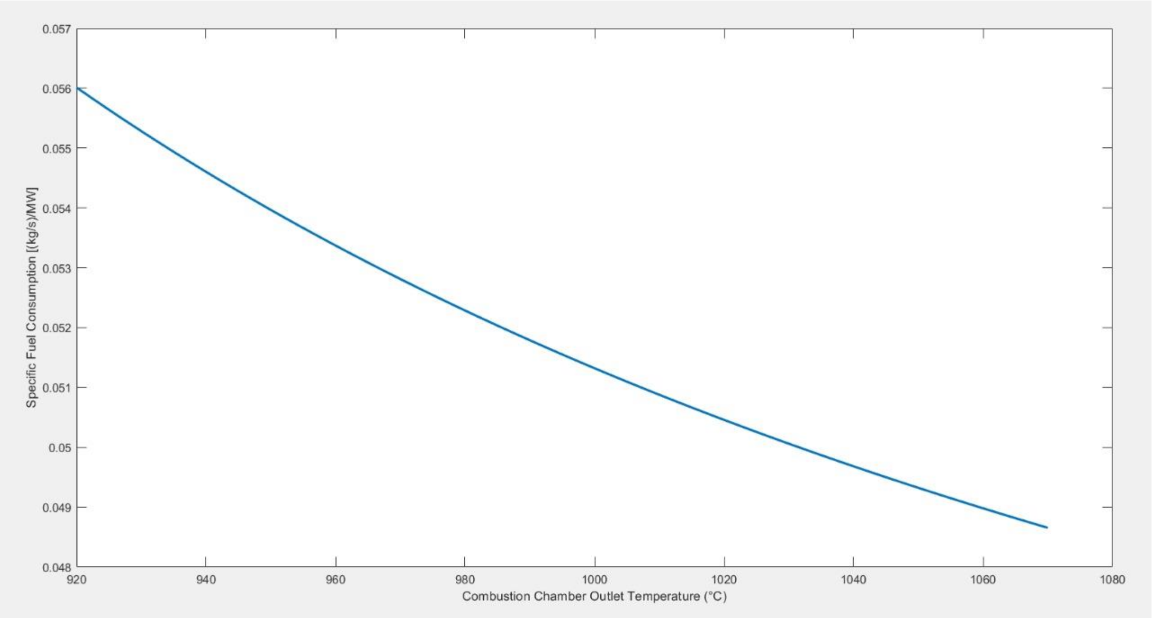


Figure 13 Turbofan- Specific Fuel Consumption Vs. COT

The specific fuel consumption decreases from 0.056 to 0.048 [(kg/s)/MW] with increase in COT from 920 to 1070 degree Celsius.

Stage 4: Shaft Configuration

The main highlights of the single vs. dual-shaft configurations are tabulated below.

Table 6 Shaft Configuration- Comparison

Single Shaft Configuration	Multi-Shaft Configuration
Low centerline height means less complex foundation design	More layout flexibility means equipment can be placed in a specific layout
Side access roadways for easier construction and maintenance	The separate gas turbine hall
Simpler plant foundations, pier foundations compared to tabletop construction	Shorter pipelines between ST and HRSG
Construction Scheduling, segregation of mechanical, electrical, and civil operations	No active generator cooling, air-cooled generators instead of hydrogen cooled
Single bigger generator compared to two smaller generators	Higher availability factor means more electricity is produced throughout the year
Less auxiliary power	Steam extraction for domestic use
Compact and relatively more integrated design	The gas turbine can be installed before the steam turbine
Requires less land space	The quality of lubricants is not as strict
Shorter hot startup times	Shorter cold startup times
Fewer generator losses due to hydrogen cooling	Lower maintenance cost
Higher efficiency due to fewer losses	

Overall, 3-5 % saving on investment	

Performance Comparison of Shaft System:

Single shaft and multi-shaft configurations have different performance characteristics, both these layouts have been tested, and calculations have been performed to evaluate their performance. The tests were performed on two gas turbines and two steam turbines, 840 MW base load CCPP. The performance comparison is explained below.

Efficiency

The efficiencies of both configurations were calculated using the following formula:

$$\eta_{Gross} = \frac{W_{GT} + W_{ST} - Generator\ losses}{\dot{m}_f . LHV}$$

At baseload, the single shaft configuration had higher efficiency and power output. When the two gas turbines are working simultaneously, the efficiency of both layouts is almost the same; this is because the steam cycle performance is identical for both configurations. However, when only one gas turbine is running, the efficiency of the single shaft layout becomes larger than multi-shaft layout; this can be explained because the steam cycle efficiency is lower for the case of multi-shaft layout with one gas turbine than the steam cycle efficiency of single shaft layout with one gas turbine. The power output of the two layouts also differs; the multi-shaft configuration can only reach 48.5% of the total capacity when one gas turbine is running, while the single shaft configuration can reach 50% of the total capacity when one gas turbine is running. The efficiency results are shown in the figure below [3].

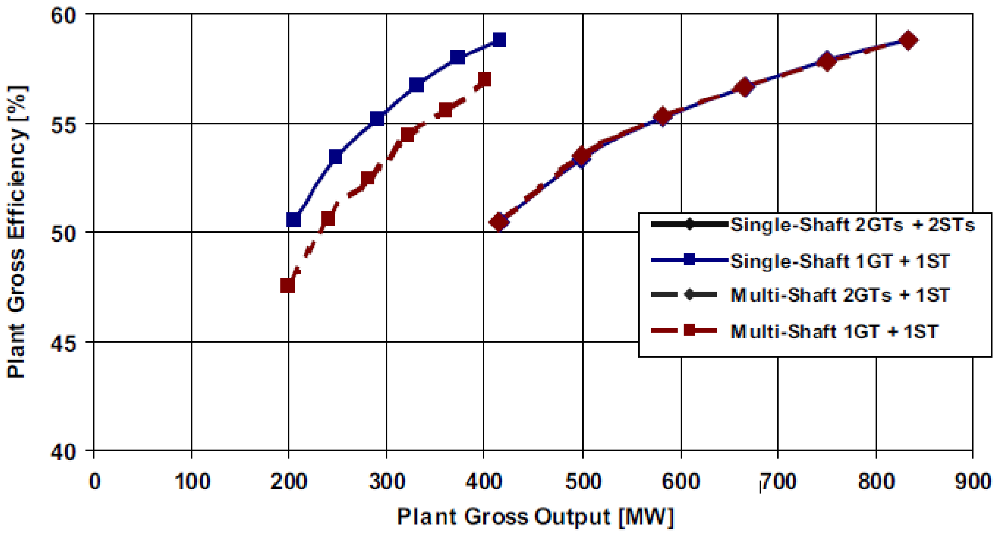


Figure 14 Shaft Analysis- Efficiencies for CCPP configurations [3]

Generator losses

Mechanical and electrical losses from the generator mainly source from the type of cooling used for the generator. In the case of a single shaft configuration, due to the high capacity of the generator, hydrogen is used as a coolant. Hydrogen has a low density and a relatively high specific heat; this is good for rotary type equipment because there are lesser tolerances in the design. Hydrogen cooling is reliable and efficient. The single shaft configuration has a single bigger hydrogen cooled generator. This has two advantages, firstly the hydrogen cooled generator has a higher efficiency than the air-cooled generators, and secondly, the single generator faces fewer losses while transmission due to having a single transformer. So, the single shaft generator has higher efficiency and higher power output [4]. Single shaft plants have an overall net efficiency advantage due to lesser auxiliary power consumption. The figure below shows the generator losses for the two configurations.

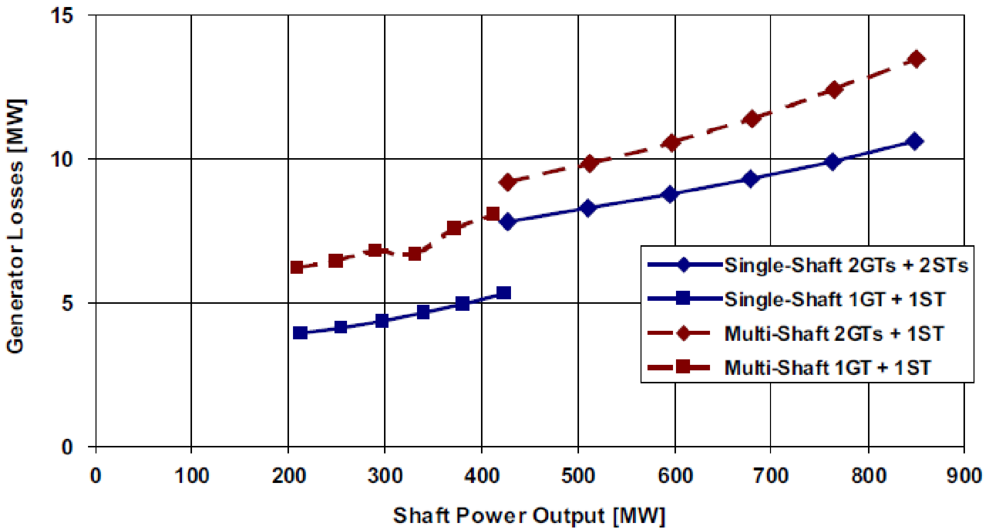


Figure 15 Shaft Analysis- Generator losses for CCPP configurations [3]

Some trends in the data are as follows:

- Generator losses in the case of two gas turbine multi-shaft configuration were almost 20% higher than single-shaft configuration.
- Losses when only one gas turbine is functional were 35% higher for multi-shaft configuration.
- Shaft power in the case of multi-shaft configuration was about 0.25% higher than single shaft configuration for two gas turbines.
- The shaft power in the case of one gas turbine running is 2.5% higher for a single shaft as compared to a multi-shaft configuration.
- The hydrogen cooled generator for the single shaft layout had a 0.2% higher efficiency than the air-cooled generator in the multi-shaft layout.

The overall trend for the power output for the single and multi-shaft layout is that the single shaft has 0.08% higher power output when compared to the multi-shaft layout; this is because of the higher efficiency of the generator and lower auxiliary losses for single-shaft configuration [3].

Auxiliary power

The tends between the single shaft and multi-shaft configurations auxiliary power are shown in the figure below.

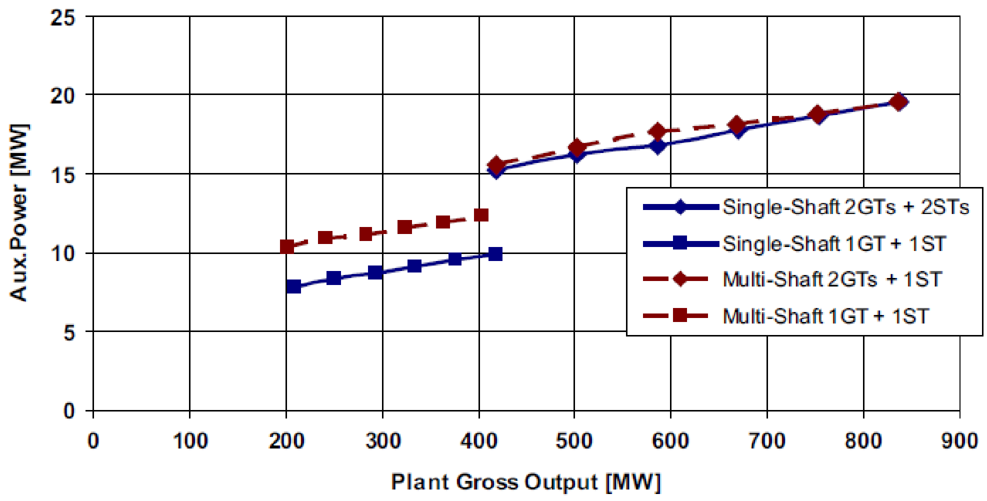


Figure 16 Shaft Analysis- Auxiliary power graphs for CCPP configurations [3]

Single and multi-shaft configurations have similar auxiliary power when two gas turbines are simultaneously working. Single shaft layout, however, has less power consumed by the auxiliaries compared to multi-shaft configurations. This is for a number of reasons explained below:

- Single shaft layout has a common lube oil system which means a single lube oil pump uses less power than two smaller pumps.
- Multi shaft layout has two generators with two sets of mechanical and electrical auxiliaries; this increases the auxiliary power consumption for multi-shaft configurations.
- Similarly, a single shaft layout has a single set of the cooling water system, which decreases the auxiliary power used by the cooling system.
- The single generator in a single shaft configuration also consumes about 0.5-1% less power for cooling.

- The other auxiliaries like the transmission systems and protection devices also increase the auxiliary power for the case of a multi-shaft layout.

The single shaft layout has an advantage, especially when only one gas turbine is working. Almost 20-30% lower power is used by the auxiliaries when compared to a multi-shaft configuration with one working gas turbine. This leads to an overall greater net efficiency for the single shaft configuration [3].

Reliability and availability

The percentage of time that depicts the availability of the plant to produce electricity is the availability factor [5]. It is affected by the outages both planned and forced. Planned outages refer to the scheduled maintenance procedures, and the forced outages are unexpected breakdowns. The availability factor is defined as:

$$AF = \frac{PH - FOH - MOH - POH}{PH}$$

Reliability in a percentage is the measure of time in between planned outages. Although reliability cannot be defined for all types of equipment, similar plants have similar reliability factors that can be compared [6]. The reliability factor is defined as:

$$RF = \frac{PH - FOH - MOH}{PH}$$

Where,

AF – availability factor
PH – period hours
MOH – unplanned maintenance outage hours
FOH – forced outage hours
POH – planned outage hours
RF – reliability factor

The following discussion is for the availability and reliability of the plant, including the main components like the gas turbine, steam turbine, compressor, etc. The forced outage and unplanned maintenance outage hours together make the unplanned outage hours. The unplanned outage hours and planned outage hours make the planned outage hours [5]. The unplanned maintenance hours, however, are very difficult to forecast. This is why the unplanned outage hours are not included in this study. Also, the maintenance hours for the balance of plant equipment are not included in the study. The North American Electric Reliability Council (NERC) says that the unplanned outage hours for the gas turbine is estimated to be 4.23%, while the forced outage hours are around 2.86%. The unplanned outage hours for the steam turbine are expected to be 1.3%, and the forced outage hours are around 0.5%. The hour percentages are calculated for a number of data values from the literature review, and then an average is taken. In the case of single shaft plants, stoppage of the gas turbine or the heat recovery, steam generator leads to a total shutdown. In the case of multi-shaft plants, the steam turbine can be operated at the same time that the gas turbine is in maintenance. The figure below shows the reliability and availability of both single and multi-shaft configurations.

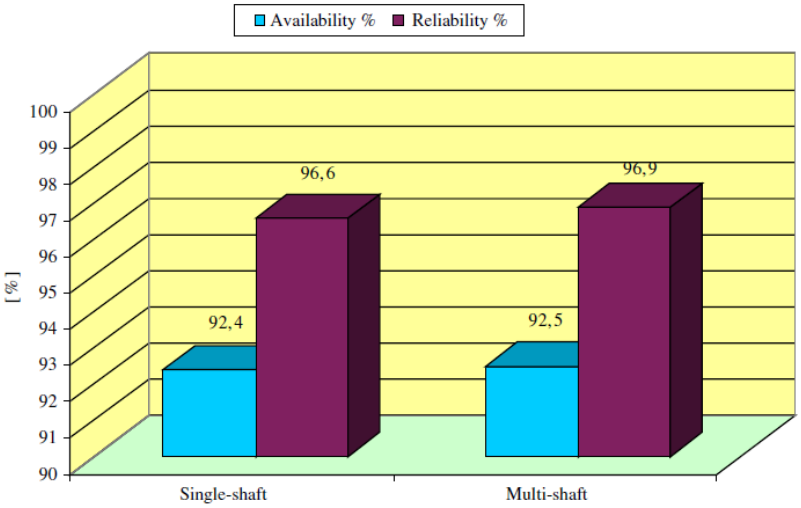


Figure 17 Shaft Analysis- Reliability and Availability Comparison [3]

The figure shows that the multi-shaft plants have a slightly higher availability factor compared to single shaft plants. The same trend is seen for the reliability factors of the two configurations. During the course of a full year, the multi-shaft plants produce more electricity than single shaft plants due to their greater availability. In practical scenarios, when the balance of plant maintenance hours is added, the availability and reliability factors become similar because single shaft plants have one set of the balance of plant equipment as compared to two sets of the balance of plant equipment in the case of multi-shaft plants [3].

Environmental impact

Pollutant emissions from gas-fueled power plants is a major concern these days, and limits are being imposed for safe limits of pollutant gases like nitrogen oxides and Sulphur oxides. The main fuel used by gas turbines is CH_4 which does not contain Sulphur, so the exhaust of the plant does not contain Sulphur oxides. Due to the presence of nitrogen in the air, nitrogen can combine with oxygen to make nitrogen oxides which need to be regulated. The amount of nitrogen oxides does not exceed the limits imposed, which is 50mg/Nm^3 when there is 15% oxygen in the exhaust gasses. NO_x emissions from a CCPP are taken care of by the manufacturer to be under the limit set. These days due to the use of low NO_x burners, the nitrogen oxides emissions are as low as 25ppmv. In the load conditions from 50-100%, the Inlet Guide Vanes (IGVs) are in premix mode and enable exhaust temperature to remain constant [7]. This is observed near the combustion reference temperature at the design point. Emissions are optimal in premix mode. When the exhaust gas temperature remains constant, the emissions in the form of nitrogen oxides are kept under control. Both single shaft and multi-shaft layouts have almost the same NO_x emissions. If the plant is capable of fast-start, the emission is substantially lower at startup [6]. The specific NO_x emissions change with the changing load conditions. In the case when one gas turbine is running, a multi-shaft layout has higher NO_x emissions than a single-shaft configuration.

Carbon dioxide emissions are very similar for both single shaft and multi-shaft configurations. The specific CO_2 emissions are related to the efficiency of the power plant. The CO_2 emissions for the single shaft and multi-shaft layout plants are presented below.

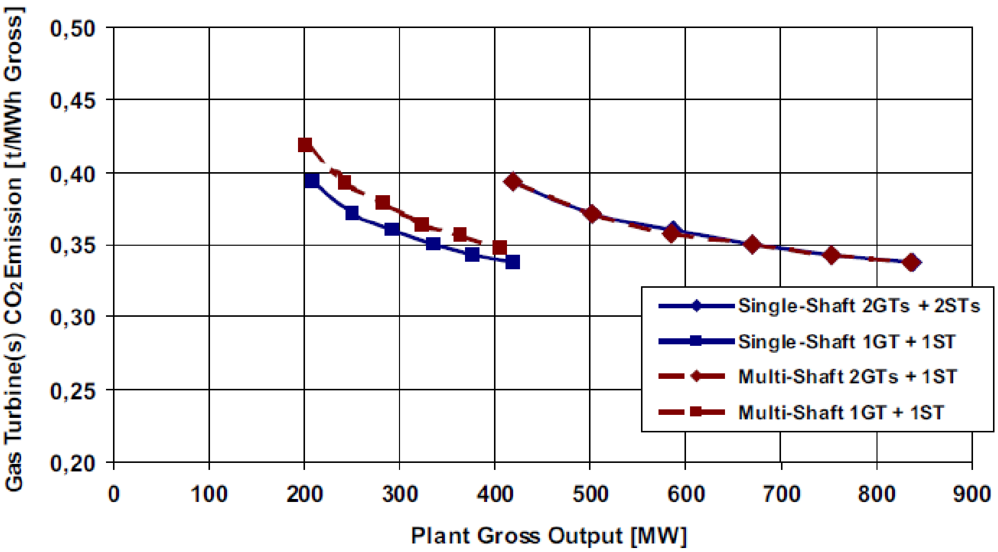


Figure 18 Shaft Analysis- Carbon dioxide emissions for CCPP configurations [3]

The carbon dioxide emissions for two gas turbines are almost the same for single and multi-shaft configurations. However, in the case of a single gas turbine, the multi-shaft layout produces almost 6% more carbon dioxide when compared to a single-shaft configuration [3].

CHAPTER 4: PROGRAM ANALYSIS

The final stage of the program is to create a graphical user interface that fulfils the following criteria:

- User intuitive design
- Has robust design.
- Support on many devices

The application has been divided into four windows.

Figure 19 Program Main Window

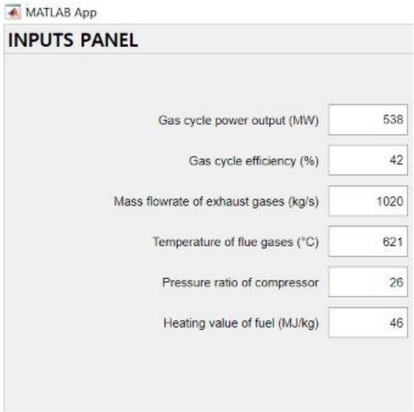
These windows provide an analysis of different stages, as mentioned in the methodology section. These sections and their features are mentioned below:

Gas Turbine Operations & Comparison:

This section of the application deals with all the calculations related to the gas turbine in simple cycle operation. The application screen is divided into three sections.

The Input Panel

The input panel shows the white boxes for entering the input values. These inputs are six in number. The units are mentioned for improving the user experience and removing any errors due to wrong units. The input panel also prompts the user if he enters any value beyond the design parameters.



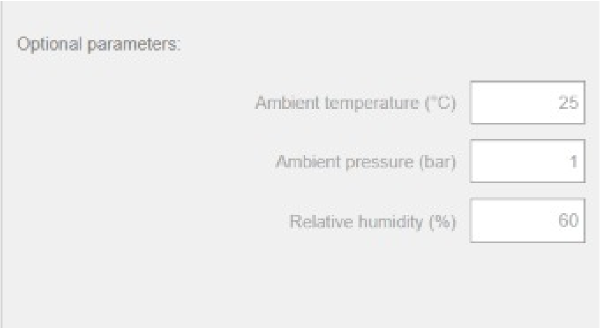
INPUTS PANEL

Gas cycle power output (MW) 538
Gas cycle efficiency (%) 42
Mass flowrate of exhaust gases (kg/s) 1020
Temperature of flue gases (°C) 621
Pressure ratio of compressor 26
Heating value of fuel (MJ/kg) 46

Figure 20 Program-Gas Turbine Input Panel

The Optional Parameters

The optional parameters contain the boxes for changing the environmental conditions. By default, we have stored the ISO standard conditions.



Optional parameters:

Ambient temperature (°C) 25
Ambient pressure (bar) 1
Relative humidity (%) 60

Figure 21 Program-Gas Turbine Optional Input Panel

Commands

After entering the values into the program, the “CALCULATE” command is pressed. The program calculates the data for the user.

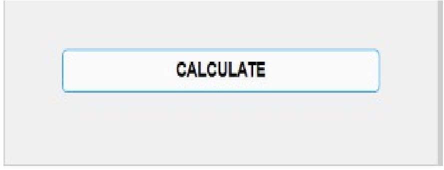
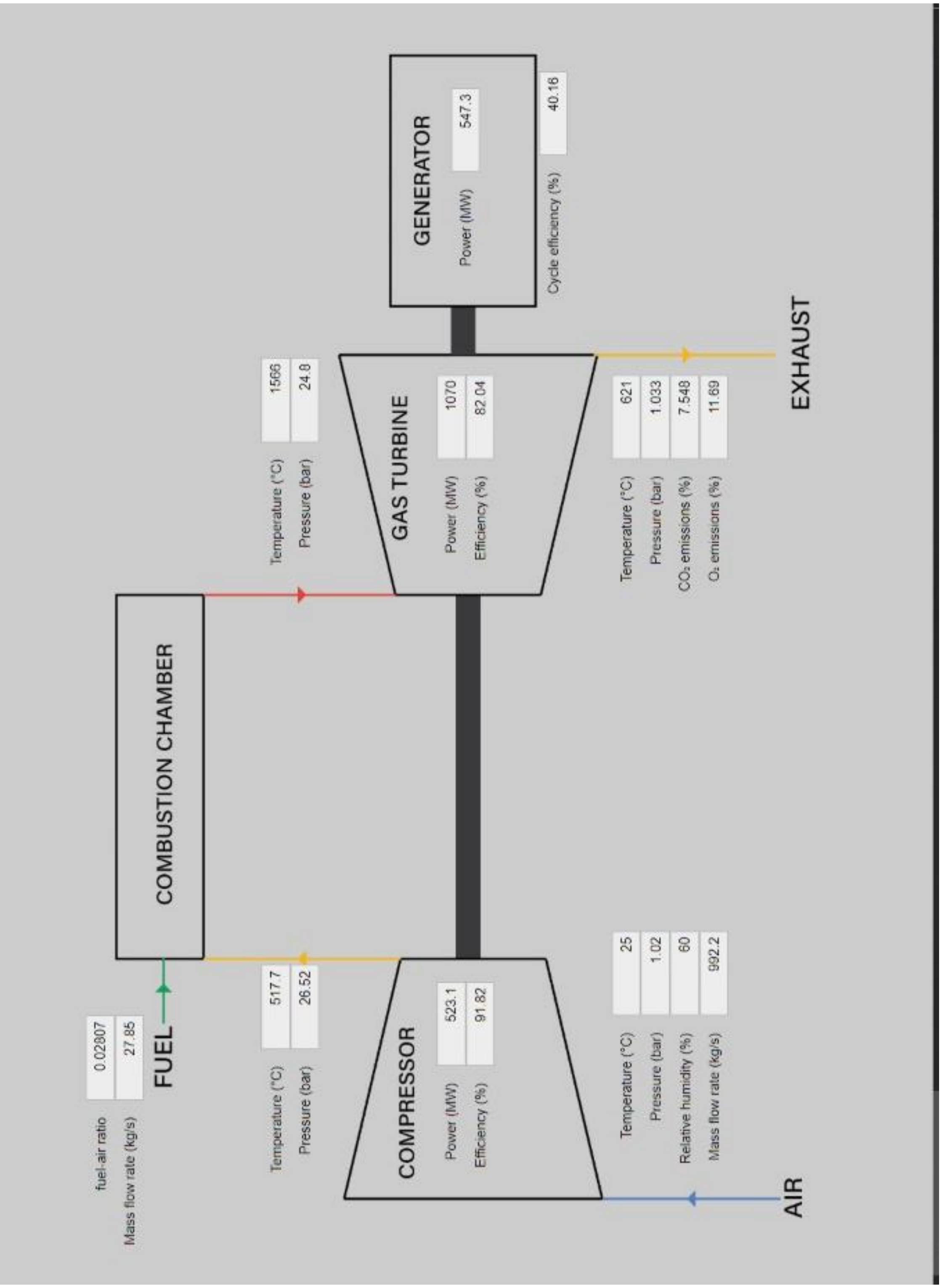


Figure 22 Program-Gas Turbine “CALCULATE” Command

The Output Panel

The output panel shows the output values on the screen. The results are shown on the graphic of the gas turbine for easy understanding. The units are also mentioned to avoid any discrepancy.



Temperature (°C) 25
Pressure (bar) 1.02
Relative humidity (%) 60
Mass flow rate (kg/s) 992.2

Power (MW) 523.1
Efficiency (%) 91.82

Temperature (°C) 517.7
Pressure (bar) 26.52

fuel-air ratio 0.02807
Mass flow rate (kg/s) 27.85

Temperature (°C) 1566
Pressure (bar) 24.8

Power (MW) 1070
Efficiency (%) 82.04

Temperature (°C) 621
Pressure (bar) 1.033
CO₂ emissions (%) 7.548
O₂ emissions (%) 11.69

Power (MW) 547.3

Cycle efficiency (%) 40.16

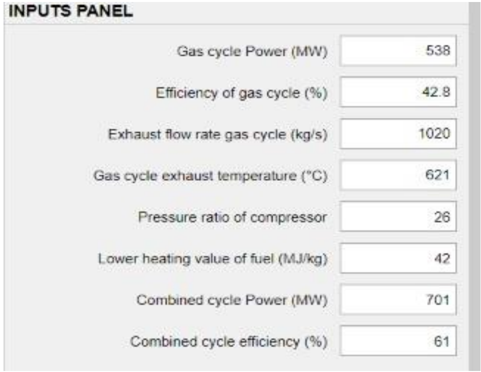
Figure 23 Program-Gas Turbine Output Panel

Combined Cycle Operation & Comparison:

This section of the application deals with all the calculations related to the gas turbine in combined cycle operation. The application screen is divided into three sections.

The Input Panel

The input panel shows the white boxes for entering the input values. These inputs are eight in number. The units are mentioned for improving the user experience and removing any errors due to wrong units. The input panel also prompts the user if he enters any value beyond the design parameters.



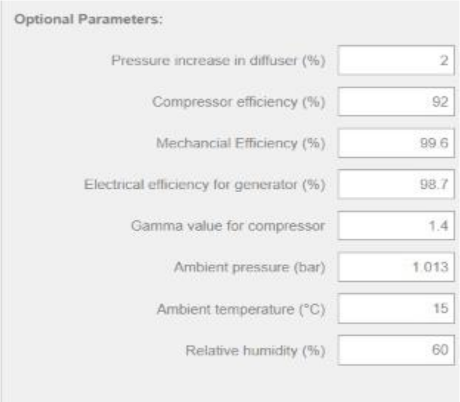
INPUTS PANEL

Gas cycle Power (MW)	538
Efficiency of gas cycle (%)	42.8
Exhaust flow rate gas cycle (kg/s)	1020
Gas cycle exhaust temperature (°C)	621
Pressure ratio of compressor	26
Lower heating value of fuel (MJ/kg)	42
Combined cycle Power (MW)	701
Combined cycle efficiency (%)	61

Figure 24 Program-CCPP Operations Input Panel

The Optional Parameters

The optional parameters contain the boxes for changing the environmental conditions. By default, we have stored the ISO standard conditions.



Optional Parameters:

Pressure increase in diffuser (%)	2
Compressor efficiency (%)	92
Mechancial Efficiency (%)	99.6
Electrical efficiency for generator (%)	98.7
Gamma value for compressor	1.4
Ambient pressure (bar)	1.013
Ambient temperature (°C)	15
Relative humidity (%)	60

Figure 25 Program-CCPP Operations Optional Input Panel

Commands

After entering the values into the program, the "CALCULATE" command is pressed. The program calculates the data for the user.

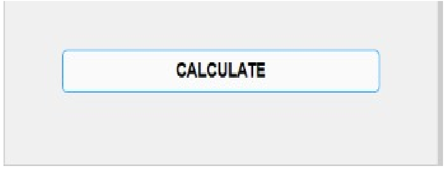
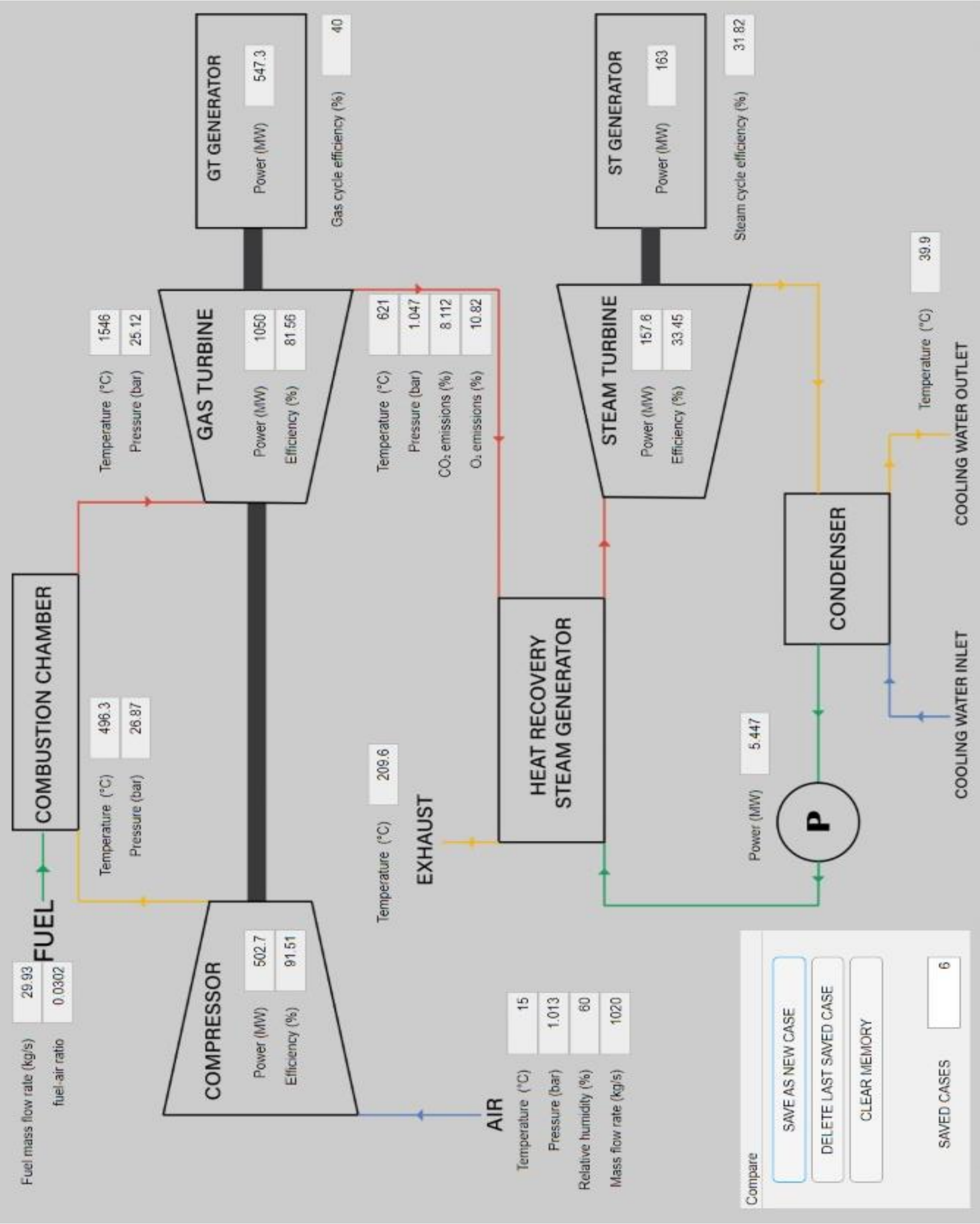


Figure 26 Program-CCPP Operations CALCULATE Command

The Output Panel

The output panel shows the output values on the screen. The results are shown on the graphic of the gas turbine for easy understanding. The units are also mentioned to avoid any discrepancy.



Fuel mass flow rate (kg/s) 29.93
fuel-air ratio 0.0302

Temperature (°C) 496.3
Pressure (bar) 26.87

Temperature (°C) 1546
Pressure (bar) 25.12

COMPRESSOR
Power (MW) 502.7
Efficiency (%) 91.51

GAS TURBINE
Power (MW) 1050
Efficiency (%) 81.56

GT GENERATOR
Power (MW) 547.3

Gas cycle efficiency (%) 40

AIR
Temperature (°C) 15
Pressure (bar) 1.013
Relative humidity (%) 60
Mass flow rate (kg/s) 1020

Temperature (°C) 621
Pressure (bar) 1.047
CO_2 emissions (%) 8.112
O_2 emissions (%) 10.82

EXHAUST
Temperature (°C) 209.6

STEAM TURBINE
Power (MW) 157.8
Efficiency (%) 33.45

ST GENERATOR
Power (MW) 163

Steam cycle efficiency (%) 31.82

Power (MW) 5.447

COOLING WATER OUTLET
Temperature (°C) 39.9

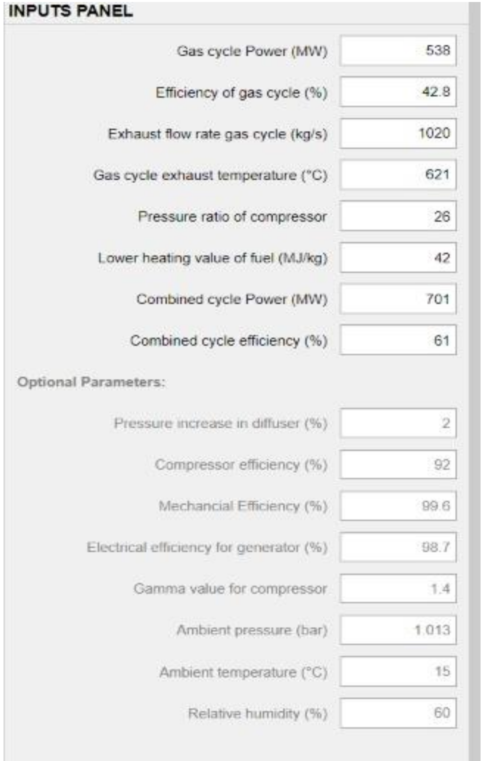
SAVED CASES 6

Figure 27 Program-CCPP Operations Output Panel

Comparison Cases:

In order to give the user the option to compare different models of gas turbines and gas turbines working at a different set of inputs, the "Case" function has been added to the program.

Enter the values in the CCPP operations input and optional input parameter.



INPUTS PANEL

Gas cycle Power (MW)	538
Efficiency of gas cycle (%)	42.8
Exhaust flow rate gas cycle (kg/s)	1020
Gas cycle exhaust temperature (°C)	621
Pressure ratio of compressor	26
Lower heating value of fuel (MJ/kg)	42
Combined cycle Power (MW)	701
Combined cycle efficiency (%)	61

Optional Parameters:

Pressure increase in diffuser (%)	2
Compressor efficiency (%)	92
Mechancial Efficiency (%)	99.6
Electrical efficiency for generator (%)	98.7
Gamma value for compressor	1.4
Ambient pressure (bar)	1.013
Ambient temperature (°C)	15
Relative humidity (%)	60

Figure 28 Program-CCPP Operations Input Panel

Select the "Calculate" to see the results on the output panel.

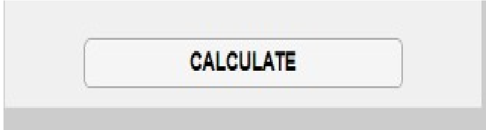


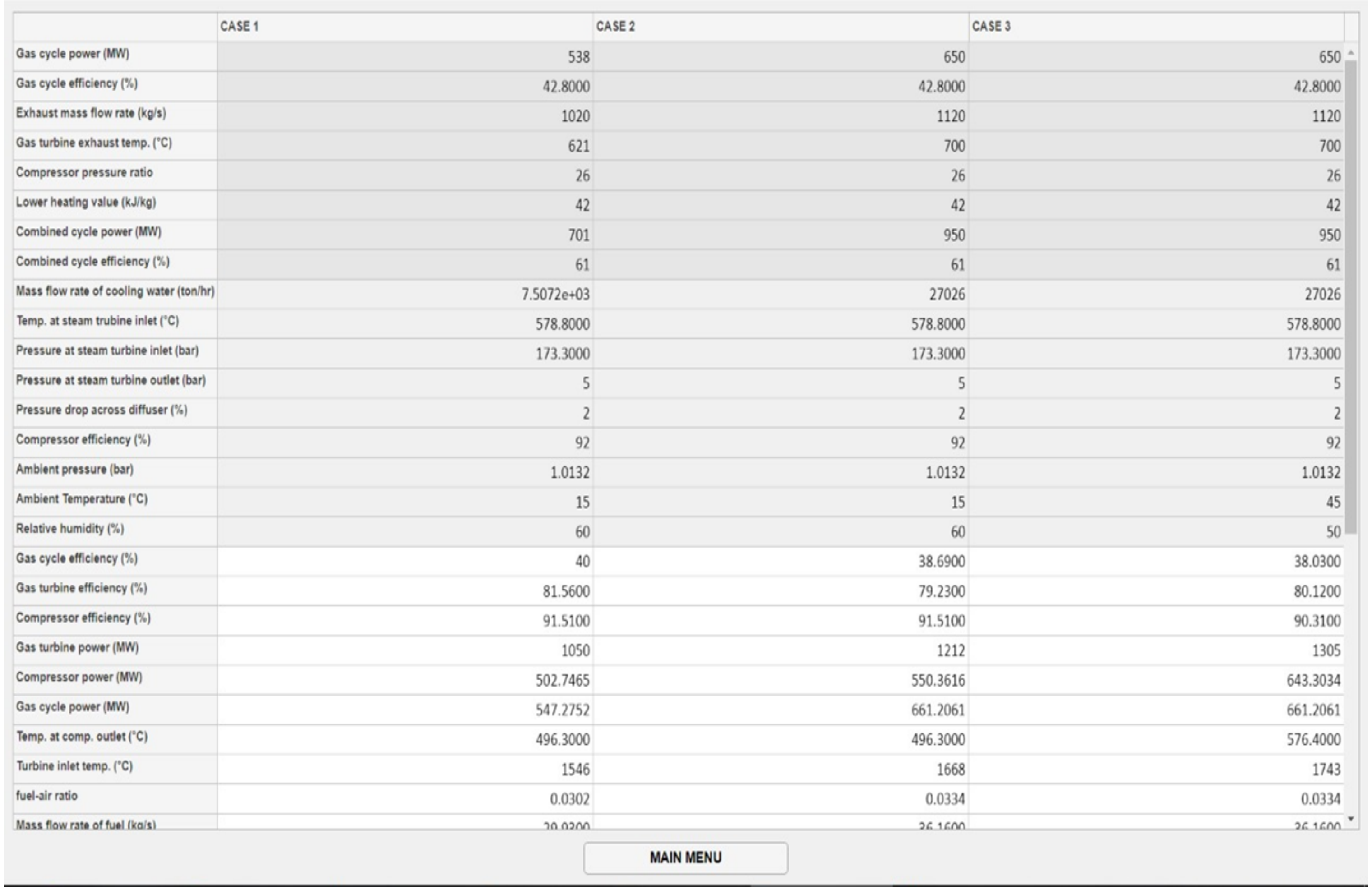
Figure 29 Program-CCPP Operations “Calculate” Command

Now, click on the “Save as New Case” in the compare panel in the lower-left corner, and the case gets stored in the table.

Figure 30 Program-CCPP Operations “Compare” Cases

To delete the immediately previous case, “Delete Last Saved Case”, and to delete all the previously saved cases, press “Clear Memory.”

The case window is shown as below:



	CASE 1	CASE 2	CASE 3
Gas cycle power (MW)	538	650	650
Gas cycle efficiency (%)	42.8000	42.8000	42.8000
Exhaust mass flow rate (kg/s)	1020	1120	1120
Gas turbine exhaust temp. (°C)	621	700	700
Compressor pressure ratio	26	26	26
Lower heating value (kJ/kg)	42	42	42
Combined cycle power (MW)	701	950	950
Combined cycle efficiency (%)	61	61	61
Mass flow rate of cooling water (ton/hr)	7.5072e+03	27026	27026
Temp. at steam trubine inlet (°C)	578.8000	578.8000	578.8000
Pressure at steam turbine inlet (bar)	173.3000	173.3000	173.3000
Pressure at steam turbine outlet (bar)	5	5	5
Pressure drop across diffuser (%)	2	2	2
Compressor efficiency (%)	92	92	92
Ambient pressure (bar)	1.0132	1.0132	1.0132
Ambient Temperature (°C)	15	15	45
Relative humidity (%)	60	60	50
Gas cycle efficiency (%)	40	38.6900	38.0300
Gas turbine efficiency (%)	81.5600	79.2300	80.1200
Compressor efficiency (%)	91.5100	91.5100	90.3100
Gas turbine power (MW)	1050	1212	1305
Compressor power (MW)	502.7465	550.3616	643.3034
Gas cycle power (MW)	547.2752	661.2061	661.2061
Temp. at comp. outlet (°C)	496.3000	496.3000	576.4000
Turbine inlet temp. (°C)	1546	1668	1743
fuel-air ratio	0.0302	0.0334	0.0334
Mass flow rate of fuel (kg/s)	[illegible]	36.1600	36.1600

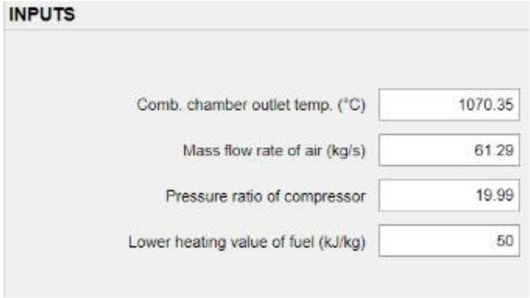
Figure 31 Program-CCPP Operations Cases

Turbofan Analysis:

The turbofan analysis has been done by taking parameters that are easily changeable by the user.

The Input Panel:

The input panel takes the input from the users. These are shown in the top left of the window.



INPUTS

Comb. chamber outlet temp. (°C) 1070.35

Mass flow rate of air (kg/s) 61.29

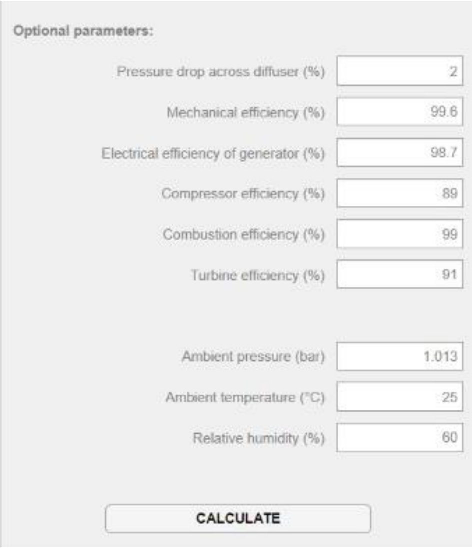
Pressure ratio of compressor 19.99

Lower heating value of fuel (kJ/kg) 50

Figure 32 Program-Turbofan Operations Input Panel

The Optional Parameters:

The Optional panel shows the parameters which have been set values by default. However, if the user wants them to change, he can enter his values. This is shown below inputs.



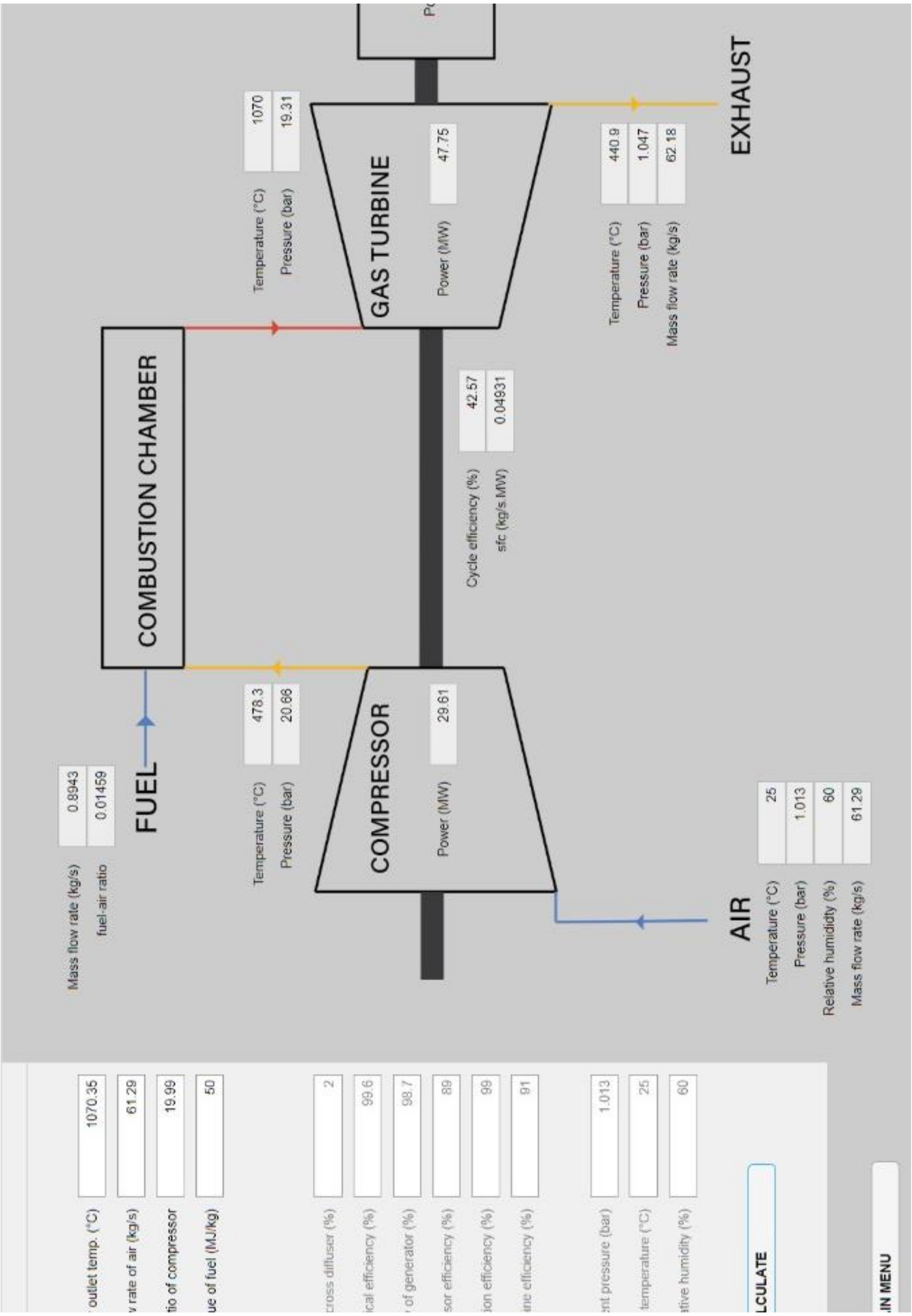
Optional parameters:

Pressure drop across diffuser (%)	2
Mechanical efficiency (%)	99.6
Electrical efficiency of generator (%)	98.7
Compressor efficiency (%)	89
Combustion efficiency (%)	99
Turbine efficiency (%)	91
Ambient pressure (bar)	1.013
Ambient temperature (°C)	25
Relative humidity (%)	60

33 Program-Turbofan Operations Optional Input Panel

The Output Panel:

The output panel shows the calculated parameters. These are shown on the graphical interface for improving the user experience.



outlet temp. (°C) 1070.35
v rate of air (kg/s) 61.29
tio of compressor 19.99
ue of fuel (MJ/kg) 50

cross diffuser (%) 2
ical efficiency (%) 99.6
of generator (%) 98.7
sor efficiency (%) 89
ion efficiency (%) 99
ine efficiency (%) 91

nt pressure (bar) 1.013
temperature (°C) 25
ative humidity (%) 60

Mass flow rate (kg/s) 0.8943
fuel-air ratio 0.01459

Temperature (°C) 478.3
Pressure (bar) 20.66
Power (MW) 29.61

Temperature (°C) 1070
Pressure (bar) 19.31
Power (MW) 47.75

Cycle efficiency (%) 42.57
sfc (kg/s.MW) 0.04931

Temperature (°C) 440.9
Pressure (bar) 1.047
Mass flow rate (kg/s) 62.18

Temperature (°C) 25
Pressure (bar) 1.013
Relative humidity (%) 60
Mass flow rate (kg/s) 61.29

34 Program-Turbofan Operations Output Panel

CHAPTER 5: CONCLUSION AND RECOMMENDATION

The project has been successful in achieving the objectives of delivering a program for the performance analysis of combined cycle power plant. The program takes in minimum inputs from the user and provides detailed analysis of CCPP including comparison of different input and output parameters using a table. Graphs of important parameters have been constructed in the software to assist user in analysis. The coding of CCPP program has been done in MATLAB environment due to its user-friendly interface and built-in app designer. The software is also capable of analyzing steam turbine as per the user requirement. The feasibility of high bypass turbofan engine for power production has been analyzed by calculating the shaft power. Using minimum modifications in the existing design of turbofan, we were able to obtain shaft power of 17 MW at design point conditions. Furthermore, the relationships between turbine inlet temperature, specific fuel consumption, power output, and thermal efficiency, have been depicted through graphs. The results are promising, with less than 5% error. The detailed analysis of different shaft configurations of CCPP has shown that a comprehensive list of the factors affects the decision between single and multi-shaft configurations. Single shaft layout for combined cycle power plant is preferred for higher net efficiency, low auxiliary power consumption, lower installed cost and lower emissions. On the contrary, multi shaft configuration is preferred for layout flexibility, low maintenance cost, higher availability factor, and shorter hot start-up times. The user must evaluate the advantages of both layouts that favors his requirement.

The developed software is robust and provides promising results, however, following are some of the areas which can be further developed.

MATLAB App Designer

MATLAB app designer has many useful features for the development of GUI, but it has deficiencies of its own. For example, complex GUI consisting of numerous components takes a lot of time to load. Furthermore, it requires MATLAB to run this program. A standalone app can be developed in future using more mature app development language with better optimization.

Fuel Options

Currently, the program only executes analysis of flue gas composition for natural gas (methane). This can be expanded to other fuels like Naphtha, Hydrogen and LNG in future.

Analysis of Gas Turbine Components

Design analysis of different gas turbine components like compressor, combustion chambers, and turbine can be added. This includes analysis of compressor and turbine blade angles, velocity triangle and pressure-velocity compounding. Similarly, design analysis of HRSG and condensers may help the user achieve better results.

Additional Configurations of Turbofan

Turbofan with high bypass ratio has been studied and analyzed. However, the analysis can be expanded to turbofans with low bypass ratio, and turbojets.

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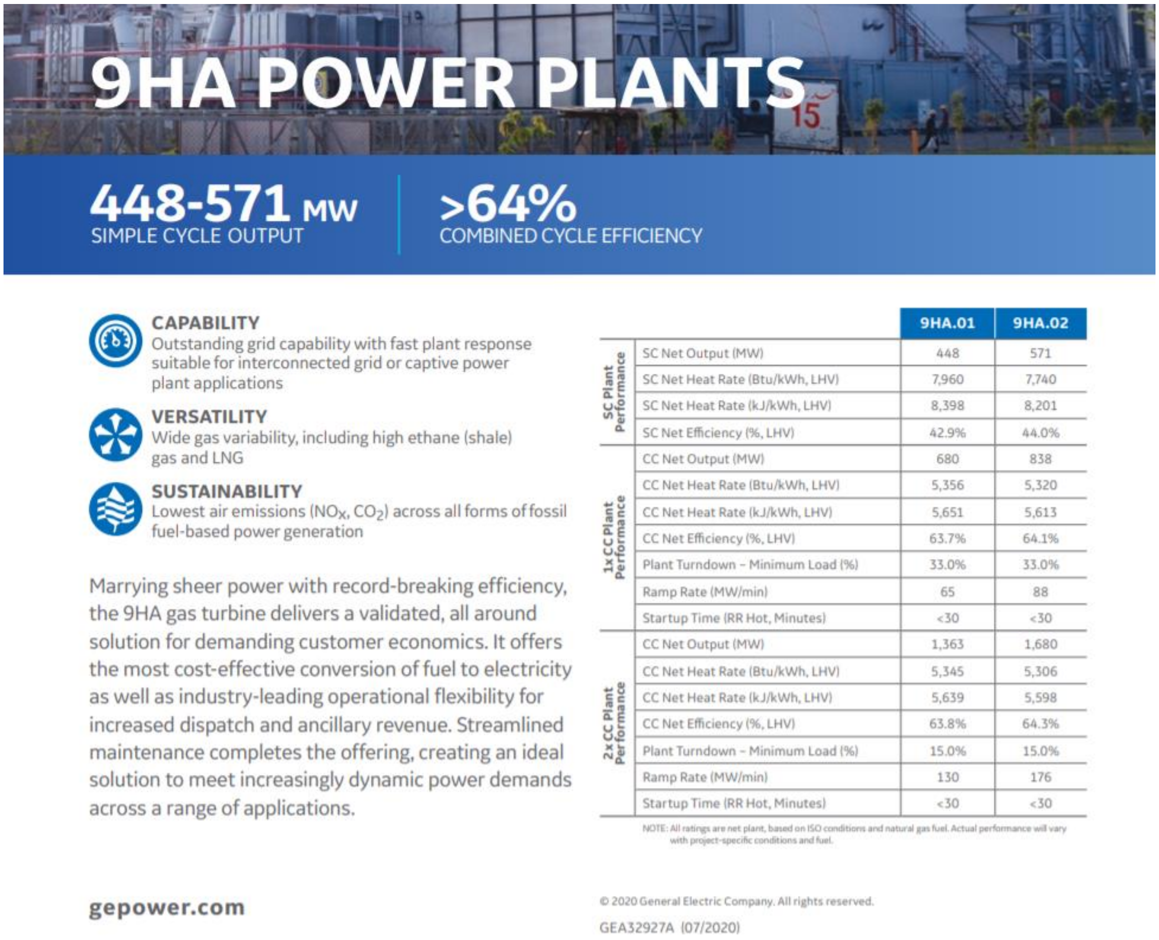
APPENDIX I: GAS TURBINE FOR ANALYSIS



9HA POWER PLANTS

448-571 MW
SIMPLE CYCLE OUTPUT

>64%
COMBINED CYCLE EFFICIENCY

CAPABILITY
Outstanding grid capability with fast plant response suitable for interconnected grid or captive power plant applications

VERSATILITY
Wide gas variability, including high ethane (shale) gas and LNG

SUSTAINABILITY
Lowest air emissions (NO_X, CO_2) across all forms of fossil fuel-based power generation

Marrying sheer power with record-breaking efficiency, the 9HA gas turbine delivers a validated, all around solution for demanding customer economics. It offers the most cost-effective conversion of fuel to electricity as well as industry-leading operational flexibility for increased dispatch and ancillary revenue. Streamlined maintenance completes the offering, creating an ideal solution to meet increasingly dynamic power demands across a range of applications.

		9HA.01	9HA.02
SC Plant Performance	SC Net Output (MW)	448	571
	SC Net Heat Rate (Btu/kWh, LHV)	7,960	7,740
	SC Net Heat Rate (kJ/kWh, LHV)	8,398	8,201
	SC Net Efficiency (%, LHV)	42.9%	44.0%
1x CC Plant Performance	CC Net Output (MW)	680	838
	CC Net Heat Rate (Btu/kWh, LHV)	5,356	5,320
	CC Net Heat Rate (kJ/kWh, LHV)	5,651	5,613
	CC Net Efficiency (%, LHV)	63.7%	64.1%
	Plant Turndown – Minimum Load (%)	33.0%	33.0%
	Ramp Rate (MW/min)	65	88
	Startup Time (RR Hot, Minutes)	<30	<30
2x CC Plant Performance	CC Net Output (MW)	1,363	1,680
	CC Net Heat Rate (Btu/kWh, LHV)	5,345	5,306
	CC Net Heat Rate (kJ/kWh, LHV)	5,639	5,598
	CC Net Efficiency (%, LHV)	63.8%	64.3%
	Plant Turndown – Minimum Load (%)	15.0%	15.0%
	Ramp Rate (MW/min)	130	176
	Startup Time (RR Hot, Minutes)	<30	<30

NOTE: All ratings are net plant, based on ISO conditions and natural gas fuel. Actual performance will vary with project-specific conditions and fuel.

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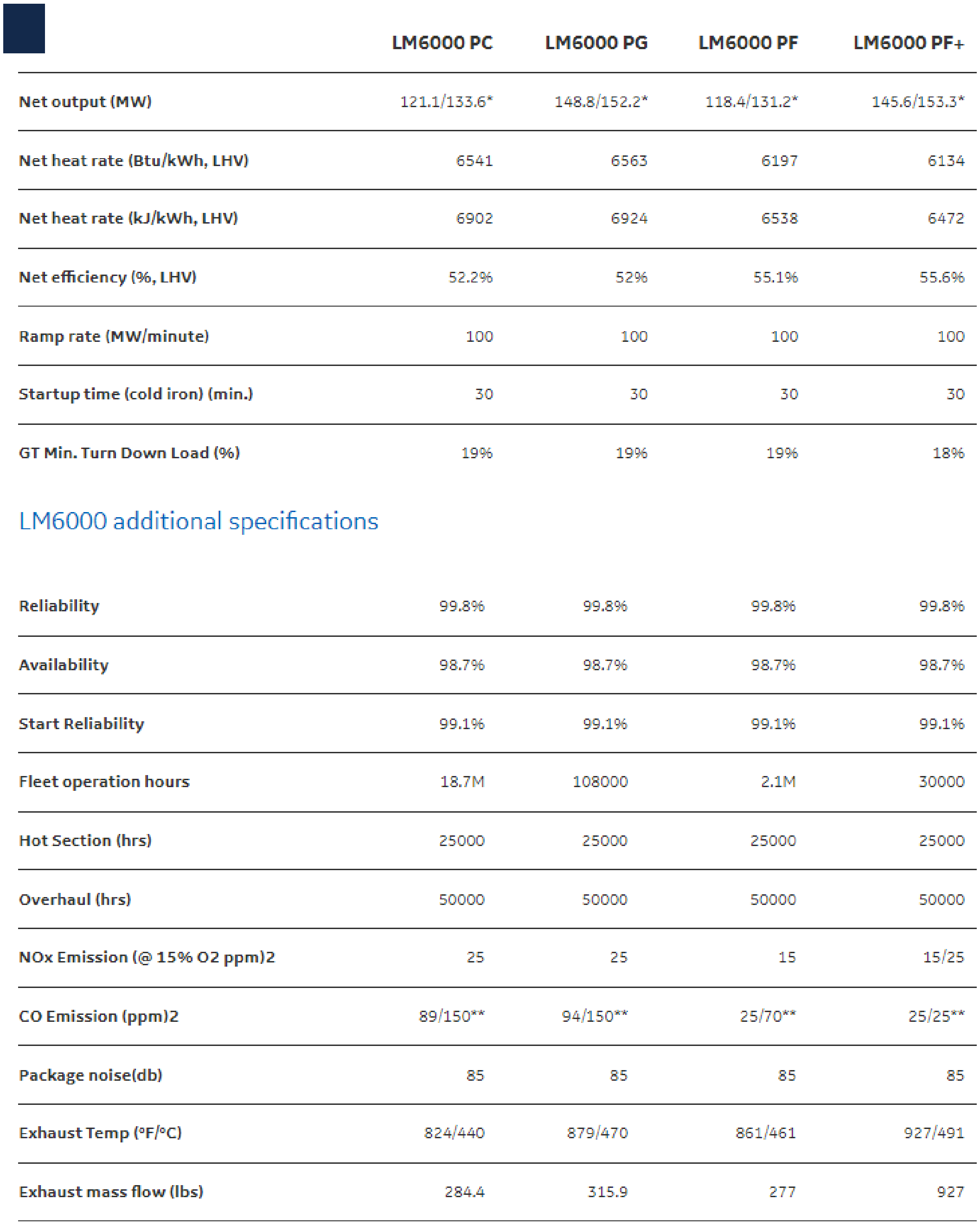
GEA32927A (07/2020)

APPENDIX II: TURBOFAN



	LM6000 PC	LM6000 PG	LM6000 PF	LM6000 PF+
Net output (MW)	121.1/133.6*	148.8/152.2*	118.4/131.2*	145.6/153.3*
Net heat rate (Btu/kWh, LHV)	6541	6563	6197	6134
Net heat rate (kJ/kWh, LHV)	6902	6924	6538	6472
Net efficiency (%, LHV)	52.2%	52%	55.1%	55.6%
Ramp rate (MW/minute)	100	100	100	100
Startup time (cold iron) (min.)	30	30	30	30
GT Min. Turn Down Load (%)	19%	19%	19%	18%

LM6000 additional specifications

Reliability	99.8%	99.8%	99.8%	99.8%
Availability	98.7%	98.7%	98.7%	98.7%
Start Reliability	99.1%	99.1%	99.1%	99.1%
Fleet operation hours	18.7M	108000	2.1M	30000
Hot Section (hrs)	25000	25000	25000	25000
Overhaul (hrs)	50000	50000	50000	50000
NOx Emission (@ 15% O2 ppm)2	25	25	15	15/25
CO Emission (ppm)2	89/150**	94/150**	25/70**	25/25**
Package noise(db)	85	85	85	85
Exhaust Temp (°F/°C)	824/440	879/470	861/461	927/491
Exhaust mass flow (lbs)	284.4	315.9	277	927