WASTE HEAT RECOVERY FROM AN IDEAL $H_2 - O_2$ FUEL CELL USING A REHEAT AND REGENERATIVE BRAYSSON CYCLE – A THERMODYNAMIC ANALYSIS

A PROJECT REPORT SUBMITTED IN PARTIAL FULFILLMENT OF THE REQUIREMENT FOR THE AWARD OF THE DEGREE OF BACHELOR OF TECHNOLOGY IN MECHANICAL ENGINEERING

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VISAKHAPATNAM (DIST.), ANDHRA PRADESH, INDIA.

2019

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This is to certify that the project report entitled "**Waste heat recovery from an ideal H_2-O_2 fuel cell using a Reheat and Regenerative Braysson cycle – a thermodynamic analysis**" has been carried out by Manyala Jayatej(315126520130),Mosuri Chandra Chaitanya (315126520140), Kadupu Gautham (315126520076), P.Kamal Kumar (315126520078), Kantumutchu Rajesh(315126520085), Madabathula Avinash (315126520119)under the esteemed guidance of, **Mr.R.Chandramouli, M.Tech , Associate Professor,** in partial fulfilment of the requirement for the award of the Degree of Bachelor of Technology in mechanical engineering by Anil Neerukonda Institute Of Technology & Sciences (AUTONOMOUS), Visakhapatnam.

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ACKNOWLEDGEMENT

We express immensely our deep sense of gratitude to **Mr.R.Chandramouli, M.Tech , Associate Professor**, **M.S.S Srinivas Rao, Sr. Assistant Professor,** Department of Mechanical Engineering, and **Dr.S.Siva Kumar, Assistant Professor,** Department of Chemistry, Anil Neerukonda Institute of Technology & Sciences, Sangivalasa, Bheemunipatnam (mandal), Visakhapatnam District for their valuable guidance and encouragement at every stage of the work made it a successful fulfilment.

We were very thankful to our **Professor T.SUBRAHMANYAM**, Principal, ANITS and **Professor B. NAGA RAJU**, Head of the Department, Mechanical Department, Anil Neerukonda Institute of Technology & Sciences for their valuable suggestions and also for encouraging and allowing us to attend a fuel cell workshop at MVGR College of Engineering, Vizianagaram.

Last but not least, we would like to convey our thanks to all who have contributed either directly or indirectly for the completion of work.

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ABSTRACT

Direct energy conversion devices are gaining prominence by virtue of their high efficiency. This is in fact due to the conversion of chemical energy directly in to electrical energy without passing through the thermal energy phase. Fuel cells, Photo-voltaic cells are few examples of Direct energy conversion devices, which have received recognition in terms of research and also practical usage. Fuel cells work on the principle of chemical reaction between the fuels like Hydrogen, Methane, propane, ammonia etc and an oxidiser. Fuel cells generally possess high first and second law efficiencies and are finding applications in remote areas like submarines, spacecrafts etc.

The exothermic reaction in the fuel cell produces an enormous quantity of heat which is dissipated to the surroundings. The working temperature of fuel cell is very high and are in the order of 500 – 1000^{o}C. The exergy associated with the waste heat is colossal and is simply lost to the atmosphere. Generally, waste heat liberated from the fuel cells was used to generate power by running the Brayton (or) Rankine cycle. But in 1997, T H Frost first proposed an Ideal Braysson cycle whose efficiency is much higher than the Brayton cycle. In this project, a combined system of Hydrogen (fuel)-Oxygen (oxidiser) fuel cell & reheat and regenerative Braysson cycle in order to recover the waste heat is proposed. Energy and exergy based evaluation of this combined system is carried out in this work.

In the analysis, H_2-O_2 fuel cell is assumed to operate at 800^{o} C and the turbine inlet temperature (TIT) range of Braysson cycle is assumed as 600 to 750^{o}C. It has been observed that there exist different optimum pressure ratio values for maximum power output and maximum efficiencies. Both the energy and exergy efficiencies of the combined cycle increases with the increase in turbine inlet temperature.

It is further observed that energy and exergy efficiencies of the fuel cell are independent of turbine inlet temperature and pressure ratio. The power obtained from the fuel cell is 12 to 25 times higher than the power obtained from the waste heat through Braysson depending on the pressure ratio and TIT. The combined system depicts energy efficiency in the range of 81.8% to 82.9% and that of the fuel cell is about 76%. Exergy destruction rates for the individual equipments and the total system are also obtained as a function of pressure ratio and TIT. The exergy destruction rates are found to be maximum in the heat transfer equipment and minimum in the fuel cell.

The waste heat from the H_2-O_2 fuel cell is found to be 3006.3 KW at turbine inlet temperature of 750^{o}C and at an optimum pressure ratio of 1.4. The power output of reheat and regenerative Braysson cycle obtained by recovering this waste heat is found to be 861.8 KW.

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ceh = chemical exergy of H_2 (KJ/Kg)

ceo = chemical exergy of O_2 (KJ/Kg)

c_p=specific heat of helium = 5.19 (KJ/Kg-K)

e_x = exergy at point x (KJ/Kg)

$\dot{m}_f$= mass flow rate of water in fuel cell (Kg/s)

$\dot{m}_{f_h}$ = mass flow rate of hydrogen in Fuel cell (Kg/s)

$\dot{m}_{f_o}$ = mass flow rate of oxygen in Fuel cell (Kg/s)

$\dot{m}_{f_{he}}$ = mass flow rate of helium in the reheat and regenerative Braysson cycle (Kg/s)

p_b= Power output of Braysson cycle (KW)

p_f= Power output of Fuel cell (KW)

p_i = pressure at point i (Bar)

q_h = TΔS = (ΔH – ΔG) (KJ/Kg)

r_p= pressure ratio of main compressor

$r_{p_1} = \left(\frac{p_4}{p_5}\right) = \left(\frac{p_6}{p_7}\right) = \sqrt{\frac{p_4}{p_7}}$

$r_{p_0} = \left(\frac{p_1}{p_9}\right)$

$q_{i.p}$= heat input to reheat and regenerative Braysson cycle (KW)

T_1=inlet temperature of main compressor (K)

T_2= inlet temperature of regenerator (K)

T_3= outlet temperature of regenerator (K)

T_4= turbine inlet temperature (K)

T_5= high pressure turbine exit temperature (K)

T_6= low pressure turbine inlet temperature (K)

T_7= low pressure turbine outlet temperature (K)

T_8= regenerator outlet temperature (K)

T_9=cooler outlet temperature (K)

T_a=exit temperature after 1st stage of multi stage compressor (K)

T_2', T_5', T_7', T_a' are ideal temperatures (K)

$v_i =$ volume at point i (m^3/Kg)

$w_{o.p}$= work output of reheat and regenerative Braysson cycle (KW)

$w_{i.p}$= work input to reheat and regenerative Braysson cycle (KW)

w_{net_o} = overall net work of combined cycle = $p_b + p_{f_1} + p_{f_2}$ (KW)

η_c is efficiency of main compressor

η_t is efficiency of turbine

η_r is efficiency of regenerator

η_{1c} is efficiency of one-stage of multi stage compressor

$\eta_{b.c}$= reheat and regenerative Braysson cycle efficiency

η_o= overall efficiency of combined cycle (fuel cell + reheat and regenerative Braysson cycle)

$\eta_{f.c}$= fuel cell efficiency

γ= 1.667 for Helium (Adiabatic constant)

η_{exergy} = exergy efficiency of combined cycle

ΔH = total enthalpy change in fuel cell (KJ/Kg)

ΔG = Gibbs free energy change i.e. electric part of fuel cell output (KJ/Kg)

$T\Delta S$ = heat dissipated from fuel cell i.e. thermal part of fuel cell output (KJ/Kg)

TFC = total fuel consumption (Kg/hr)

SFC = specific fuel consumption (Kg/ KW-hr)

CHAPTER 1

1. INTRODUCTION

Thermodynamics plays a key role in the study of thermodynamic systems and devices that include transfer and transformation of energy. The word “thermodynamics” comes from Greek language “thermo” (heat) and “dynamics” (force) which basically means converting heat into work. All the activities in the nature involve interaction between energy and matter.

The science of energy (thermodynamics) presents a clear picture of interactions between energy and matter. All along our technological history, the development of sciences has enhanced our ability to harness energy and use it for society's needs. The increased awareness that the world's energy resources are limited has caused to re-examine the energy policies by countries and take drastic measures waste and new techniques were developed for better utilization of the existing limited resources and that concept is known as Exergy.

The second law or exergy analysis offers a new insight into the true nature of losses in a thermal system which is generally overlooked by the first law analysis, also called energy analysis. The actual amount of energy that a source contains is estimated from energy analysis, which is generally of little value to build a power plant. The amount of energy that we can extract as a useful work from the source gives the work potential of that source which is of greater value known as Exergy. The concept of exergy and its importance is clearly understood from the study of the topics of energy & entropy. Energy, entropy and exergy concepts come from thermodynamics and are applicable to all fields of science and engineering.

1.1 Energy

The concept of energy was first introduced in mechanics by Newton when he hypothesized about kinetic and potential energies. However, the emergence of energy as a unifying concept in physics was not adopted until the middle of the 19th century and was considered one of the major scientific achievements in that century. Energy is a scalar quantity that cannot be observed directly but can be recorded and evaluated by indirect measurements. Nature allows the conversation of work completely into heat, but heat is taxed when converted into work. Most of our daily activities and engineering applications involve energy transfer and energy change. The human body is a familiar example of biological system in which the chemical energy of the food or body fat is transformed into other forms of energy such as heat transfer and work transfer. Gas turbine engines commonly used for aircraft, propulsion, convert the chemical energy of the fuel into thermal energy that is used to run a gas turbine. Low temperature boiling fluids such as ammonia and refrigerant-134a absorb in the form of heat transfer, as they vaporize in the evaporator causing a cooling effect in the region being cooled. Therefore, a careful study of this topic is required to improve the design and performance of energy transfer systems.

1.2 Laws of Thermodynamics and their Significance

The science of thermodynamics is built primarily on three fundamental natural laws.

- The first law of thermodynamics state that "energy can change from one form to another but the total amount of energy remains constant" - law of conservation of energy.
- The second law of thermodynamics asserts that "energy has quality as well as quantity, and actual process occur in the direction of decreasing quality of energy"-law of degradation of energy.
- The third law states that "it is impossible by any procedure, no matter how idealised, to reduce any system to the absolute zero of temperature in a finite number of operations".

1.2.1. The first law of thermodynamics (FLT)

The First law of thermodynamics states that energy can be neither created nor destroyed; it just changes form. It defines internal energy as a state function and provides a formal statement of the conservation of energy. It provides no information about the ability of any thermodynamics process to convert heat into mechanical work with full efficiency. The total energy E represents the sum of all forms of energy a system possesses, and the change in the energy content of a system during a process is expressed as ΔE system. In the absence of electrical, magnetic, surface etc., effects the total energy in that case can be expressed as the sum of the internal, kinetic, and potential energies as

$$\mathrm{E} = \mathrm{U} + \mathrm{KE} + \mathrm{PE} \ \text{ and } \ \Delta\mathrm{E}_{\mathrm{system}} = \Delta\mathrm{U} + \Delta\mathrm{KE} + \Delta\mathrm{PE}$$

Energy can be transferred to or from a system in three forms: heat Q. work W, and mass flow m. Energy interactions are recognized at the system boundary as they cross it, and they represent the energy gained or lost by a system during a process. Then the FLT or energy balance for any system under going any kind of a process can be expressed as

$$\mathrm{E}_{\mathrm{in}} - \mathrm{E}_{\mathrm{out}} = \Delta\mathrm{E}_{\mathrm{system}}$$

That is, the net change (increase or decreases) in the total energy of the system during a process is equal to the difference between the total energy entering and the total energy leaving the system during that process.

The only two forms of energy interactions associated with a fixed mass or closed system are transfer and work. For a closed system undergoing a cycle, the initial and final states are identical and thus

$$\Delta\mathrm{E}_{\mathrm{system}} = \mathrm{E}_2 - \mathrm{E}_1 = \mathrm{E}_{\mathrm{out}}$$

Noting that a closed system does not involve any mass flow across its boundaries, the energy balance for a cycle can be expressed in terms of heat and work interactions as

$$W_{net,out} = Q_{net,in}$$

This is the network output during a cycle equal to net heat input for a cycle.

1.2.2. The second law of thermodynamics (SLT)

The first law of thermodynamics gives no information about direction; it merely states that when one form of energy is converted into other forms, an energy balance is maintained but it does not specify about the feasibility of the process. In this regard, events could be visioned that would not violate the FLT. e.g. transfer of a certain quantity of heat from allow temperature body to a high temperature body, without expenditure of work. However. the reality shows that this is impossible and FLT becomes inadequate in picturing the complete energy transfer. Furthermore, experiments indicated that when energy in the form of heat is transferred to a system, only a portion of heat can be converted into work.

The SLT establishes the differences in quality between different forms of energy and explains why some processes can spontaneously occur. The second law of thermodynamics defines the fundamental physical quantity entropy as a randomized energy state unavailable for direct conversion to work. It also states that all spontaneous processes both physical and chemical, proceed to maximize entropy, that is, to become more randomized and to convert energy into a less available form.

1.3. Exergy

Exergy also known as available energy is the maximum useful work that can be obtained from a system through a reversible process, when it is brought to a dead state. Exergy is a property which depends not only on the state of the system but also its surroundings. Hence, exergy is generally defined as the property of the composite system and surroundings. Since all natural processes are irreversible in nature, exergy is destroyed during a process. The exergy destruction or the increase of entropy is a measure of the irreversibility of a natural process.

As already stated, exergy represents the useful form of work, it is customary to evaluate the exergy content of different forms of energy like heat energy, kinetic energy, potential energy, tidal energy, wind energy, geothermal energy, etc. Generally, since K.E and P.E can be completely converted into work ideally, the exergy quantum will be equal to the amount of K.E or P.E. However, with regards to heat energy, the quantum of exergy contained in a given heat energy depends on the temperature of the source of the heat.

Like energy, exergy can be transferred or transported across the boundary of a system. Foreach type of energy transfer or transport there is a corresponding exergy transfer or transport.

1.3.1Exergy analysis

Exergy analysis is a method that uses the conservation of mass and conservation of energy principles together with the SLT for the analysis, design and improvement of thermal systems. The exergy analysis forms the main part of modern thermodynamic approach in studying a thermal system. In general, more meaningful efficiency is evaluated with exergy analysis rather than energy analysis, since exergy efficiencies are always a measure of the approach to the ideal case. Engineers generally suggest that the thermodynamic performance of a process is best evaluated by performing an exergy analysis in addition to conventional energy analysis because exergy analysis appears to provide more insights and to be more useful in efficiency improvement efforts than energy analysis. It is important to highlight that exergy analysis can lead to a substantially reduced rate in the use of natural resources and the environment pollution by reducing the rate of discharge of waste products.

1.3.2 Energy balance for steady flow-system

Most devices encountered in practice are steady flow devices, such as turbines, heat exchangers, pumps, condensers, etc. Their mass, energy and entropy and volume remain constant during a steady flow process.

The steady flow energy equation represents the energy balance in a steady flow process. It is given by the expression,

$$\mathrm{h_1 + \frac{C_1^2}{2} + gz_1 + q_{1-2} = h_2 + \frac{C_2^2}{2} + gz_2 + W_s}$$

Applying the steady flow energy equation to the turbine while neglecting potential energy and kinetic energy and assuming that the process is isentropic then

$$\mathrm{h_1 = h_2 + W_s}$$
$$\mathrm{W_s = h_1 - h_2}$$

Similarly by applying steady flow energy equation to a pump while neglecting potential energy and kinetic energy and assuming that the process is isentropic, we have

$$h_2 = h_1 + W_s$$
$$W_s = h_2 - h_1$$

1.4Second Law Efficiency (or) Exergy Efficiency

A common measure on energy used efficiency is the first law efficiency. The first law efficiency is defined as the ratio of the output energy of a device to the input energy of device. The first law is concerned only with the quantities of energy, and disregards the forms in which the energy exists. It does not also discriminate between the energies available at different temperatures. It is the second law of thermodynamics which provides a means of assigning a quality index to energy. The concept of available energy or exergy provides a useful measure of energy quality.

With this concept, it is possible to analyse means of minimizing the consumption of available energy to perform a given process, thereby ensuring the most efficient possible conversion of energy for the required task.

The second law efficiency of a process is defined as the ratio of the minimum available energy or exergy which must be consumed to do a task divided by the actual amount of energy consumed in performing the task.

$$\eta_{II} = \frac{\text{minimum exergy intake to perform the given task}}{\text{actual exergy intake to perform the same task}}$$

This definition is specifically used for devices like turbines, pumps etc which either produce or consume shaft work.

The second law efficiency can also be defined as the ratio of exergy recovered from a system to the exergy supplied. This definition holds for devices like heat exchangers boilers, condensers etc.

$$\eta_{II} = \frac{\text{Energy Recovered}}{\text{Energy Supplied}}$$

1.5 Fuel cell:

A fuel cell is an electro chemical cell that converts the potential energy from a fuel into electricity through an electrochemical reaction of hydrogen fuel with oxygen or another oxidizing agent. Fuel cells are different from batteries in requiring a continuous source of fuel and oxygen (usually from air) to sustain the chemical reaction, whereas in a battery the chemical energy comes from chemicals already present in the battery. Fuel cells can produce electricity continuously for as long as fuel and oxygen are supplied.

There are many types of fuel cells, but they all consist of an anode, a cathode, and an electrolyte that allows positively charged hydrogen ions (protons) to move between the two sides of the fuel cell. At the anode a catalyst causes the fuel to undergo oxidation reactions that generate protons (positively charged hydrogen ions) and electrons. The protons flow from the anode to the cathode through the electrolyte after the reaction. At the same time, electrons are drawn from the anode to the cathode through an external circuit, producing direct current electricity. At the cathode, another catalyst causes hydrogen ions, electrons, and oxygen to react, forming water.

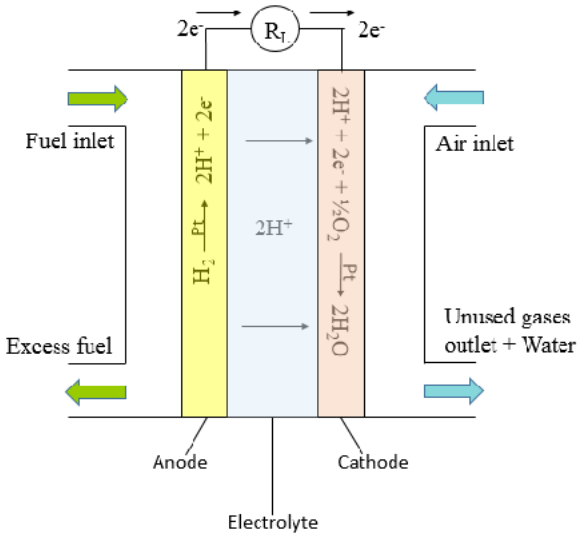


Fig 1.1 H_2-O_2 Fuel Cell

1.5.1 History:

The origin of fuel cell technology is credited to Sir William Robert Grove (1811-1896). Grove developed an improved wet-cell battery in 1838 which brought him fame. Using his research and knowledge that electrolysis used electricity to split water into hydrogen and oxygen he concluded that the opposite reaction must be capable of producing electricity. Using this hypothesis, Grove developed a device which would combine hydrogen and oxygen to produce electricity. Grove had developed the world's first gas battery. It was this gas battery which has become known as the fuel cell.

Ludwig Mond (1839-1909) along with assistant Carl Langer conducted experiments with a hydrogen fuel cell that produced 6 amps per square foot at 0.73 volts.

It was Friedrich Wilhelm Ostwald (1853-1932), the founder of the field of physical chemistry, who experimentally determined the relationship between the different components of the fuel cell, including the electrodes, electrolyte, oxidizing and reducing agent, anions and cations. Ostwald's work opened doors into the area of fuel cell research by supplying information to future fuel cell researchers.

During the first half of the twentieth century, Emil Baur (1873-1944) conducted extensive research into the area of high temperature fuel cell devices which used molten silver as the electrolyte. His work was performed along with students at Braunschweig and Zurich.

Francis Thomas Bacon (1904-1992) performed research and significant developments with high pressure fuel cells. Bacon was successful in developing a fuel cell that used nickel gauze electrodes and operated at pressures up to 3000 psi.

1.5.2 Types:

Fuel cells come in many varieties; however, they all work in the same general manner. They are made up of three adjacent segments: the anode, the electrolyte, and the cathode. Two chemical reactions occur at the interfaces of the three different segments. The net result of the two reactions is that fuel is consumed, water or carbon dioxide is created, and an electric current is created, which can be used to power electrical devices, normally referred to as the load.

At the anode a catalyst oxidizes the fuel, usually hydrogen, turning the fuel into a positively charged ion and a negatively charged electron. The electrolyte is a substance specifically designed so ions can pass through it, but the electrons cannot. The freed electrons travel through a wire creating the electric current. The ions travel through the electrolyte to the cathode. Once reaching the cathode, the ions are reunited with the electrons and the two react with a third chemical, usually oxygen, to create water or carbon dioxide.

Fuel cells are classified by the type of electrolyte they use and by the difference in start up time ranging from 1 second for proton exchange membrane fuel cells (PEM fuel cells, or PEMFC) to 10 minutes for solid oxide fuel cells (SOFC). A related technology is flow batteries, in which the fuel can be regenerated by recharging. Individual fuel cells produce relatively small electrical potentials, about 0.7 volts, so cells are "stacked", or placed in series, to create sufficient voltage to meet an application's requirements. In addition to electricity, fuel cells produce water, heat and, depending on the fuel source, very small amounts of nitrogen dioxide and other emissions. The energy efficiency of a fuel cell is generally between 40–60%; however, if waste heat is captured in a cogeneration scheme, efficiencies up to 85% can be obtained.

Types of fuel cell include:

Fuel cells can be classified in several ways.

1. Based on the type of electrolyte:(i) Phospohoric Acid Fuel cell (PAFC)(ii) Alkaline Fuel Cell (AFC)(iii) Solid Polymer Fuel Cell (SPFC)(iv) Molten Carbonate Fuel Cell (MCFC)(v) Solid Oxide Fuel Cell (SOFC)
2. Based on types of the fuel and oxidant:(i) Hydrogen – Oxygen Fuel Cell(ii) Hydrogen – Air Fuel Cell(iii) Ammonia – Air Fuel Cell(iv) Hydrocarbon – Air Fuel Cell
3. Based on operating temperature:(i) Low temperature fuel cell (below 150 degrees)(ii) Medium temperature fuel cell (150-250 degrees)(iii) High temperature fuel cell (250-800 degrees)(iv) Very high temperature fuel cell (800-1100 degrees)
4. Based on application:(i) Fuel cell for space applications(ii) Fuel cell for vehicle propulsion(iii) Fuel cell for submarines(iv) Fuel cell for defense applications(v) Fuel cell for commercial applications
5. Based on chemical nature of electrolyte:(i) Acidic electrolyte type(ii) Alkaline electrolyte type(iii) Neutral electrolyte type

1.5.3 Applications:

The first commercial use of fuel cells came more than a century later in NASA space programs to generate power for satellites and space capsules. Since then, fuel cells have been used in many other applications. Fuel cells are used for primary and backup power for commercial, industrial and residential buildings and in remote or inaccessible areas. They are also used to power fuel cell vehicles, including forklifts, automobiles, buses, boats, motorcycles and submarines.

1.6 Evolution Of Braysson Cycle

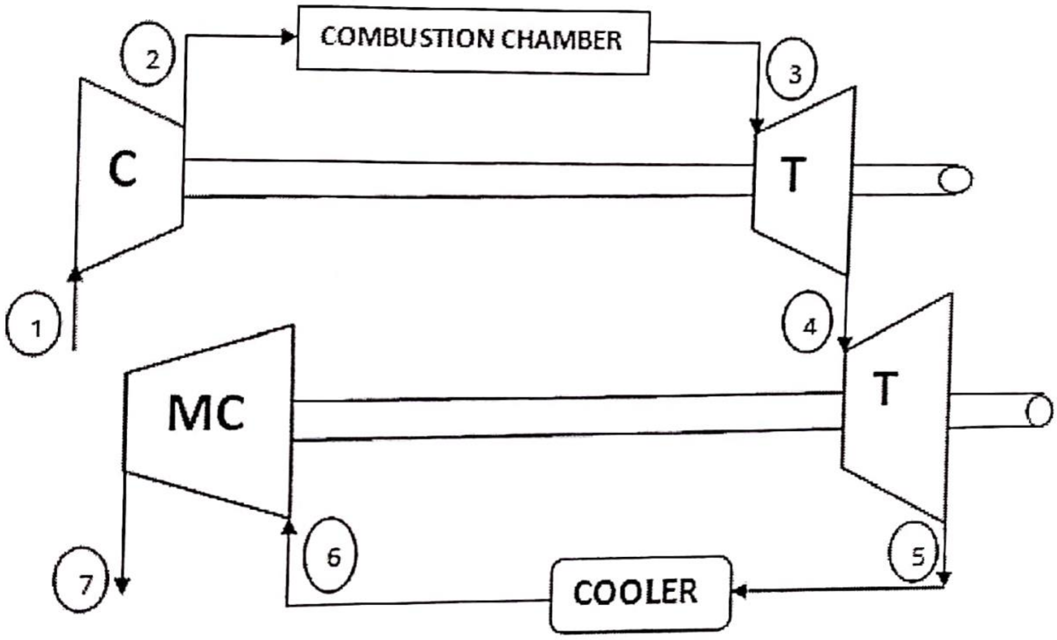


Fig 1.2 Layout of Braysson cycle with cooler and multi stage compressor

A power generation cycle has highest efficiency when it runs on reversible cycle with isothermal heat addition and low temperature isothermal heat rejection .The temperature of heat rejection can be decreased by implementing a combined cycle power plant in which heat rejected from Brayton cycle is used to drive the steam turbine cycle. Such cycles are being used in the world due to their higher energy and exergy efficiencies.

In 1997 T H Frost first proposed an alternative to the combined cycles and termed it as Braysson cycle. The Braysson cycle is inherently an air driven cycle and therefore the complexities of a combined cycle plant are totally eliminated in this cycle.

Later in 2015 reheat regenerative Braysson cycle was proposed, its efficiency was observed to be almost equal to ideal Braysson cycle.

Braysson is a hybrid of high temperature heat addition Brayton cycle and the low temperature heat rejection Ericsson cycle. It incorporates the advantages of both the cycles.

1.6.1 Brayton cycle:

Gas turbines are described thermodynamically by the Brayton cycle, in which air is compressed isentropically, combustion occurs at constant pressure, expansion occurs isentropically and heat is rejected isobarically to the ambient .Its components are:

- Compressor
- Combustion chamber
- Turbine
- Heat Exchanger

Process:

- Isentropic compression process: Ambient air is drawn into the compressor.
- Isobaric heat addition process: The compressed air then runs through a combustion chamber, where fuel is burned, heating that air at constant-pressure process.
- Isentropic expansion process: The heated air is expanded through the turbine. Some of the work extracted by the turbine is used to drive the compressor.
- Isobaric heat rejection process : Heat rejected to atmosphere.

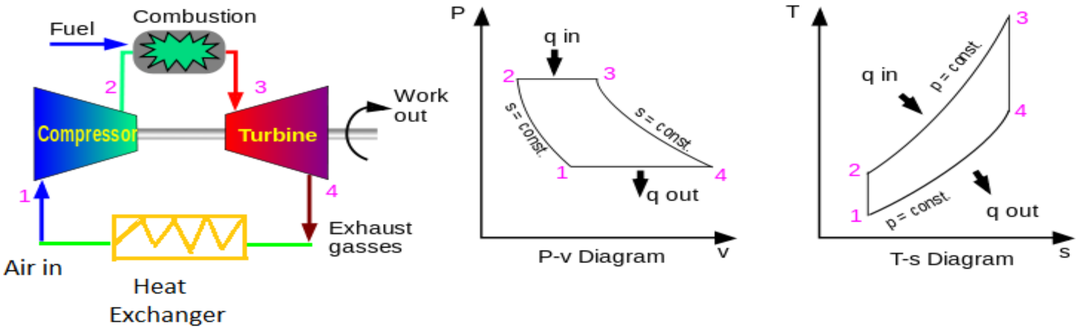


Fig 1.3 Layout of a Brayton cycle with P-V & T-S plot

1.6.2 Ericsson cycle:

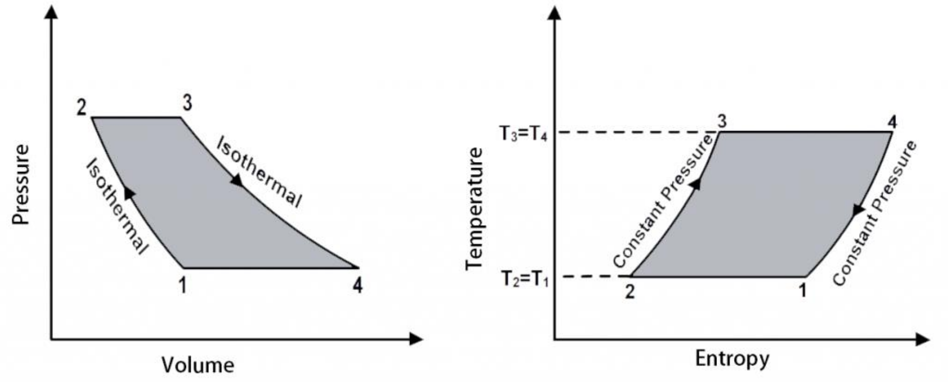


Fig 1.4 P-V & T-S plot for an Ericsson cycle

The Ericsson cycle consists of two isothermal and two constant pressure processes.

- Process1-2: Reversible Isothermal compression.
- Process2-3: Isobaric heat addition.
- Process3-4: Reversible Isothermal expansion.
- Process4-1: Isobaric heat rejection.

The heat addition and rejection take place isothermally. The net effect is that the heat need to be added only at constant temperature T3=T4 and rejected at the constant temperature TI=T2. The advantage of the Ericsson cycle over the Carnot and Sterling cycles is its smaller pressure ratio for a given ratio of maximum to minimum specific volume with higher mean effective pressure.

The thermal efficiency of Ericsson cycle is given by

$$\eta_{th} = \frac{T_H - T_L}{T_H} = 1 - \frac{T_L}{T_H}$$

The Ericsson cycle does not find practical application in piston engines but is approached by a gas turbine employing a large number of stages with heat exchangers, insulators and reheaters.

1.6.3 Concept of ideal cycle:

Ideal Braysson cycle, also known as reversible cycle is a hybrid cycle consists of a gas turbine coupled with a bottoming turbine (Ericsson cycle) where the working fluid expands to attain ambient temperature thereby expanding to vacuum pressure (0.04 bar) The bottoming turbine is coupled with multi stage intercooled compressor for isothermal heat rejection. All the processes in the cycle are reversible and thus the second law efficiency of individual components is obtained as 100%. The exergy loses are considered in the combustion chamber as the heat addition takes place at finite temperature difference.

- Process1-2: Reversible Isentropic compression.
- Process2-3: Isobaric heat addition.
- Process3-4: Reversible Isentropic expansion.
- Process4-1: Isothermal heat rejection.

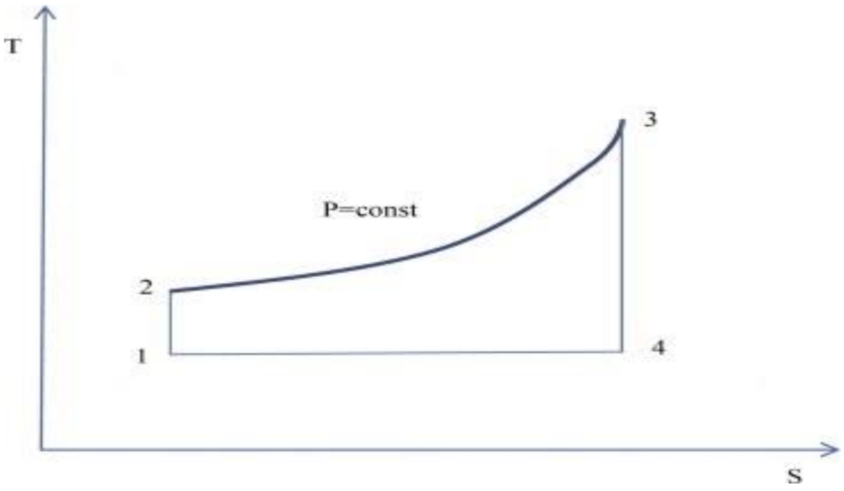


Fig 1.5 T-S plot for an ideal Braysson cycle.

1.7 Reheat & Regenerative Braysson Cycle

1.7.1 Regeneration:

The Process during which heat is transferred to a thermal energy storage device, during one part of the cycle and is transferred back to the working fluid during another part of the cycle The high pressure air leaving the compressor can be heated by transferring heat to it from the hot exhaust gases in a counter flow heat exchanger, which is also known as a regenerator or a recupeerator.

1.7.2 System description:

A schematic diagram of Braysson cycle with regeneration and reheating is shown in fig 1.6 . The cycle consists of a compressor, combustion chamber, main gas turbine, reheater, regenerator, reheat gas turbine, cooler and a multistage compressor. Both the main turbine and the reheat gas turbine are mechanically coupled to electric generators and compressors. The gases at the exit of the main turbine are reheated to the maximum temperature of the cycle before being passed into the reheat turbine where they further expand to sub-atmospheric pressure. The regenerator improves the cycle efficiency by utilizing the waste heat of the gases on the downstream of reheat turbine. The gases exiting the regenerator are cooled further before letting them into the multistage compressor. The gases are then pressurized to atmospheric pressure in the multi stage compressor and exited to the ambient.

For the purpose of reheating, we have to use another fuel cell for the temperature requirement. From the calculations, The temperature rise in reheater and normal heating are almost similar. Hence we can use the same fuel cell with same specifications for reheating also.

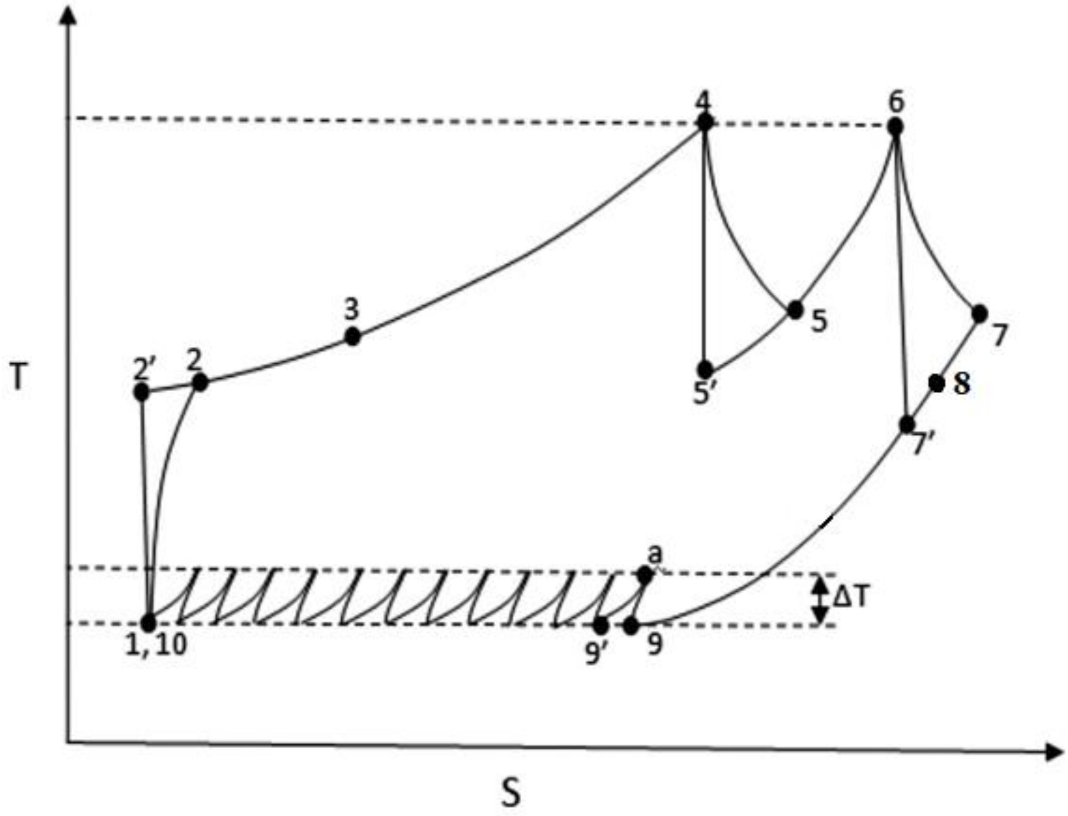


Fig 1.6 T-S diagram for Reheat & Regenerative Braysson cycle

(1)-(2): Polytropic Compression in compressor
(2)-(3): Regeneration at Constant Pressure
(3)-(4): Isobaric Heat Addition
(4)-(5): Polytropic Expansion in High Pressure Turbine
(5)-(6): Isobaric Heat Addition in Reheater
(6)-(7): Polytropic Expansion In Low Pressure Turbine
(7)-(8): Regeneration At Constant Pressure
(8)-(9): Isobaric Heat Rejection In Cooler

(9)-(10): Isothermal Compression In Multi-stage Compressor

1.7.2.1 Polytropic expansion (1-2):

The compression process is accomplished using a compressor that is coupled to the primary turbine. The process is assumed to be polytrophic process and the efficiency of the compressor is taken as 80%. However it is assumed that there are no heat losses to the surroundings. The compressor pressurizes the gas from ambient pressure to the required pressures. The ratio of output pressure to the input pressure of the compressor is taken as pressure ratio of the system(r_p).

1.7.2.2 Regeneration (2-3):

In Regenerator, the high pressure air leaving the compressor is heated by transferring heat to it from the hot exhaust gases coming from the secondary turbine. This Process occurs at constant pressure. Then the compressed air at high temperature enters the combustion chamber.

1.7.2.3 Isobaric heat addition (3-4):

The heat addition process takes place at constant pressure in the heat exchanger by transferring heat from the fuel cell to the working fluid of the Braysson cycle(helium)

1.7.2.4 Polytropic expansion (4-5) & (6-7):

The expansion of working fluid takes place in the main and reheat gas turbines with intermediate reheat. The intermediate pressure at which reheating is carried out is optimized for maximum work output of the turbines. The downstream pressure of reheat turbine is considered as vacuum pressure

1.7.2.5 Isobaric heat addition in Reheater (5-6):

The work output of a turbine operating between two pressure levels can be increased by expanding the gas in stages and reheating it in between, (i.e) utilizing multistage expansion with reheating. The heat transfer from the fuel cell to the air takes place in the reheater at constant pressure to increase the working fluid temperature to the maximum temperature of the cycle.

1.7.2.6 Regeneration at constant pressure (7-8):

The exchange of heat takes place between hot gases coming from the turbine and the compressed air obtained from the compressor. The hot gases transfer their heat to the compressed air and come out at lower temperature and then enter the cooler. This process occurs at constant pressure.

1.7.2.7 Isobaric heat rejection (8-9):

This Process is done using cooler for further decreasing of the temperature of the hot gases, thereby decreasing the compressor work. There are no pressure changes during the process

1.7.2.8 Isothermal heat rejection (9-10):

The isothermal heat rejection is achieved with the help of a multistage intercooled compressor which is powered by the bottoming turbine. The heat rejection and compression takes place simultaneously in the multi-stage intercooled compressor. The compression is considered as isentropic process and the heat rejection take place at constant pressure in every stage. The optimum number of stages is taken as 4 from the thermodynamic considerations. The pressure increases from vacuum pressure to ambient pressure. The intercooling is achieved by using hollow stators as suggested by Frost et.al. However the temperature drop per stage should be limited to around 10℃to maintainnearly isothermal conditions. Since the additional power required to drive thisunit is drawn from a bottoming turbine the net work output remains almost same when compared with a conventional Brayton cycle based gas turbine operating under the same conditions. The heat is rejected to a low temperature sink (atmosphere).

CHAPTER 2

2. LITERATURE REVIEW

Frost et al. [1] proposed an alternative to the combined cycles and termed it as Braysson cycle. The Braysson cycle is inherently an air driven cycle, and therefore the complexities involved in installing and running the heat recovery steam generator, condenser and other auxiliaries of a combined cycle plant are totally eliminated in this cycle. Braysson cycle is a hybrid of the high temperature heat addition Brayton cycle and the low temperature heat rejection Ericsson cycle. The Braysson cycle was subjected to further studies based on both the first and the second law analysis by many researchers.

Zheng et al. [2] carried out an exergy analysis for an irreversible Braysson cycle and analysed the influence of various parameters on its performance. It has been shown that both the power output and the efficiency of the cycle are greater than those of Brayton cycle.

Zheng et al. [3] also derived the analytical formula for power output, efficiency, maximum power output and the corresponding efficiency of an endo-reversible Braysson cycle with the heat resistance losses in the hot and cold-side heat exchangers using finite time thermodynamics. He also analysed the influence of the design parameters on the performance of the cycle.

Zheng et al. [4] carried out the optimization of the above parameters of endo-reversible Braysson cycle. Furthermore the effects of various design parameters on those optimum values were studied.

Yasin et al. [5] performed the analysis of endo-reversible Braysson cycle based on ecological criteria. The ecological objective function was defined and its maximization was achieved for various design parameters.

Sreenivas et al. [6] performed the second law analysis of an irreversible Braysson cycle. The overall second law efficiency and the component-wise second law efficiencies were derived. The thermodynamic losses occurring in each component were obtained.

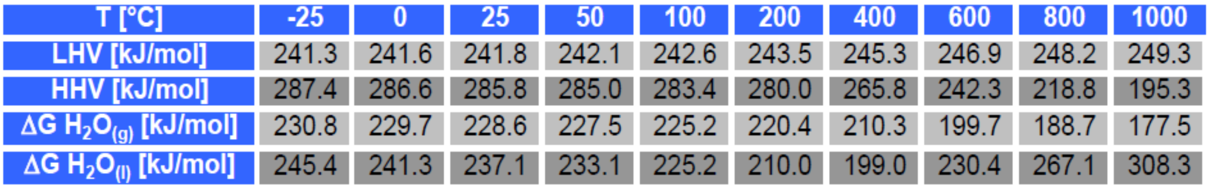
Zhang et al. [7] presented a novel model of the solar-driven thermodynamic cycle system consisting of a solar collector and a Braysson heat engine. The performance characteristics of the system were optimized on the basis of the linear heat-loss model of a solar collector and the irreversible cycle model of a Braysson heat engine. The main drawback of Braysson cycle is the difficulty in achieving isothermal compression in multistage intercooled compressor. However, a few proposals were made by some researchers.

Georgiou and Xenos[8] incorporated a regulated water injection, which was coordinated with the compression process, so that the evaporation of water droplets may maintain a near constant temperature of the fluid. The study provided an analysis for the water injection rate and showed that the additional work needed to drive the process was not affected significantly by the injection.

Georgiou et al. [9] also proposed a multistep intercooled compression process on a solar-driven Braysson heat engine as a feasible solution for implementing isothermal compression in Braysson cycle. The results indicated that such a plant may reach efficiency levels of above 30%, i.e. exceeding the efficiencies of the conventional Photovoltaic plants by a wide margin.

However, Chandramouli et al. [10] have recently proposed reheat and regenerative Braysson cycle with the inclusion of cooler and showed that it reaches the efficiency of the conventional Braysson cycle at a very lower pressure ratio. The study also included the influence of number of stages of multistage intercooled compressor on exergy efficiency and came to the conclusion that it can work with fewer stages (N =10) and attain higher efficiency than the conventional Braysson cycle with isothermal compression (which is an ideal proposition). Thus one need not go for isothermal compression. Hence a parametric analysis of this reheat and regenerative Braysson cycle is required to study the effect of different parameters on the cycle performance for its practical implementation.

From the work, Fuel Cell Formulary by Dr. Alexander Kabza[11] , in an H2/O2 electrochemical device hydrogen is oxidized by oxygen to water in an exothermic reaction and ΔH and ΔG are dependent on temperature; therefore also the corresponding voltage equivalents are functions of temperature. The temperature dependency (of absolute values) is as follows:



T [°C]	-25	0	25	50	100	200	400	600	800	1000
LHV [kJ/mol]	241.3	241.6	241.8	242.1	242.6	243.5	245.3	246.9	248.2	249.3
HHV [kJ/mol]	287.4	286.6	285.8	285.0	283.4	280.0	265.8	242.3	218.8	195.3
ΔG $H_2O_{(g)}$ [kJ/mol]	230.8	229.7	228.6	227.5	225.2	220.4	210.3	199.7	188.7	177.5
ΔG $H_2O_{(l)}$ [kJ/mol]	245.4	241.3	237.1	233.1	225.2	210.0	199.0	230.4	267.1	308.3

Table 2.1: ΔH and ΔG values at different temperatures

Thermodynamic efficiency: The thermodynamic or maximum or ideal efficiency is the ratio between enthalpy (or heating value) ΔH and Gibbs free enthalpy ΔG (reflecting the maximum extractible work) of any electrochemical device:

$$\eta_{thermodynamic} = \frac{\Delta G}{\Delta H}$$

Y.Haselli[12] worked on 'Maximum conversion efficiency of hydrogen fuel cells'where he stated that the maximum conversion efficiency takes place at the reactants temperature of 298.15 K. However, by increasing the reactants temperature, the efficiency first decreases, then remains unaltered over a temperature range, and finally begins to rise. The efficiency plateau for the hydrogen-oxygen, hydrogen-air, and methane-air takes place at 1350-1540 K, 1170-1300 K, and 1590-1730 K, respectively. At a given reactants temperature, the maximum efficiency of the methane-air fuel cell is the highest, whereas that of the hydrogen-air fuel cell is the lowest, and that of the hydrogen-oxygen fuel cell in between. The lowest value of the maximum efficiency is 82.1%, 75.7%, and 79.3%, respectively, for CH4-air fuel cell, H2eO2 fuel cell, and H2-air fuel cell and the corresponding highest maximum efficiency is 92.7%, 82.7% and 82.7%

Mohamad Alijanpour Sheshpoli et al.[13] worked on 'Thermodynamic analysis of waste heat recovery from hybrid system of proton exchange membrane fuel cell and vapour compression refrigeration cycle by recuperative organic Rankine cycle' in which two working fluids were surveyed including R-245fa and R-134a. Results indicate that hybrid system thermal efficiency falls down by increase in turbine pressure ratio. The maximum system consumption power was dedicated in the case in which the fuel cell has its highest thermal efficiency in addition to minimum net produced power. Additionally, R-134a was determined as the best working fluid. Net output power and efficiency of the system with R-134a are about 1.2 and 20% more than R-245fa, respectively.

L. van Biert et al.[14] in his work, ‘A thermodynamic comparison of solid oxide fuel cell-combined cycles’ studied a stand-alone SOFC system is thermodynamically analysed and compared to configurations combined with a gas turbine or steam turbine, as well as a novel SOFC-reciprocating engine combined cycle system. The results are mapped in contour plots for the entire SOFC operating envelope, revealing the influence of fuel utilisation, cell voltage, average stack temperature and gas turbine pressure ratio on different combined cycles.

Masoud Rokni in his work ‘Thermodynamic analysis of an integrated solid oxide fuel cell cycle with a rankine cycle’ [15] studied hybrid systems consisting of solid oxide fuel cells (SOFC) on the top of a steam turbine (ST). The plants are fired by natural gas (NG). A desulfurization reactor removes the sulfur content in the fuel while a pre-reformer breaks down the heavier hydro-carbons. The pre-treated fuel enters then into the anode side of the SOFC. The remaining fuels after the SOFC stacks enter a burner for further burning. The off-gases are then used to produce steam for a Rankine cycle in a heat recovery steam generator (HRSG).

Tianjun Liao et al. through his work ‘Efficiently exploiting the waste heat in solid oxide fuel cell by means of thermophotovoltaic cell’[16] has studied the combination of the current models of solid oxide fuel cells (SOFCs) and thermophotovoltaic cells (TPVCs), and a new model of the hybrid device composed of an SOFC, a regenerator, and a TPVC with integrated back surface reflector (BSR) is proposed. Analytical expressions for the power output and efficiency of two subsystems and hybrid device are derived. The relations between the performance of the TPVC and the operating current density of the SOFC in the hybrid device are revealed. The performance characteristics of the hybrid device are discussed in detail. The maximum power output density is calculated. The optimally operating region of the hybrid device is determined, compared with the performance of the SOFC in the hybrid device. The choice criteria of some key parameters are given. Moreover, it is proved that the proposed model can exploit the waste heat produced in SOFCs more efficiently than other SOFC-based hybrid systems.

Ali Volkan Akkaya et al. in his work ‘A study on performance of solid oxide fuel cell-organic Rankine cycle combined systems’[17] presented an energetic performance analysis for a combined power generation system consisting of a solid oxide fuel cell (SOFC) and an organic Rankine cycle (ORC). In order to simulate the SOFC–ORC combined system under steady-state conditions, a mathematical model is developed. The developed model is used to determine the potential effects caused by the changes of the design parameters on the energetic performance of the combined system. As design parameters, turbine inlet pressure, condenser temperature, fuel utilization, current density, compressor pressure ratio, and cell operating temperature are taken into account. In this regard, the electrical power and First Law efficiency are estimated by parametrical analysis and discussed comprehensively. Results of these analyses show that the efficiency is increased about 14–25% by recovering SOFC waste heat through ORC based on investigated design parameter conditions.

CHAPTER 3

3. THERMODYNAMIC ANALYSIS

3.1 SYSTEM DESCRIPTION

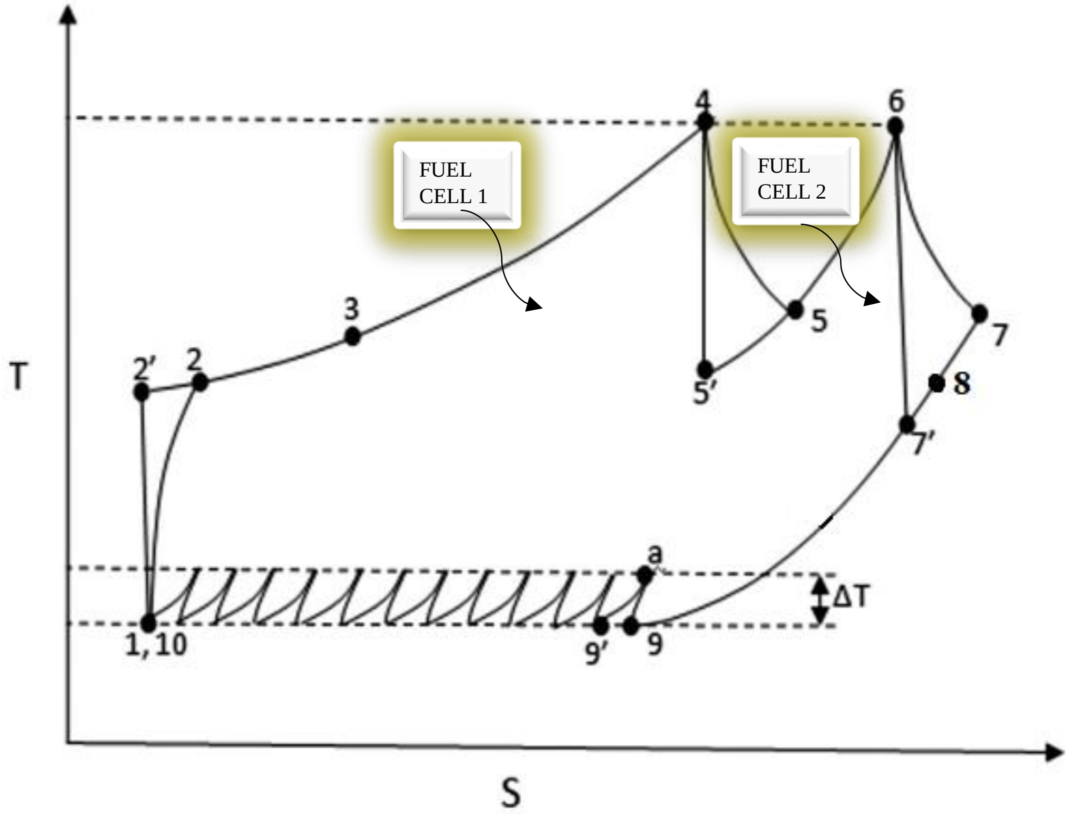


Fig 3.1 T-S diagram for Reheat & Regenerative Braysson cycle

The T-S plot of the Thermodynamic cycle is represented described below.

1. Isentropic compression (1-2)
2. Regeneration (2-3) & (7-8)
3. Isobaric heat addition (3-4)
4. Isentropic expansion (4-5) & (6-7)
5. Isobaric heat addition in reheater (5-6)
6. Isobaric heat rejection (8-9)
7. Isothermal heat rejection using multi stage compressor (9-1)

3.2 Energy analysis:

3.2.1 Isentropic compression (1-2)

The temperature of the air after compression can be calculated using the following equation

$$p_1 v_1{}^{\gamma} = p_2 v_2{}^{\gamma}$$

$$p_1 \left(\frac{T_1}{p_1}\right)^{\gamma} = p_2 \left(\frac{T_2{}'}{p_2}\right)^{\gamma}$$

$$(p_1)^{1-\gamma} * (T_1)^{\gamma} = (p_2)^{1-\gamma} * (T_2{}')^{\gamma}$$

$$\left(\frac{T_2{}'}{T_1}\right) = \left(r_p\right)^{\frac{\gamma-1}{\gamma}}$$

$$\eta_c = \frac{T_2{}' - T_1}{T_2 - T_1}$$

$$T_2 = T_1 + \frac{T_1 * \left(r_p{}^{\frac{\gamma-1}{\gamma}} - 1\right)}{\eta_c} \ldots\ldots\ldots\ldots\ldots\ldots (1)$$

3.2.2 Isentropic expansion (4-5)

The temperature at the outlet of high pressure turbine can be calculated by using following equation

$$p_4 * v_4{}^{\gamma} = p_5 * v_5{}^{\gamma}$$

$$\left(\frac{T_5{}'}{T_4}\right) = \left(\frac{p_5}{p_4}\right)^{\frac{\gamma-1}{\gamma}} = \left(\frac{1}{r_{p_1}}\right)^{\frac{\gamma-1}{\gamma}} = r_{p_1}{}^{\left(\frac{1-\gamma}{\gamma}\right)}$$

$$\eta_t = \frac{T_4 - T_5}{T_4 - T_5{}'}$$

$$T_5 = T_4 + \eta_t (T_5{}' - T_4)$$

$$T_5 = T_4 + \eta_t \left(r_{p_1}{}^{\frac{1-\gamma}{2\gamma}} - 1\right) \ldots\ldots\ldots\ldots\ldots\ldots (2)$$

The temperature at the end of reheat process is observed as same temperature at inlet of high pressure turbine.

$$T_6 = T_4 \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (3)$$

Note:

Regeneration will be possible only if $T_5 > T_2$

When the gas expands through the reheat turbine the same temperature are observed as in case of expansion through the main turbine.

$$\mathrm{T_7} = \mathrm{T_5} \ldots\ldots (4)$$

3.2.3 Regeneration (2-3) & (7-8)

The temperature at the end of regeneration process can be calculated by using the following equation

$$\eta_\mathrm{r} = \frac{\mathrm{T_3} - \mathrm{T_2}}{\mathrm{T_7} - \mathrm{T_2}}$$

$$\mathrm{T_3} = \eta_\mathrm{r} * (\mathrm{T_7} - \mathrm{T_2}) + \mathrm{T_2} \ldots\ldots (5)$$

The temperature at the end of regeneration process can be calculated by following equation

$$\mathrm{T_8} = \mathrm{T_7} - \mathrm{T_3} + \mathrm{T_2} \ldots\ldots (6)$$

The temperature at the end of the isobaric heat rejection is same as the input temperature of the cycle

$$\mathrm{T_9} = \mathrm{T_1} \ldots\ldots (7)$$

3.2.4 Isothermal heat rejection using multi stage compressor (9-1)

The temperature at the end of multi stage intercooled compressor can be determined by the following equation

$$\frac{\mathrm{T_a}'}{\mathrm{T_9}} = \mathrm{r_{p_i}}^{\frac{\gamma-1}{\gamma}}$$

$$\eta_\mathrm{1c} = \frac{\mathrm{T_a}' - \mathrm{T_9}}{\mathrm{T_a} - \mathrm{T_9}}$$

$$\mathrm{T_a} = \mathrm{T_9} + \frac{(\mathrm{r_{p_o}}^{\frac{\gamma-1}{\gamma}} - 1)}{\eta_\mathrm{1c}} \ldots\ldots (8)$$

Work output of Braysson cycle can be obtained by

$$\mathrm{w_{o.p}} = \mathrm{c_p} * (\mathrm{T_4} - \mathrm{T_5}) + \mathrm{c_p} * (\mathrm{T_6} - \mathrm{T_7})$$

Work input to Braysson cycle is obtained by

$$\mathrm{w_{i.p}} = \mathrm{c_p} * (\mathrm{T_2} - \mathrm{T_1}) + \mathrm{n}\left(\mathrm{c_p}(\mathrm{T_a} - \mathrm{T_9})\right)$$

Heat input to Braysson cycle is obtained by

$$\mathrm{q_{i.p}} = \mathrm{q_h} * \left(\dot{\mathrm{m}}_{\mathrm{f_1}} + \dot{\mathrm{m}}_{\mathrm{f_2}}\right)$$

Where,

m_{f_1} *and* m_{f_2} are mass flow rates of water in fuel cells 1 and 2 respectively

Braysson cycle efficiency is obtained by

$$\eta_{\mathrm{b.c}} = \frac{\mathrm{w_{o.p}}\text{of braysson} - \mathrm{w_{i.p}}\text{ of braysson}}{\mathrm{q_{i.p}}}$$

Overall efficiency is obtained by

$$\eta_{\mathrm{o}} = \frac{\mathrm{p_b} + \mathrm{p_{f_1}} + \mathrm{p_{f_2}}}{\Delta\mathrm{H_o}}$$

Fuel cell efficiency is given by

$$\eta_{\mathrm{f.c}} = \frac{\Delta G}{\Delta H} \qquad (9)$$

Where,

$$\Delta\mathrm{H_o} = \Delta\mathrm{H} * \left(\dot{\mathrm{m}}_{\mathrm{f_1}} + \dot{\mathrm{m}}_{\mathrm{f_2}}\right)$$

$$\mathrm{p_b} = \mathrm{w_{o.p}}\text{of Braysson} - \mathrm{w_{i.p}}\text{ of Braysson}$$

$$\mathrm{p_{f_1}} = \dot{\mathrm{m}}_{\mathrm{f_1}} * \Delta\mathrm{G}$$

$$\mathrm{p_{f_2}} = \dot{\mathrm{m}}_{\mathrm{f_2}} * \Delta\mathrm{G}$$

$$\mathrm{q_h} = (\Delta\mathrm{H} - \Delta\mathrm{G})$$

Mass flow rate of $\mathrm{H_2O}$ can be obtained from the equation

$$\dot{\mathrm{m}}_{\mathrm{f_{he}}} * \mathrm{c}_p * (\mathrm{T_4} - \mathrm{T_3}) = \dot{\mathrm{m}}_{\mathrm{f_1}} * \mathrm{Q_h} \qquad (10)$$

$$\dot{\mathrm{m}}_{\mathrm{f_{he}}} * \mathrm{c_p} * (\mathrm{T_6} - \mathrm{T_5}) = \dot{\mathrm{m}}_{\mathrm{f_2}} * \mathrm{Q_h} \qquad (11)$$

Mass flow rate of hydrogen in fuel cell 1, $\dot{\mathrm{m}}_{\mathrm{f_{h_1}}} = \frac{1}{9}\left(\dot{\mathrm{m}}_{\mathrm{f_1}}\right)$

Mass flow rate of hydrogen in fuel cell 2, $\dot{\mathrm{m}}_{\mathrm{f_{h_2}}} = \frac{1}{9}\left(\dot{\mathrm{m}}_{\mathrm{f_2}}\right)$

Mass flow rate of oxygen in fuel cell , $\dot{\mathrm{m}}_{\mathrm{f_{o_1}}} = 8(\dot{\mathrm{m}}_{\mathrm{f_{h_1}}})$

Mass flow rate of oxygen in fuel cell 2,$\dot{m}_{f_{o_2}}$ = 8($\dot{m}_{f_{h_2}}$)

TFC = $\left(\dot{m}_{f_{h_1}} + \dot{m}_{f_{h_2}}\right) * 3600$

SFC = $\frac{TFC}{W_{net_o}}$

Where ,

$$W_{net_o} = p_b + p_{f_1} + p_{f_2}$$

3.3 Exergy analysis:

Rate of exergy supplied =Rate of exergy recovered + Rate of exergy destroyed

Therefore,

Rate of exergy destroyed = Rate of exergy supplied-Rate of exergy recovered… (12)

Exergy efficiency = $\frac{\text{Rate of exergy recovered}}{\text{Rate of exergy supplied}}$……………………………………….. (13)

3.3.1 Isentropic compression (1-2)

Rate of exergy supplied = $c_p * (T_2 - T_1)$

$$= c_p * \frac{T_1 * \left(r_p^{\frac{\gamma-1}{\gamma}} - 1\right)}{\eta_c} \text{……………………………………… (14)}$$

Rate of exergy recovered = $c_p * (T_2 - T_1) - T_0 * (s_2 - s_1)$

$$= c_p \frac{T_1\left(r_p^{\frac{\gamma-1}{\gamma}} - 1\right)}{\eta_c} - T_0 c_p \left(\ln\left(\frac{T_2}{T_1}\right) - \left(\frac{\gamma-1}{\gamma}\right)\ln\left(r_p\right)\right) \text{…….. (15)}$$

3.3.2 Regeneration (2-3) & (7-8)

$$\eta_e = \frac{e_3 - e_2}{e_7 - e_8}$$

$$= \frac{(h_3 - T_0 s_3) - (h_2 - T_0 s_2)}{(h_7 - T_0 s_7) - (h_8 - T_0 s_8)}$$

$$= \frac{c_p(T_3 - T_2) - T_0(s_3 - s_2)}{c_p(T_7 - T_8) - T_0(s_7 - s_8)}$$

$$=\frac{c_p(T_3-T_2)-T_0 c_p \ln\left(\frac{T_3}{T_2}\right)}{c_p(T_7-T_8)-T_0 c_p \ln\left(\frac{T_7}{T_8}\right)} \quad \text{(16)}$$

Rate of exergy destroyed = $c_p\left[(T_7-T_8)-T_0\ln\left(\frac{T_7}{T_8}\right)\right]-c_p\left[(T_3-T_2)-T_0\ln\left(\frac{T_3}{T_2}\right)\right]$ …………………………………………………………… (17)

3.3.3 Fuel Cells 1 and 2

Chemical Exergy supplied $H_{2,}\mathrm{ceh} = 116557\ {}^{\mathrm{KJ}}/_{\mathrm{Kg\ of\ Hydrogen}}$

Chemical Exergy supplied $O_2,\ \mathrm{ceo} = 123.3\ {}^{\mathrm{KJ}}/_{\mathrm{Kg\ of\ Oxygen}}$

Exergy recovered from Fuel cell 1 = $\dot{m}_{f_1}\left[q_h * \left(1-\frac{T_0}{T}\right)+\Delta G\right]$………………. (18)

Exergy supplied to fuel cell 1 = $\left(\dot{m}_{f_{h_1}} * \mathrm{ceh}\right)+\left(\dot{m}_{f_{o_1}} * \mathrm{ceo}\right)$ ………………. (19)

Exergy recovered from Fuel cell 2 = $\dot{m}_{f_2}\left[q_h * \left(1-\frac{T_0}{T}\right)+\Delta G\right]$………………. (20)

Exergy supplied to fuel cell 2 = $\left(\dot{m}_{f_{h_2}} * \mathrm{ceh}\right)+\left(\dot{m}_{f_{o_2}} * \mathrm{ceo}\right)$………………. (21)

3.3.4 Heating of fluid (3-4) & (5-6)

Exergy recovered (3-4) = $c_p * (T_4-T_3)-c_p * T_0 * \left(ln\left(\frac{T_4}{T_3}\right)\right)$………………. (22)

Exergy supplied (3-4) = $\dot{m}_{f_1} * q_h * \left(1-\frac{T_0}{T}\right)$………………………………….. (23)

Exergy recovered (5-6) = $c_p * (T_6-T_5)-c_p * T_0 * \left(ln\left(\frac{T_6}{T_5}\right)\right)$………………. (24)

Exergy supplied (5-6) = $\dot{m}_{f_2} * q_h * \left(1-\frac{T_0}{T}\right)$……………… ………………….(25)

3.3.5 Isentropic expansion (4-5), (6-7)

Rate of exergy supplied = $\mathrm{c_p}(\mathrm{T_4}-\mathrm{T_5})-\mathrm{c_p}\mathrm{T_0}\left[\ln\left(\frac{\mathrm{T_4}}{\mathrm{T_5}}\right)-\left(\frac{\gamma-1}{\gamma}\right)\ln \mathrm{r_{p_1}}\right]$………… (26)

Rate of exergy recovered = $\mathrm{c_p}(\mathrm{T_4}-\mathrm{T_5})$ ……………………………………... (27)

3.3.6 Cooler (8-9)

Exergy recovered = 0 …………………………………………………………… (28)

Exergy supplied = $c_p * (T_8 - T_9) - c_P * T_0 * ln\left(\frac{T_8}{T_9}\right)$ …………………………… (29)

3.3.7 Multistage compressor (9-a-1)

Exergy recovered in compressor = $N * c_p * T_9 * \left(\frac{r_{p_0}{}^{\left(\frac{\gamma-1}{\gamma N}\right)}-1}{\eta_{1c}}\right) + Nc_p * T_0 *$

$\left(ln\left(1+\frac{r_{p_0}{}^{\left(\frac{\gamma-1}{\gamma N}\right)}-1}{\eta_{1c}}\right)\right) + Nc_p * T_0 * \frac{(\gamma-1)(\ln r_{p_0})}{\gamma N}$ ……………………………….. (30)

Exergy recovered in Intercooler = $(N-1)c_p * (T_a - T_9) - (N-1) * c_p * T_0 *$

$\ln\left(1+\frac{r_{p_0}{}^{\left(\frac{\gamma-1}{\gamma N}\right)}-1}{\eta_{1c}}\right)$ ……………………………………………………… (31)

Total exergy recovered in multi stage compressor system, = eq(30) – eq(31)

3.3.8 Exergy efficiency of combined system (Braysson cycle + fuel cell)

$$\eta_{\text{exergy}} = \frac{\mathrm{p_b}+\mathrm{p_{f_1}}+\mathrm{p_{f_2}}}{\left(\left(\dot{\mathrm{m}}_{\mathrm{f_{H_1}}}+\dot{\mathrm{m}}_{\mathrm{f_{H_2}}}\right) * \text{chemical exergy of } \mathrm{H_2}\right)+\left(\left(\dot{\mathrm{m}}_{\mathrm{f_{o_1}}}+\dot{\mathrm{m}}_{\mathrm{f_{o_2}}}\right) * \text{chemical exergy of } \mathrm{O_2}\right)}$$

$$=1-\frac{\text{overall destroyed}}{\text{supplied}}$$

CHAPTER 4

4. RESULTS AND DISCUSSIONS

Waste heat recovery from an ideal H_2-O_2 fuel cell using a Reheat and Regenerative Braysson cycle is analysed in this work. The following assumptions have been considered in the analysis. The number of stages in the multistage compressor is fixed at 4, the back pressure of low pressure turbine is fixed to 0.4 Bar and the turbines, compressors & regenerator efficiencies are assumed as 80%. It is also assumed that only 80% of waste heat liberated from the fuel cell is utilized for running the reheat and regenerative Braysson cycle and the effectiveness of regenerator is 1. It has been assumed that there are no pressure drops of the working fluid in the system. The analysis has been performed considering helium as working fluid. From the expressions developed, the exergy efficiency and exergy destruction of each device is obtained. The overall energy and exergy efficiencies of the cycle are also evaluated. The chemical exergies of hydrogen and oxygen are 116557 KJ/ and 123.3 KJ/Kg respectively [19].

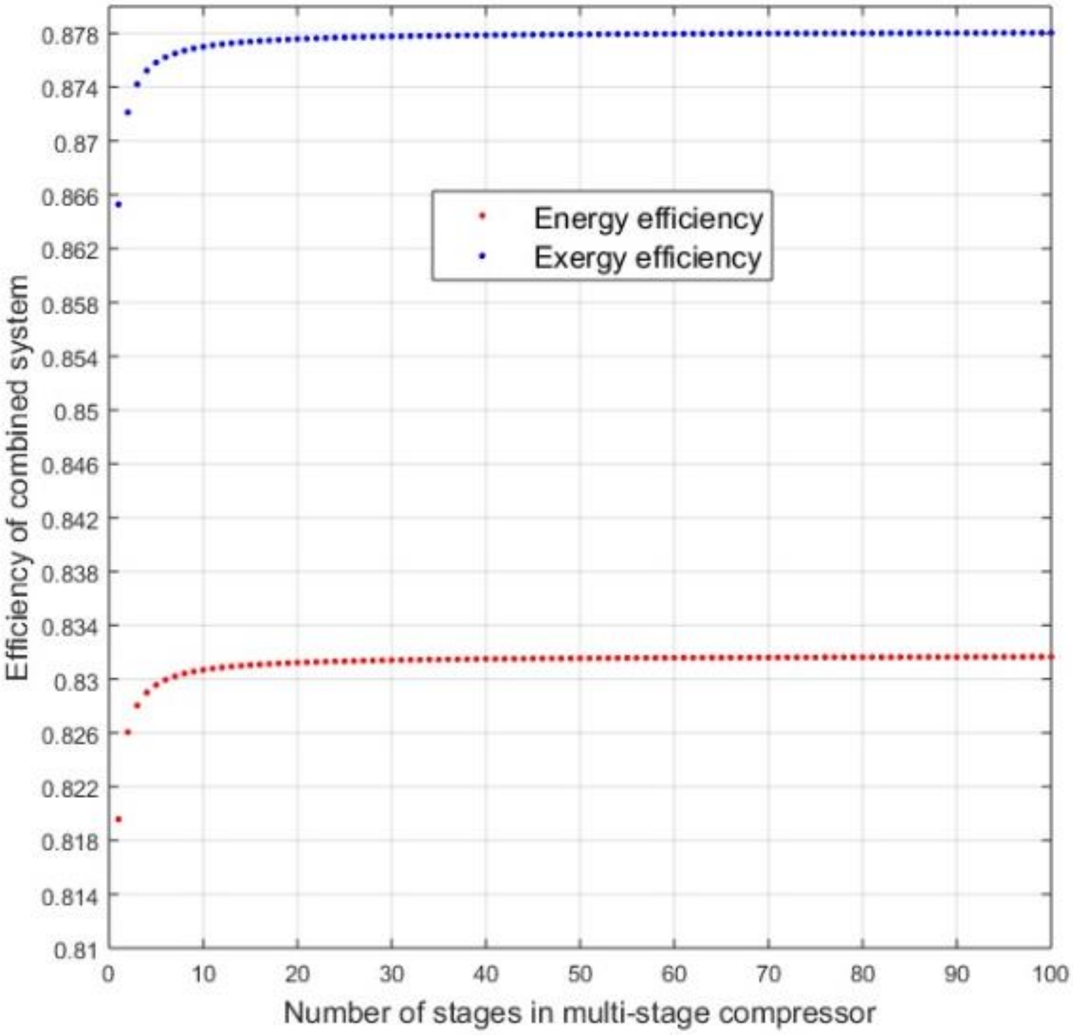


Fig 4 (a) Efficiency of combined system vs. Number of stages in multi-stage compressor

Energy efficiency value at N=4 is 0.829 and at N=100 is 0.832.

Similarly, Exergy efficiency value at N=4 is 0.875 and at N=100 is 0.878.

It is seen that after 4 number of stages in the multistage compressor, there is no much change in the energy and exergy efficiency values.

Hence the number of stages is fixed to 4.

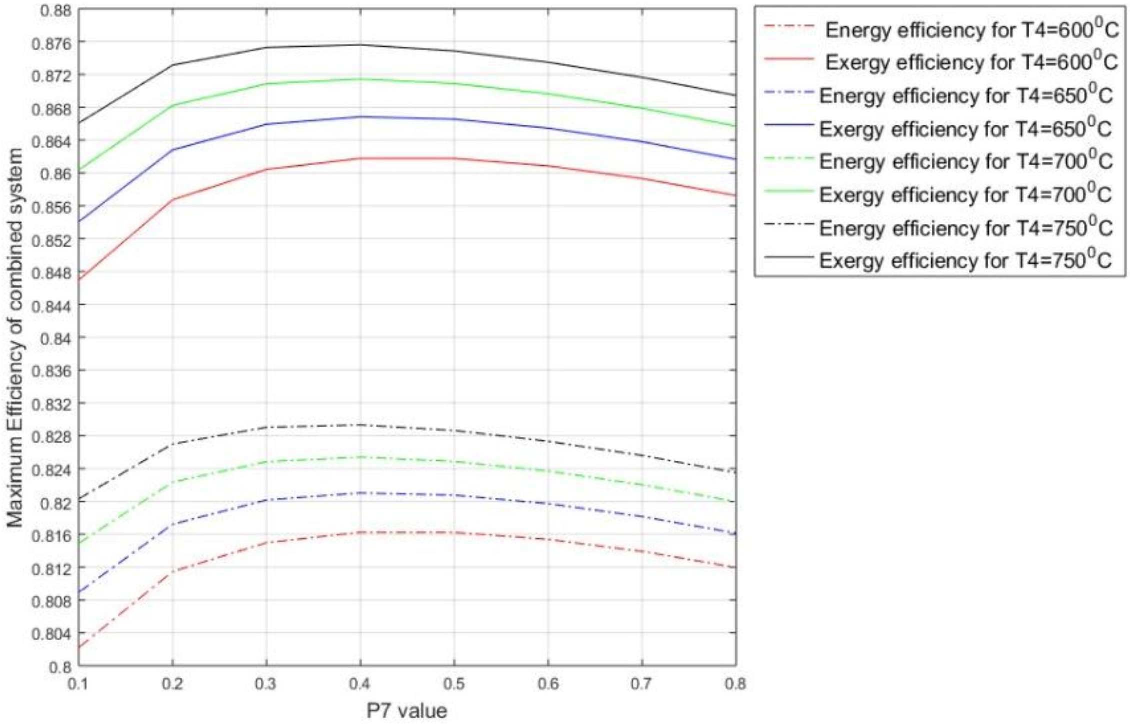


Fig 4 (b) Maximum Efficiency of combined system vs. P_7 value (back pressure of low pressure turbine)

Maximum efficiency is compared at different T_4 values against different turbine back pressure,P_7 as in the figure.

It is found that maximum efficiency occurs at P_7=0.4 for all T_4 values.

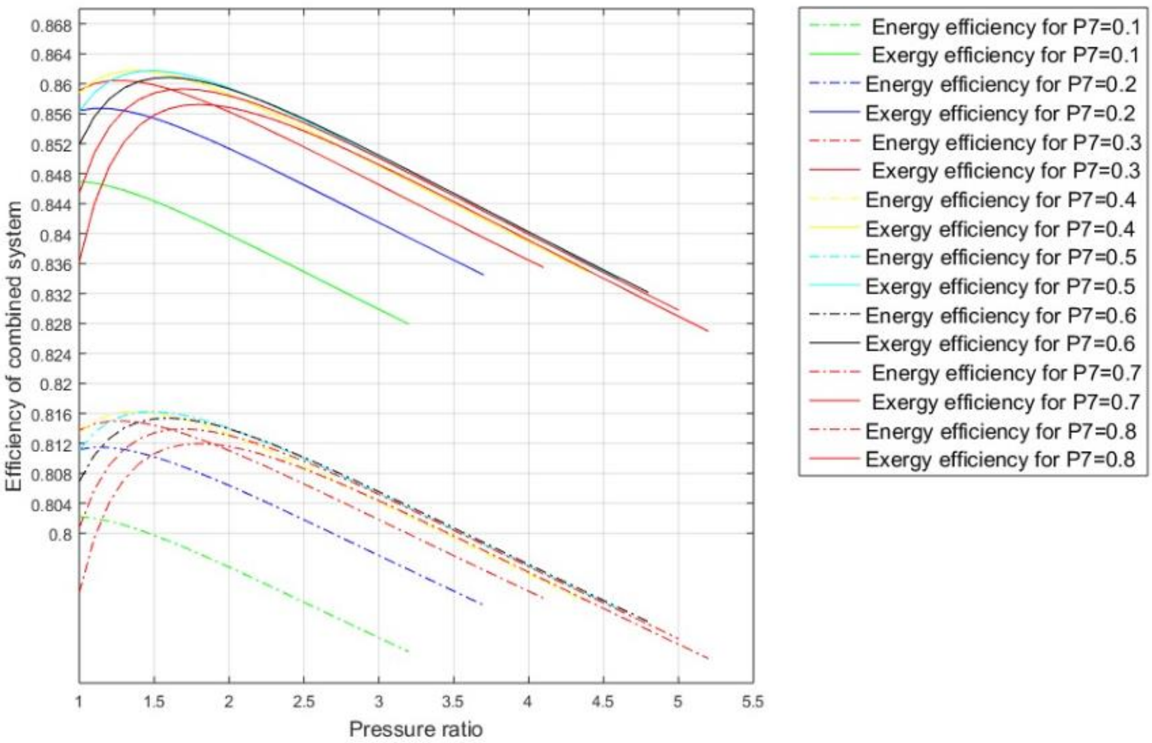


Fig 4 (c) Efficiency of combined system vs. Pressure ratio for different P_7 values (back pressure of low pressure turbine)

Maximum efficiency is compared at different P_7 values against different pressure ratios as in the figure.

It is found that maximum efficiency occurs at $P_7=0.4$ for pressure ratio value nearly 1.4.

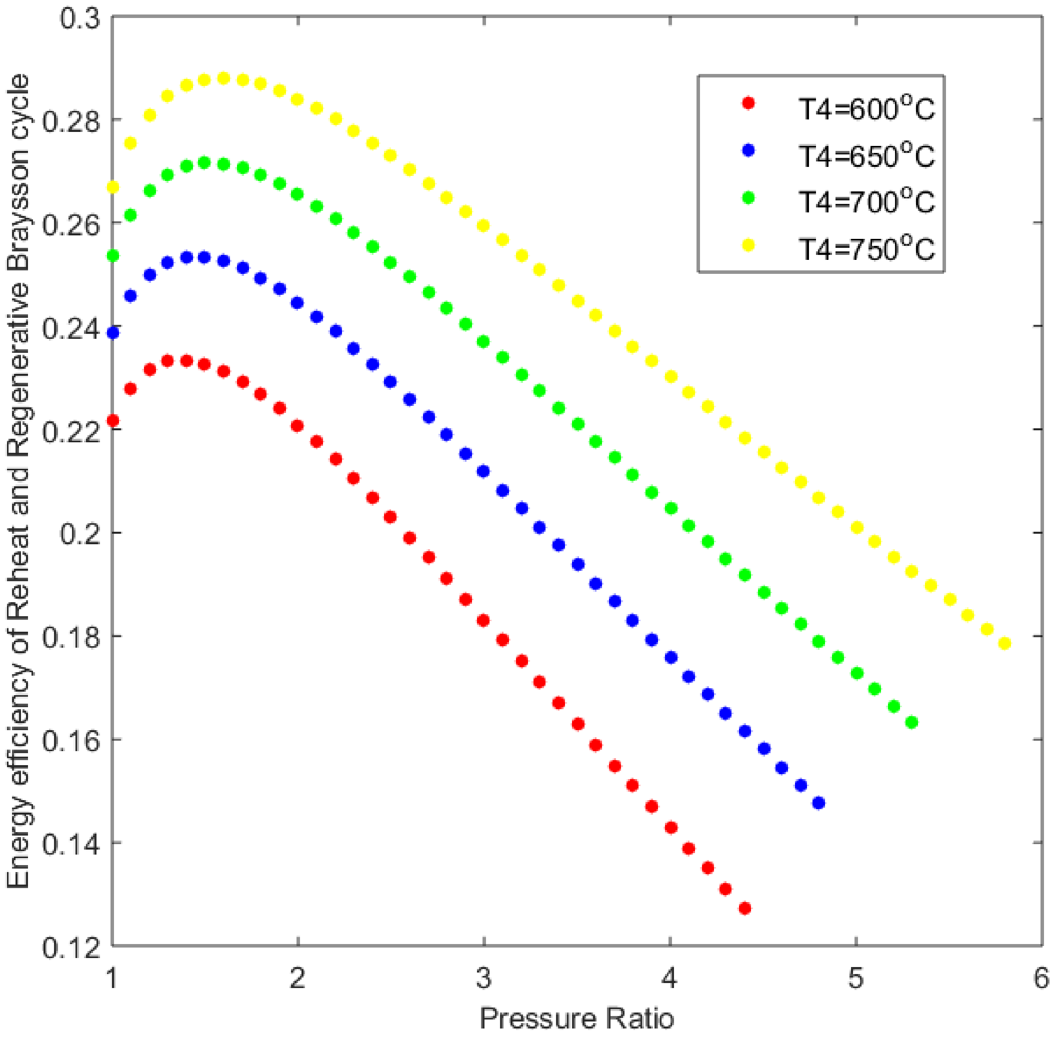


Fig 4.1 Energy efficiency of Reheat and Regenerative Braysson cycle vs. Pressure ratio at different TIT

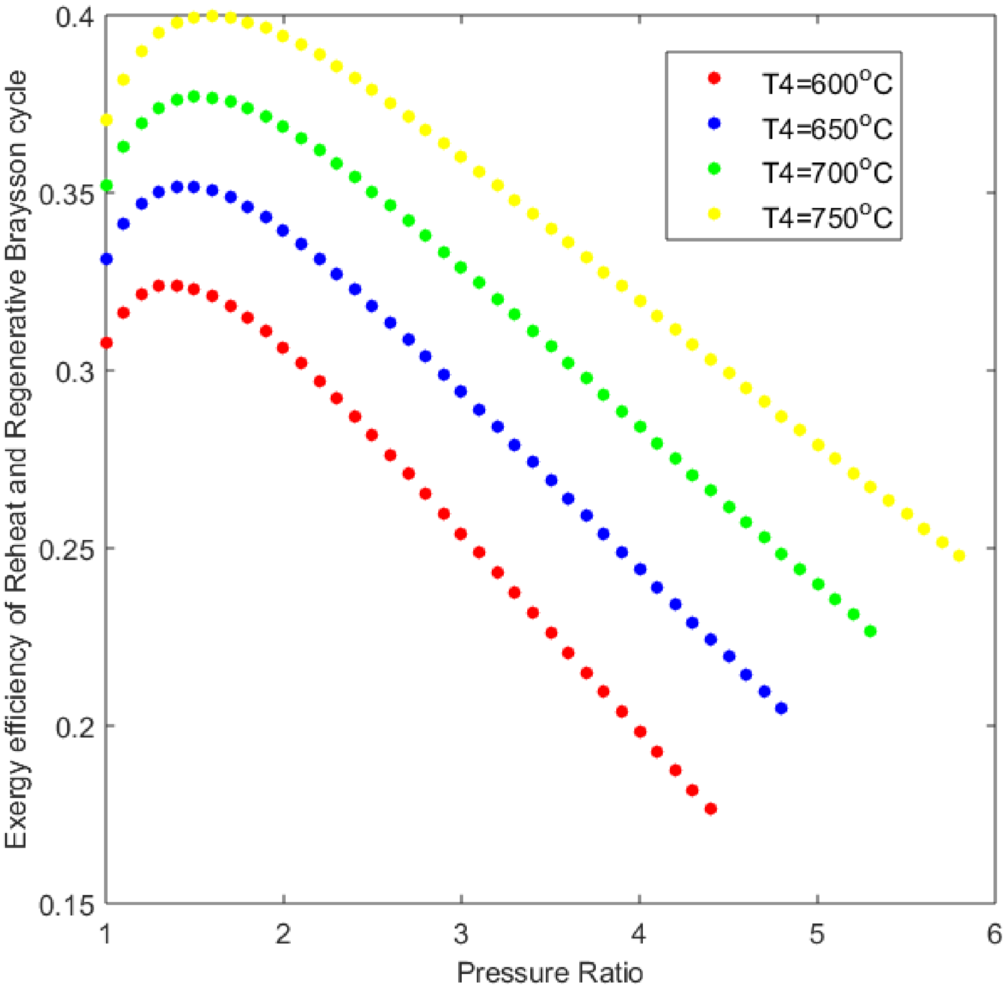


Fig 4.2 Exergy efficiency of Reheat and Regenerative Braysson cycle vs. Pressure ratio at different TIT

It has been observed that there is a limiting pressure ratio, when regeneration is adopted. Though regeneration increases the thermal efficiency of the cycle, it imposes a limit on the maximum pressure ratio in the cycle. Pressure ratios higher than the limiting value would mean that the temperature of compressed air exceeds the temperature of gases at the exit of reheat turbine. In such eventuality, regeneration becomes impracticable. This can be observed from the figure 1.6.

As T_4 increases, corresponding value of limiting pressure ratio also increases. The reason for this is as T_4 increases the exit temperature of reheat turbine, T_7 also increases. So, the limiting condition for regeneration i.e $T_7>T_2$ is satisfied for higher pressure ratios also. Therefore, as the value of T_4 increases, corresponding value of limiting pressure ratio also increases.

Also, both the efficiencies increase abruptly with pressure ratio up to the optimum value, and thereafter decline gradually with further rise in pressure ratio as shown in the figures 4.1 and 4.2. For lesser pressure ratio, the work output of the turbines is minimal, though regeneration is effective and reduces the heat input from the external source. Therefore efficiencies increase up to an optimum value. At higher pressure ratios above the optimum value, the influence of regeneration diminishes, thereby lessening the cycle efficiency. It is because at higher pressure ratios T_2 increases. Also, T_7 decreases. So, the difference, (T_7-T_2) decreases. Hence, the range of regeneration, (T_3-T_2) decreases with increase in pressure ratio i.e regeneration becomes less effective.

As T_4 increases, both the energy and exergy efficiencies of the regenerative and reheat Braysson cycle increase. This is due to the fact that as T_4 (Turbine inlet temperature) increases, turbine gives more work output, as the gases expands over a higher range of temperatures.

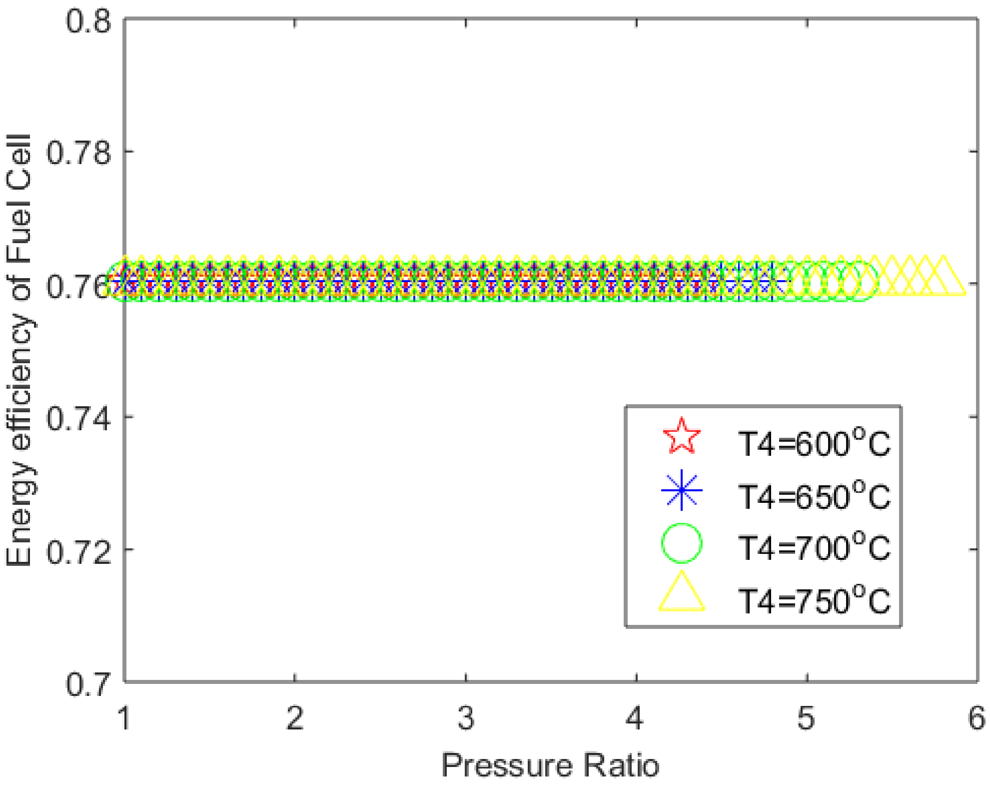


Fig 4.3 Energy efficiency of Fuel Cell vs. Pressure Ratio for different TIT

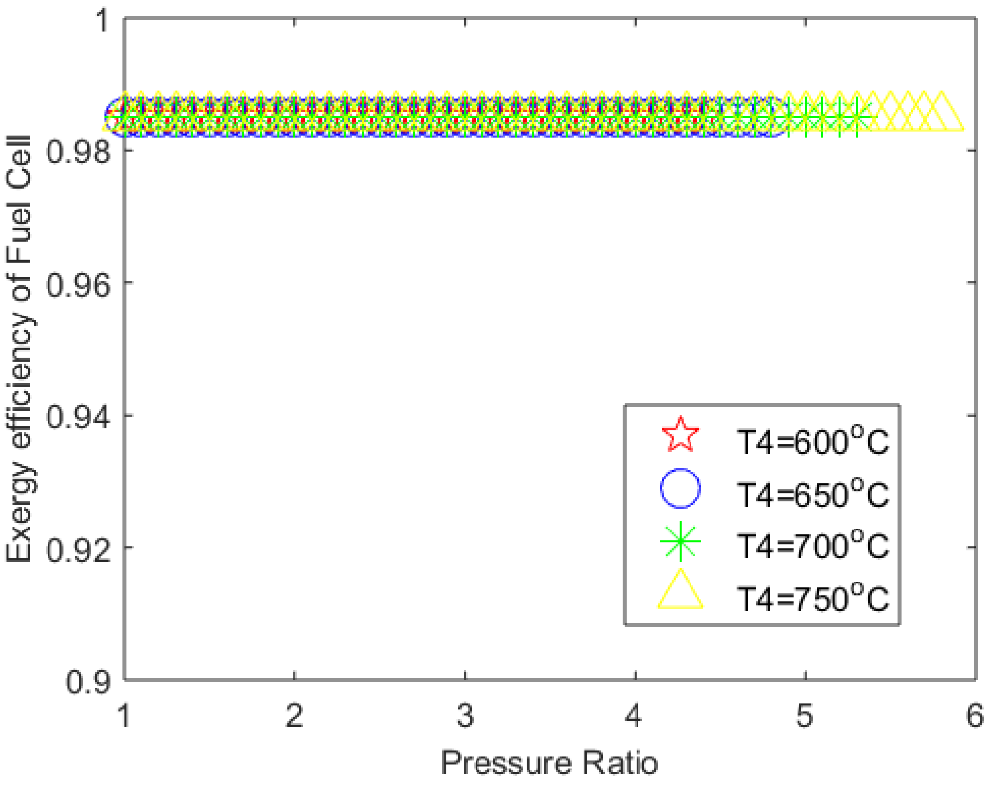


Fig 4.4 Exergy efficiency of Fuel Cell vs. Pressure Ratio for different TIT

Both the energy and exergy efficiencies of fuel cell are independent of pressure ratio as shown in the fig 4.3 & 4.4 since these terms are independent of mass flow rate of water in the fuel cell as shown in equations (9), (13), (18), (19).

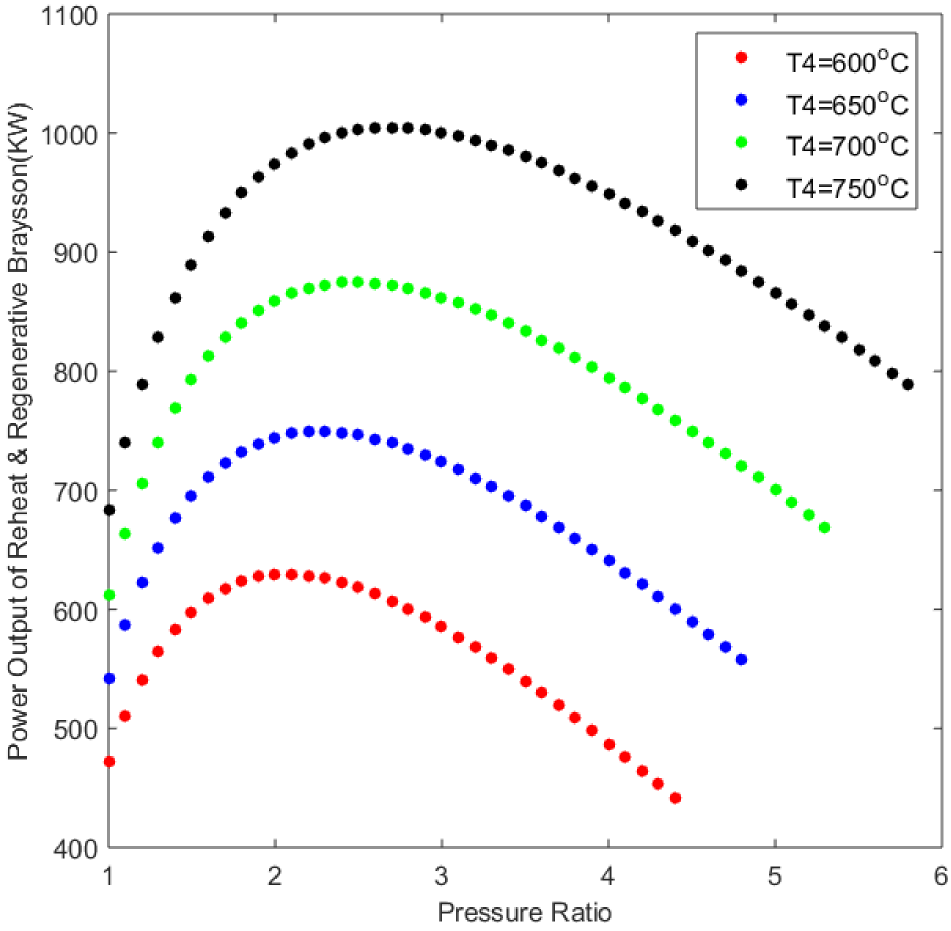


Fig 4.5 Power Output of Reheat & Regenerative Braysson Cycle vs. Pressure Ratio for different TIT

It can be observed from the figure 4.5 that as the pressure ratio increases power output from the Braysson cycle increases initially and then decreases, this is due to the fact that as the pressure ratio increases work output from turbines increase but at the same time, compressor work input is also increasing. Therefore, net power output from the Braysson cycle increases with pressure ration till an optimum value and then decreases.

As T_4 increases, work output of turbines increases and hence net power output increases with increasing T_4.

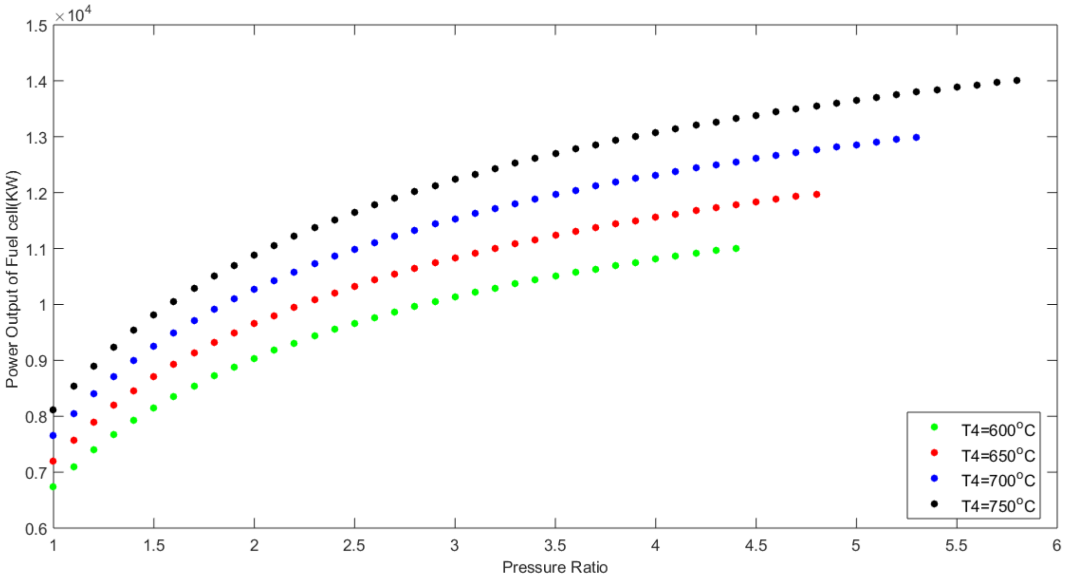


Fig 4.6 Power Output of Fuel Cell vs. Pressure Ratio for different TIT

It can be seen from the figure 4.6 that power output of fuel cell increases with increase in T_4 and with increase in pressure ratio.

As T4 increases, the difference, (T_4-T_3) increases and hence more heat is to be supplied to the Braysson cycle. Hence, the mass flow rate of water in the fuel cell must be more (eq 10) and hence power output of fuel cell also increases.

Also, as pressure ratio increases, power output of fuel cell increases. This is because as mentioned already in fig. 4.1 and 4.2, as pressure ratio increases, T_3 value decreases as regenerator becomes less effective. So, the difference (T_4-T_3) increases and thereby more heat is to supplied from the fuel cell. Hence, the mass flow rate increases thereby increasing the power output of fuel cell.

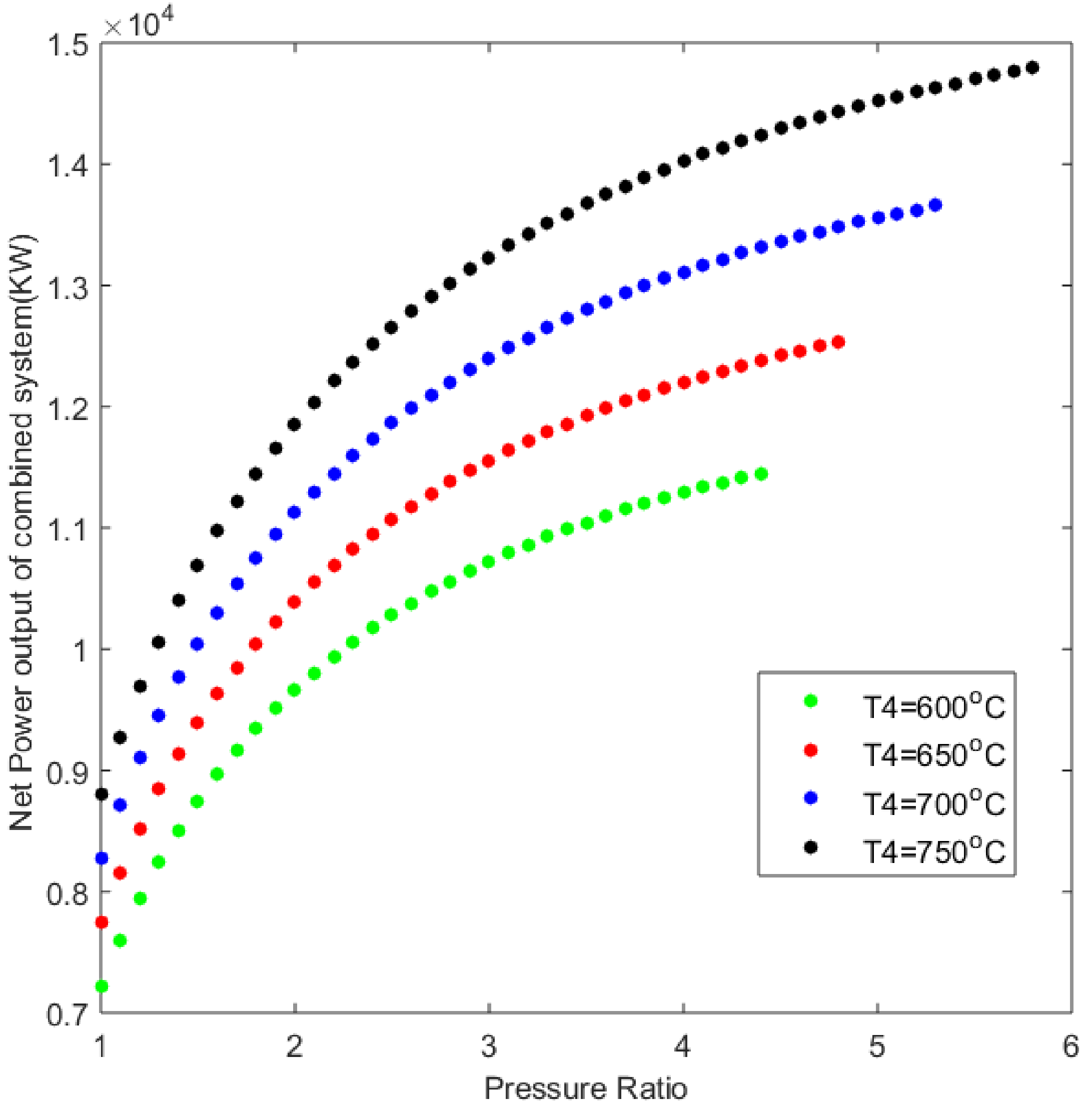


Fig 4.7 Net power output of combined system (KW) vs Pressure ratio for different TIT

The net power output of combined cycle increases with pressure ratio and TIT. Also, there does not exists an optimum pressure ratio because the effect of fuel cell is dominating (which showed increasing trend as given in fig-4.6) when compared to the Braysson cycle power output(which showed increasing and decreasing trend as given in fig- 4.5).

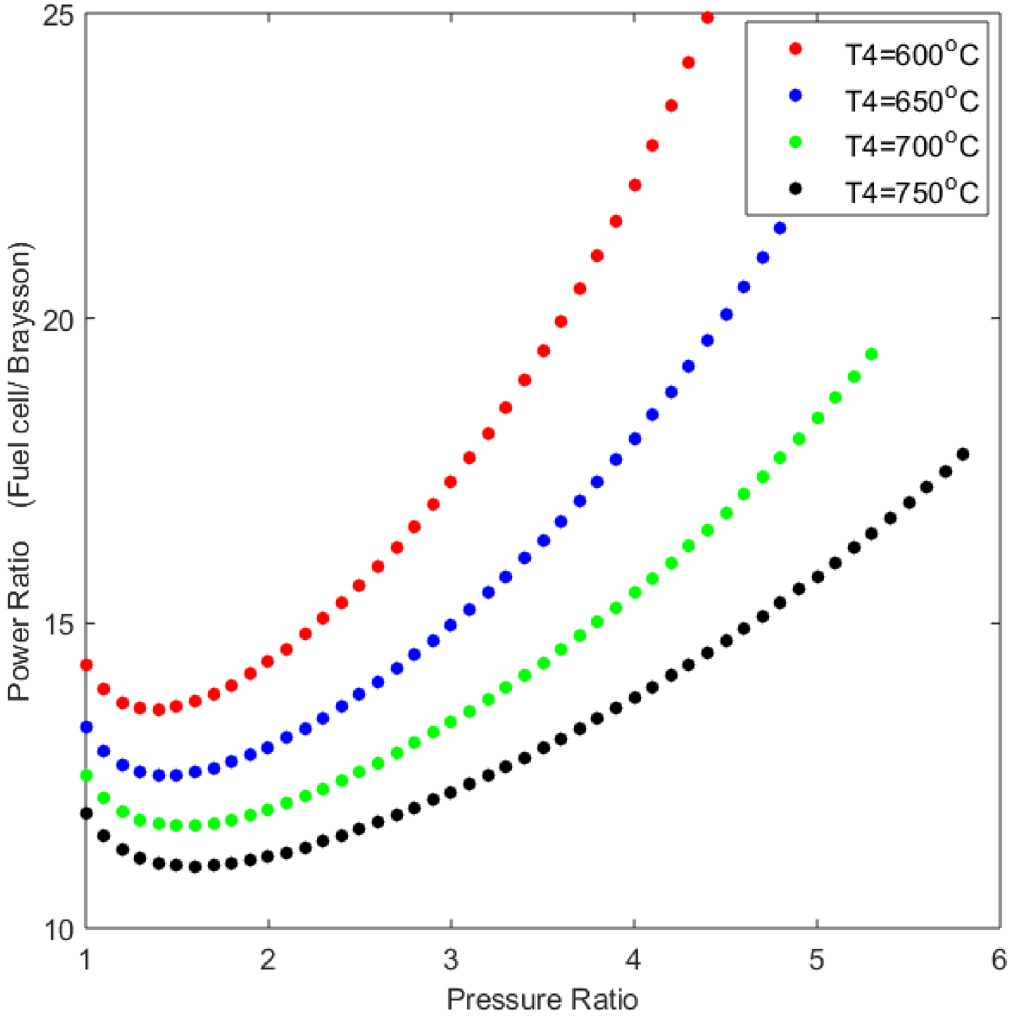


Fig 4.8 Power Ratio (Fuel cell/Braysson) vs. Pressure Ratio at different TIT

It can be observed from the figure 4.8 that power ratio (Fuel cell/Braysson cycle) first decreases till a particular pressure ratio and then increases.

Power outputs of both Braysson cycle and Fuel cell increase initially but the rate of increase in power output of Braysson cycle is more than that of the fuel cell with pressure ratio, these can be observed from the figures 4.6 & 4.7. So, the graph initially is decreasing. After a critical point, power output of Braysson cycle decreases and fuel cell increases with increase in pressure ratio. Therefore, the Power ratio (Fuel cell/Braysson cycle) graph keeps on increasing from then.

Power ratio (Fuel cell/Braysson cycle) decreases with increasing in TIT. This is because power outputs of both Braysson cycle and Fuel cell increase initially but the rate of increase in power output of Braysson cycle is more than that of the fuel cell with TIT.

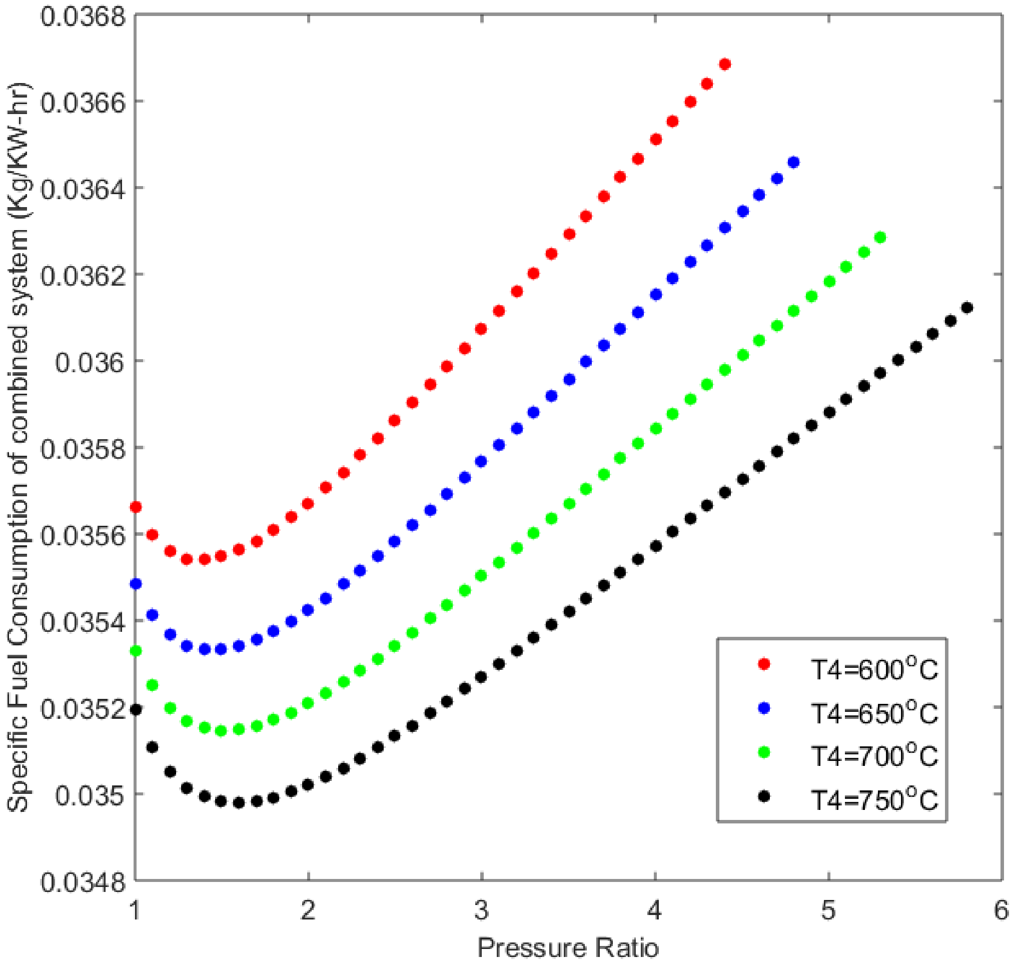


Fig 4.9 Specific Fuel Consumption of combined system(Kg/KW-hr) vs. Pressure Ratio at different TIT

It can be observed from the figure 4.9 that specific fuel consumption first decreases till a particular pressure ratio and then increases. It is because efficiencies first increase and then decrease with pressure ratio.

Specific fuel consumption decreases with increasing in T_4. It is because efficiencies increase with increase in T_4.

An optimum pressure ratio is found between 1 and 2 (nearly 1.4) where fuel consumption is least and efficiencies are maximum.

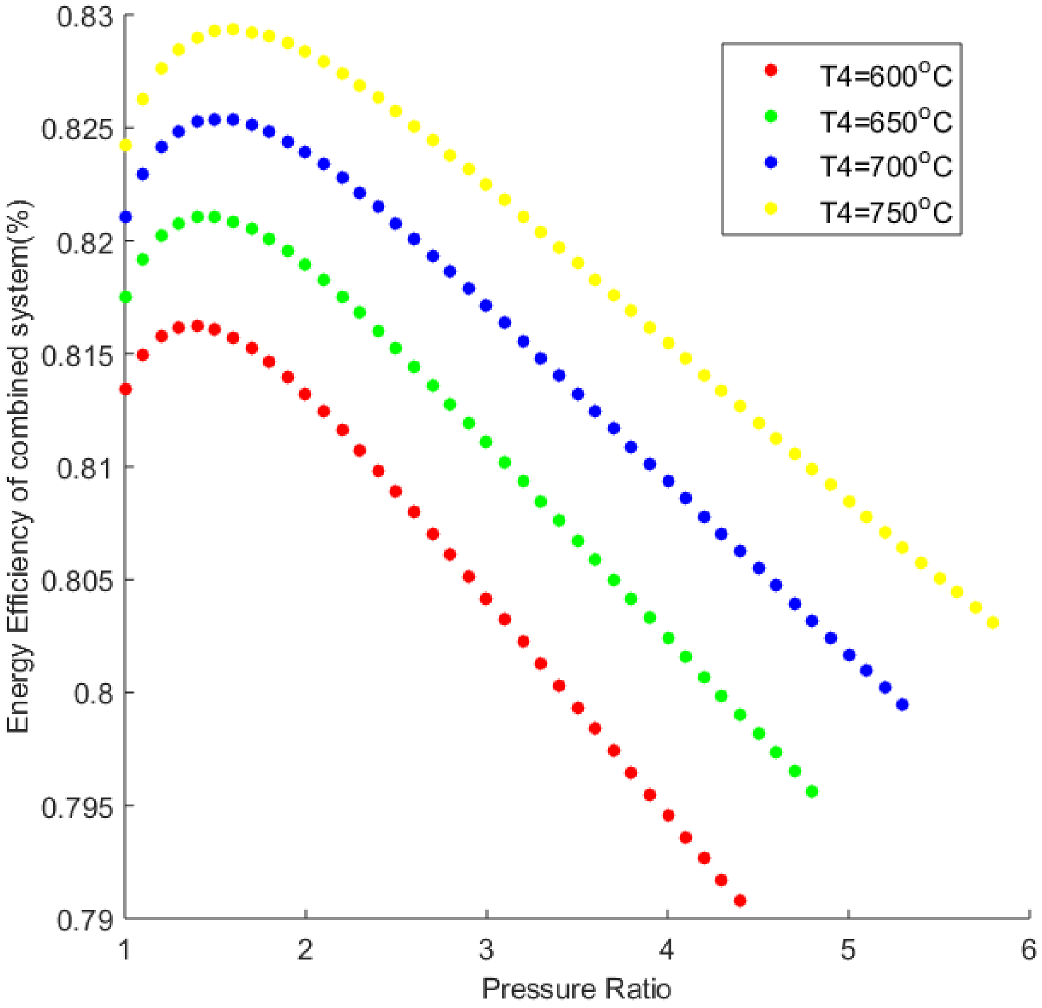


Fig 4.10 Energy Efficiency of combined system(%) vs. Pressure Ratio at different TIT

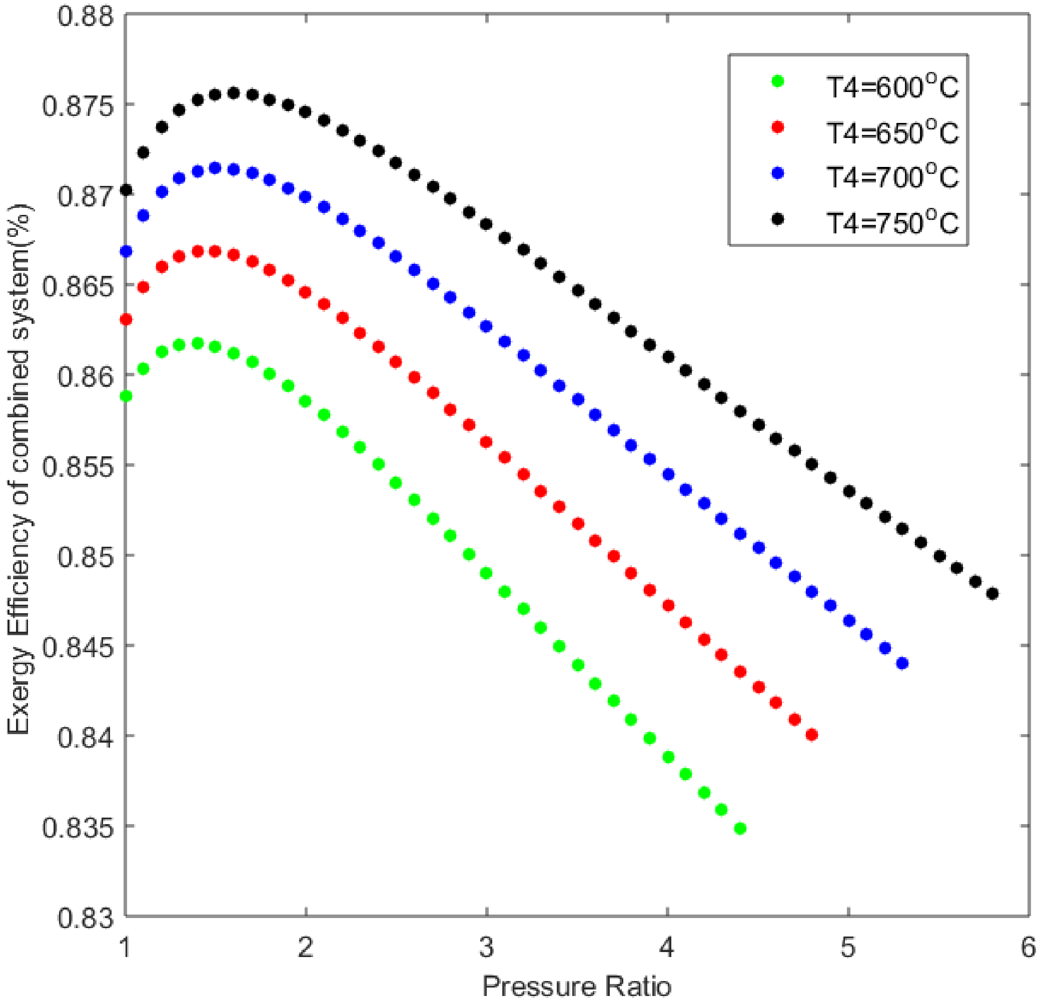


Fig 4.11 Exergy Efficiency of combined system(%) vs. Pressure Ratio at different TIT

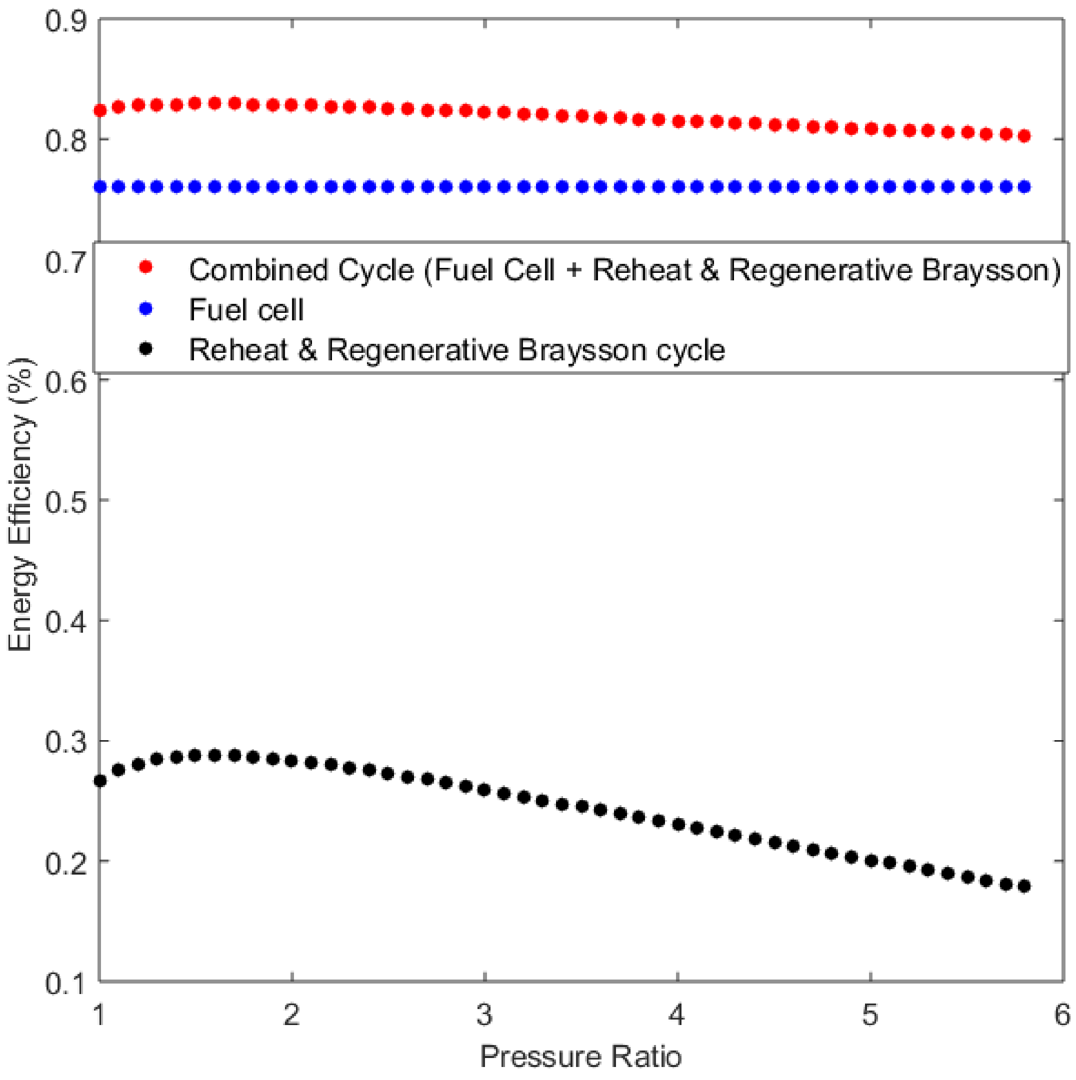


Fig 4.12 Energy Efficiency(%) vs Pressure Ratio

It can be observed from the figures 4.10, 4.11 & 4.12 that both the energy and exergy efficiencies of the combined cycle increase with increase in pressure ratio, then reach an optimum value and then decreases.

Both the energy and exergy efficiencies of the combined cycle increases with increase in T_4 value.

An optimum pressure ratio is found between 1 and 2 where maximum efficiency of the combined cycle is observed.

These plots are similar to those of the reheat and regenerative Braysson cycle because the energy and exergy efficiencies of the reheat and regenerative Braysson cycle depend upon pressure ratio and TIT as shown in figure 4.1 and 4.2 whereas these efficiencies of fuel cell as shown in figure 4.3 and 4.4 are independent of pressure ratio and TIT.

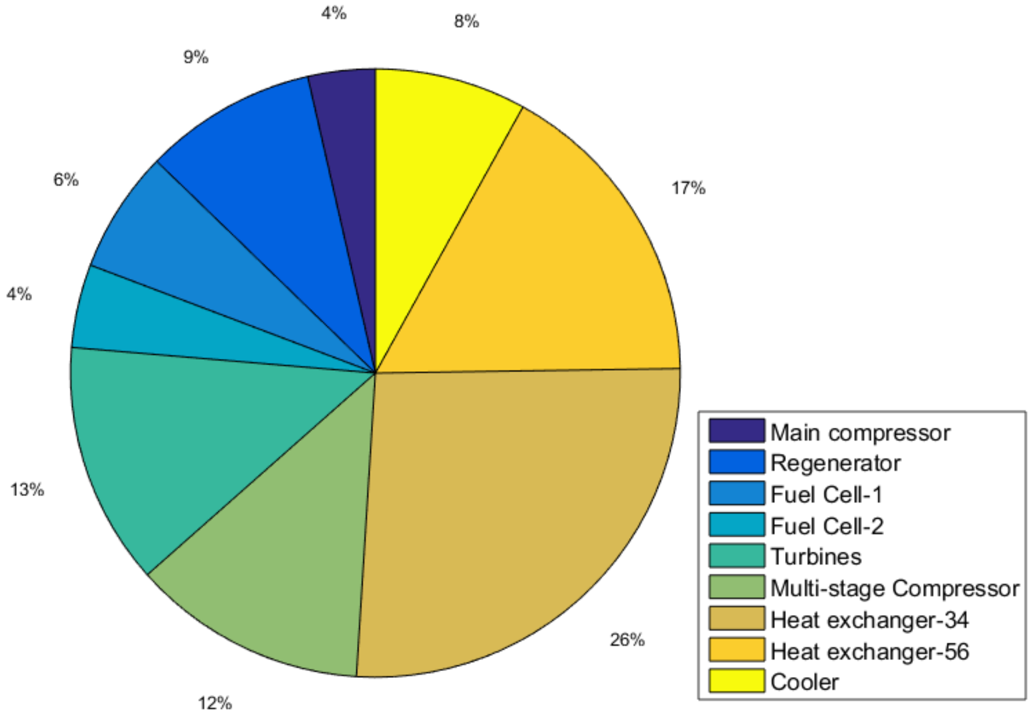


Fig 4.13 Pie chart representing component wise exergy destruction rates at an optimum pressure ratio of 1.4 and TIT=600 ^{o}C

Component wise exergy destruction rates at the optimum pressure ratio of 1.4 and T_4=600 ^{o}C value is shown in the figure 4.13.

It can be observed that most amount of exergy is destroyed in the cooler followed by the heat exchangers and then in turbines.

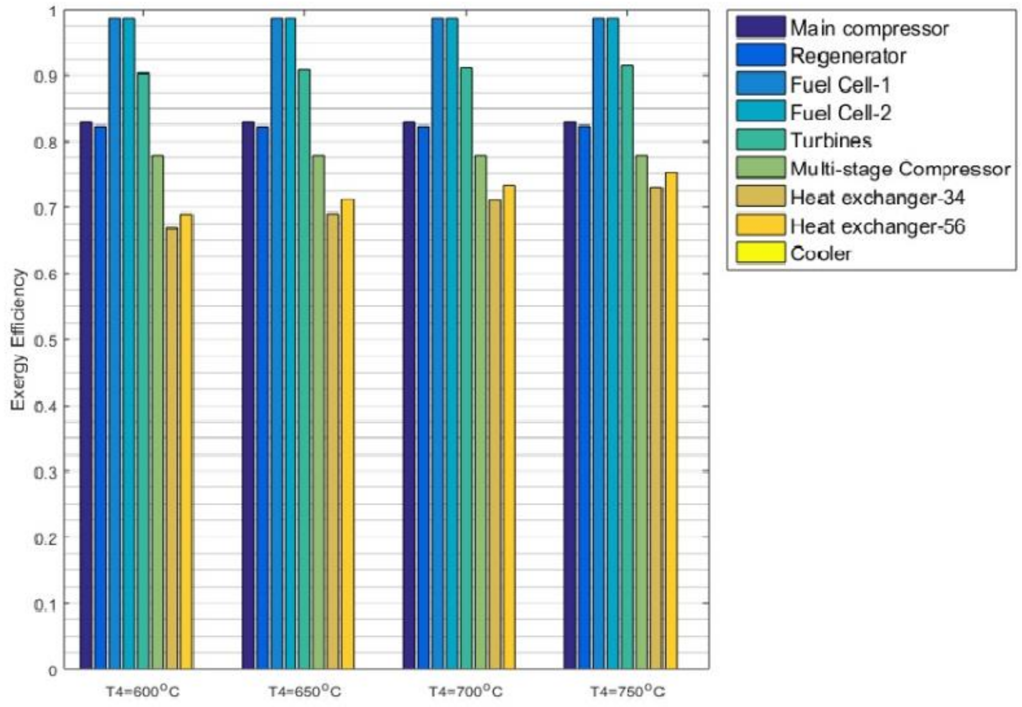


Fig 4.14 Bar chart representing component wise exergy efficiency rate at different TIT values at optimum pressure ratio of 1.4

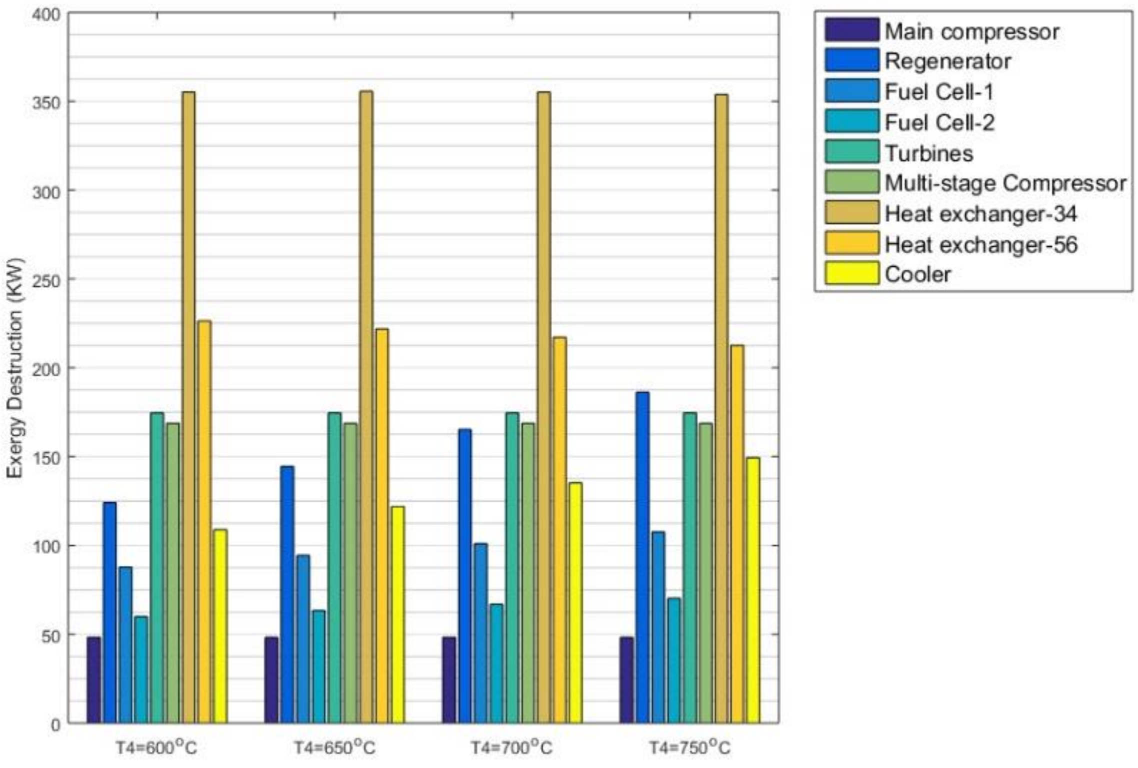


Fig 4.15 Bar chart representing component wise exergy destruction rate at different TIT values at optimum pressure ratio of 1.4

Figure 4.14 and 4.15 show component wise Exergy efficiency and Exergy destruction rate at different TIT values. The following observations are made from these charts:

Main Compressor: Exergy efficiency and exergy destruction of main compressor are independent of T_4 and hence remain constant.

Regenerator: Exergy efficiency is constant and exergy destruction rate increase with T_4 value. As T_4 increases, T_7 increases. So, irreversibilities increase as the difference (T_7-T_2) increases and hence exergy destruction of the regenerator increases.

Fuel Cells: Maximum exergy efficiency is found in fuel cells among all the components.

Exergy efficiency is constant because it is independent of mass flow rate in the fuel cell from equations (13), (18), (19) and exergy destruction rate increase with T_4 value because as T_4 increases, mass flow rate in the fuel cell increases since (T_4-T_3) increases from equation (10) thereby increasing the exergy destruction rate.

Turbines: Exergy destruction rate is constant with T_4 value since at a given pressure ratio, T_4/T_5 is constant and also pressure ratio, P_4/P_7 remains constant. Exergy efficiency increases since exergy recovered increases as T_4 increases and exergy destroyed remains constant since it is independent of T_4 as T_5 is a function of T_4 and r_{p1} is a constant from equations (12), (26) and (27).

Multi stage Compressor: Exergy efficiency and exergy destruction of main compressor are independent of T_4 and hence remain constant.

Heat exchangers: Exergy efficiency increases and exergy destruction rate decreases with T_4 value. In Heat exchangers, as the temperature difference between the source and working fluid decreases, the exergy efficiency of the heat exchangers increases.

Cooler: Exergy efficiency of cooler is zero and exergy destruction of cooler increases with increase in T_4 value. In cooler, the exergy of cooling water is not recovered and is lost as waste heat to the environment. Hence it can be concluded that the exergy efficiency of the cooler is zero.

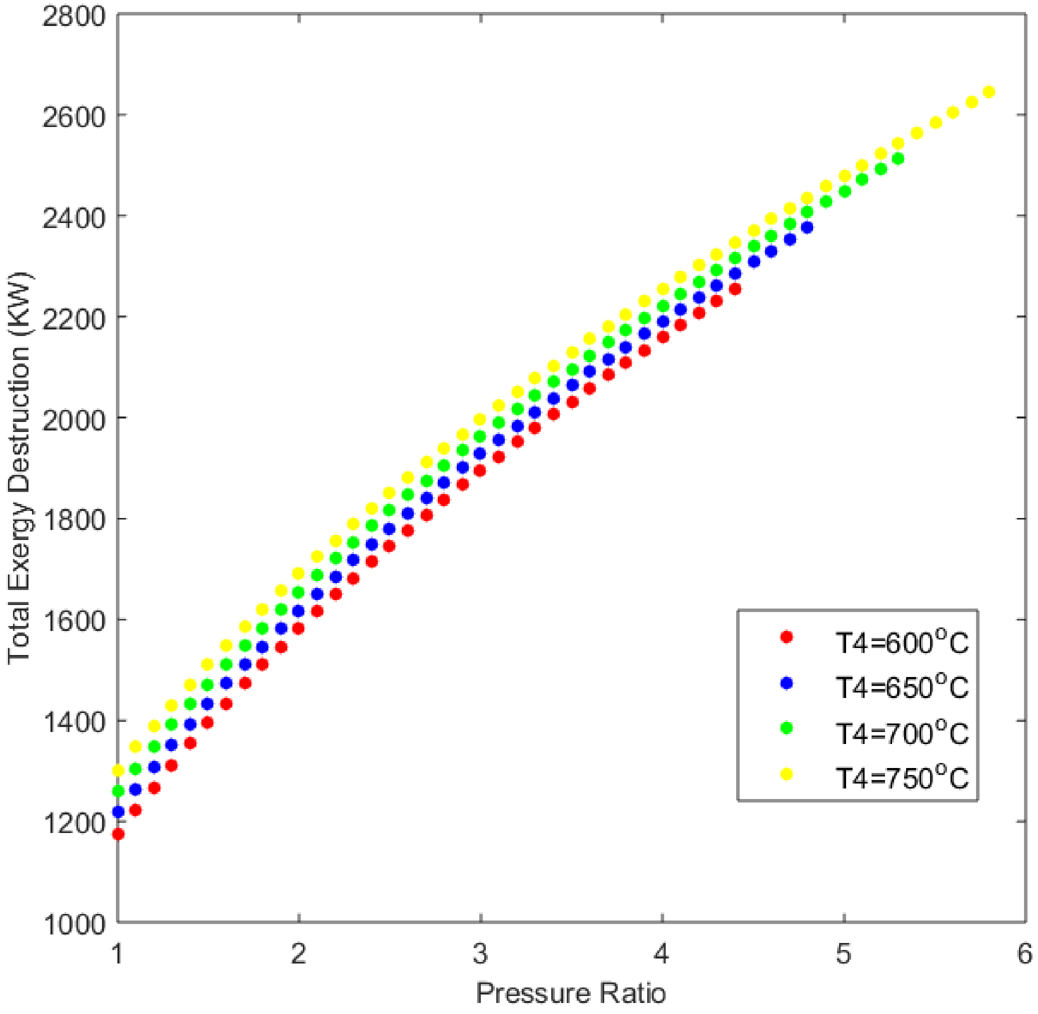


Fig 4.16 Total Exergy Destruction vs Pressure ratio at different TIT

It is found that as pressure ratio increases, total exergy destruction rate increases and as TIT increases, the total exergy destruction rate rate decreases.

Waste heat from fuel cell at 800 ^{O}C at TIT = 750 ^{O}C and r_p=1.4 from equation() is given by $(q_h * (\dot{m}_{f_1} + \dot{m}_{f_2}))$ = 3006.3 KW.The amount of work developed by reheat and regenerative Braysson cycle using this waste heat at TIT = 750 ^{O}C and r_p=1.4 is given by $(w_{o.p}\text{of Braysson} - w_{i.p}\text{ of Braysson})$ = 861.8KW. In 2014, an electrified Indian household consumed about 90 units (KWh) of electricity per month on an average i.e. 450 KJ of energy per hour; enough to run four tube-lights, four ceiling fans, a television, a small refrigerator, and small kitchen appliances with typical usage hours and efficiency levels in India[18]. Hence, if this power from the H_2-O_2 fuel cell – reheat and regenerative Braysson cycle is harnessed, it amounts to giving power to 6900 such homes whose power consumption is 90 units (KWh) per month.

CHAPTER 5

5. CONCLUSIONS

Waste heat recovery from an ideal H_2-O_2 fuel cell using a Reheat and Regenerative Braysson cycle is analysed in this work. The following important conclusions are made:

- As maximum cycle temperature increases, corresponding value of limiting pressure ratio also increases.
- It can be observed that both the energy and exergy efficiencies of the combined cycle increase with increase in pressure ratio, then reach an optimum value and then decreases.
- Both the energy and exergy efficiencies of the combined cycle increases with increase in maximum cycle temperature value.
- In the analysis, H_2-O_2 fuel cell is assumed to operate at 800^o C and the turbine inlet temperature (TIT) range of Braysson cycle is assumed as 600 to 750^oC. It has been observed that there exist different optimum pressure ratio values for maximum power output and maximum efficiencies.
- Both the energy and exergy efficiencies of fuel cell are independent of pressure ratio.
- The power obtained from the fuel cell is 12 to 25 times higher than the power obtained from the waste heat through Braysson depending on the pressure ratio and TIT.
- Even when pressure ratio of main compressor is 1, this Braysson cycle has an efficiency.
- The number of stages in the multistage compressor is fixed to 4.
- It is found that maximum efficiency occurs at back pressure of low pressure turbine at 0.4 bar for a pressure ratio value nearly 1.5.
- The combined system depicts energy efficiency in the range of 81.8% to 82.9% and that of the fuel cell is about 76%. Exergy destruction rates for the individual equipments and the total system are also obtained as a function of pressure ratio

and TIT. The exergy destruction rates are found to be maximum in the heat transfer equipment and minimum in the fuel cell.

- The waste heat from the H_2-O_2 fuel cell is found to be 3006.3 KW at turbine inlet temperature of 750^{o}C and at an optimum pressure ratio of 1.4. The power output of reheat and regenerative Braysson cycle obtained by recovering this waste heat is found to be 861.8 KW i.e. 31,02,480 KJ of energy per hour.

- In 2014, an electrified Indian household consumed about 90 units (KWh) of electricity per month on an average i.e. 450 KJ of energy per hour; enough to run four tube-lights, four ceiling fans, a television, a small refrigerator, and small kitchen appliances with typical usage hours and efficiency levels in India[18]. Hence, if this power from the H_2-O_2 fuel cell – reheat and regenerative Braysson cycle is harnessed, it amounts to giving power to 6900 such homes whose power consumption is 90 units (KWh) per month.

CHAPTER 6

6. FUTURE SCOPE

A combined system of Hydrogen (fuel)-Oxygen (oxidiser) fuel cell & reheat and regenerative Braysson cycle in order to recover the waste heat is studied in this work with the fuel cell temperature constant at 800^oC.

The same can be studied with different fuel cells like Phospohoric Acid Fuel cell (PAFC), Alkaline Fuel Cell (AFC), Solid Polymer Fuel Cell (SPFC), Molten Carbonate Fuel Cell (MCFC), Solid Oxide Fuel Cell (SOFC) etc.

Also, the study can be conducted with the fuel cells operating at different temperatures.

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APPENDIX

MATLAB CODE

Main Programme:

```
T=800+273.15;
T1=300;
%t4=700;
j=1;
for t4=600:50:750
T4=t4+273.15;
p7=0.4;
pat=1.013;
eta1c=0.8;
N=4;
deltaG=10483.33; % value at 800 degree celcius (KJ/kg);
deltaH=13788.8;% value at 800 degree celcius (KJ/kg);
cesh2=116557;%chemical exergy supplied for H2 (KJ/kg);
ceso=123.3;%chemical exergy supplied for O2 (KJ/kg);
Cph=5.19;%CP of helium in KJ/kgK;
mf=1;%mf is mass flow rate of braysson = 1kg/s;
qh=(deltaH-deltaG); % qh is heat from fuel cell;
etareg=0.8;
etat=0.8;
etac=0.8;
%rp=4;
gama=1.667;
T6=T4;
T9=T1;
T0=T1;
%for N=1:1:100
i=1;
for rp=1:.1:100
    p4=rp*pat;
    rp1=sqrt(p4/p7);
    rpo=pat/p7;
T2=T1+T1*(rp^((gama-1)/gama)-1)/etac;

T5=T4+etat*T4*(rp1^((1-gama)/(gama))-1);
if T2<T5
    pr(i,1)=rp;
T7=T5;
T3=etareg*(T7-T2)+T2;
T8=T7-T3+T2;
%if T3<T8
Ta=T9+(T9*((rpo^((gama-1)/(N*gama)))-1)/eta1c);
mfh2o1=mf*Cph*((T4-T3))/(qh*0.8);
mfh2o2=mf*Cph*((T6-T5))/(qh*0.8);
mfh21=(1/9)*mfh2o1;
mfh22=(1/9)*mfh2o2;
mfo1=8*mfh21;
mfo2=8*mfh22;

esc=Cph*(T2-T1);%Exergy supplied for compressor;
erc=Cph*(T2-T1)-T0*Cph*(log(T2/T1)-((gama-1)*log(rp)/gama));%Exergy
recovered;
edc=esc-erc;%Exery destroyed;
eeffc=erc/esc;%Exergy efficiency of compressor;
```

```
%Exergy efficiency of regenerator;
eeffr=((T3-T2)-T0*log(T3/T2))/((T7-T8)-T0*log(T7/T8));
edr=Cph*((T7-T8)-T0*log(T7/T8))-Cph*((T3-T2)-T0*log(T3/T2));

%Exergy efficiency of fuel cell;

eefffc1=(mfh2o1*((qh)*(1-
(T0/T))+deltaG))/((mfh21*cesh2)+(mfo1*ceso));
eefffc2=(mfh2o2*((qh)*(1-
(T0/T))+deltaG))/((mfh22*cesh2)+(mfo2*ceso));
eeffwoqhfc1=(mfh2o1*(deltaG))/((mfh21*cesh2)+(mfo1*ceso));
eeffwoqhfc2=(mfh2o2*(deltaG))/((mfh22*cesh2)+(mfo2*ceso));
edfc1=((mfh21*cesh2)+(mfo1*ceso))-(mfh2o1*((qh)*(1-(T0/T))+deltaG));
edfc2=((mfh22*cesh2)+(mfo2*ceso))-(mfh2o2*((qh)*(1-(T0/T))+deltaG));
edfwoqhc1=((mfh21*cesh2)+(mfo1*ceso))-(mfh2o1*(deltaG));
edfwoqhc2=((mfh22*cesh2)+(mfo2*ceso))-(mfh2o2*(+deltaG));
edwh1=mfh2o1*0.2*(qh)*(1-(T0/T));%exergy destruction by gases(waste
heat) in fuel cell
edwh2=mfh2o2*0.2*(qh)*(1-(T0/T));
%Exergy efficiency of Turbine;
est=2*(Cph*(T4-T5)-Cph*T0*(log(T4/T5)-((gama-1)*log(rp1)/gama)));
ert=2*(Cph*(T4-T5));
edt=est-ert;
eefft=ert/est;

%Exergy efficiency of multistage compressor with intercooling;
first=N*Cph*T9*(rpo^((gama-1)/(gama*N))-1)/eta1c;
sec=-N*Cph*T0*(log(1+((rpo^((gama-1)/(gama*N))-1)/eta1c)));
thir=(N*Cph*T0*(gama-1)*log(rpo))/(gama*N);
ermc=first+sec+thir;
%ermc=N*Cph*((T9*(rpo^((gama-1)/(gama*N))-1))/eta1c)-
T0*log(1+((rpo^((gama-1)/(gama*N))-1))/eta1c)+T0*((gama-
1)*log(rpo)/(gama*N)));
ermi=(N-1)*Cph*((Ta-T9)-T0*log(1+((rpo^((gama-1)/(gama*N))-
1))/eta1c));
ermct=ermc-ermi;
esmct=N*Cph*(Ta-T9);
edmct=esmct-ermct;
eeffmct=ermct/esmct;
%exergy in heating of the fluid (3-4)& (5-6) process
erhf34=Cph*((T4-T3)-T0*(log(T4/T3)));
eshf34=mfh2o1*(qh)*(1-(T0/T));
edhf34=eshf34-erhf34;
eehf34=erhf34/eshf34;

erhf56=Cph*((T6-T5)-T0*(log(T6/T5)));
eshf56=mfh2o2*(qh)*(1-(T0/T));
edhf56=eshf56-erhf56;
eehf56=erhf56/eshf56;
edcool=Cph*((T8-T9)-T0*log(T8/T9));

Wopb=Cph*(T4-T5)+Cph*(T6-T7);

Winb=Cph*(T2-T1)+N*Cph*(Ta-T9);

Wopf=(mfh2o1+mfh2o2)*deltaG;

Qin=deltaH*(mfh2o1+mfh2o2);
```

```
%Effb=Wopb/qh;
%p=Wopb-Winb;
Efff=deltaG/deltaH;
%Effb=(Wopb-Winb)/Qin;
%Effov=(Wopb+Wopf-Winb)/Qin;
Effb=(Wopb-Winb)/(qh*(mfh2o1+mfh2o2));
Effov=(Wopb+Wopf-Winb)/Qin;
%Total Exergy efficiency of Braysson and Fuel cell cycle;
tes=((mfh21*cesh2)+(mfo1*ceso))+((mfh22*cesh2)+(mfo2*ceso));%total
exergy supplied;
NW=Wopb+Wopf-Winb;
NWB=Wopb-Winb;
TFC=(mfh21+mfh22)*3600;
SFC=TFC/NW;
Workratio=Wopf/NWB;
eeffov=(Wopb+Wopf-
Winb)/(((mfh21*cesh2)+(mfo1*ceso))+((mfh22*cesh2)+(mfo2*ceso)));
Texd=(1-eeffov)*tes;%Total Exergy Destroyed;

ted=edc+edr+edfc1+edfc2+edt+edmct+edhf34+edhf56+edcool;%sum of
exergy destruction of individual;

difference=Texd-ted;
percentage=difference*100/tes;
%plot(rp,Effov,'b.',rp,Efff,'r.',rp,Effb,'g.')
%plot(rp,eeffov,'m.')
%plot(rp,eeffov,'r.',rp,Effov,'b.')

%hold on
tesb=eshf34+eshf56;
erb=NWB;
eeffb=erb/tesb;

ted1(i,1)=ted;
eeffb1(i,1)=eeffb;
eefffc11(i,1)=eefffc1;
eefffc21(i,1)=eefffc2;

Effov1(i,1)=Effov;
eeffov1(i,1)=eeffov;
Efff1(i,1)=Efff;
Effb1(i,1)=Effb;
WR(i,1)=Workratio;
SFC1(i,1)=SFC;
Wopf1(i,1)=Wopf;
NWB1(i,1)=NWB;
NW1(i,1)=NW;
i=i+1;
else
%end
%else
end
if t4==600
    if rp==1.4

    figure(6)
    fig = figure(6);
u = fig.Color;
fig.Color = 'w';
pie([edc edr edfc1 edfc2 edt edmct edhf34 edhf56 edcool])
```

```
legend({'Main compressor','Regenerator','Fuel Cell-1','Fuel Cell-
2','Turbines','Multi-stage Compressor','Heat exchanger-34','Heat
exchanger-56','Cooler'},'location','best','fontsize',13)
    end
end
hold on
end
edc1(j,1)=edc;
edr1(j,1)=edr;
edfc11(j,1)=edfc1;
edfc21(j,1)=edfc2;
edt1(j,1)=edt;
edmct1(j,1)=edmct;
edhf341(j,1)=edhf34;
edhf561(j,1)=edhf56;
edcool1(j,1)=edcool;
eeffc1(j,1)=eeffc;
eeffr1(j,1)=eeffr;
eefffc11(j,1)=eefffc1;
eefffc21(j,1)=eefffc2;
eefft1(j,1)=eefft;
eeffmct1(j,1)=eeffmct;
eehf341(j,1)=eehf34;
eehf561(j,1)=eehf56;
eecool(j,1)=0;
j=j+1;
figure(1)
fig = figure(1);
u = fig.Color;
fig.Color = 'w';

%p=plot(pr,Effov1,'k.',pr,Efff1,'r.','markersize',8);
if t4==600
    plot(pr,Effov1,'r.','markersize',20);
%p(1).Marker = '*';
%p(2).Marker = '*';
end
if t4==650
    plot(pr,Effov1,'g.','markersize',20);
%p(1).Marker = 'o';
%p(2).Marker = 'o';
end
if t4==700
    plot(pr,Effov1,'b.','markersize',20);
%p(1).Marker = '.';
%p(2).Marker = '.';
end
if t4==750
    plot(pr,Effov1,'y.','markersize',20);
%p(1).Marker = 'p';
%p(2).Marker = 'p';
end
legend({' T4=600^{o}C',' T4=650^{o}C',' T4=700^{o}C','
T4=750^{o}C'},'location','best','fontsize',13)

%legend({'Hybrid Cycle (Fuel Cell + Reheat & Regenerative
Braysson)','Fuel Cell'},'location','best','fontsize',13)
xlabel('Pressure Ratio','fontsize',13)
ylabel('Energy Efficiency of combined system(%)','fontsize',13)
%axis([1 5 0.73 0.83])
axis square
```

```
ax = gca;
c = ax.FontSize;
ax.FontSize = 13;
hold on
figure(2)
fig = figure(2);
u = fig.Color;
fig.Color = 'w';
%p2=plot(pr,Effov1,'g.',pr,eeffov1,'r.','markersize',8)
if t4==600
    plot(pr,eeffov1,'g.','markersize',20)
%p2(1).Marker = '*';
%p2(2).Marker = '*';
end
if t4==650
    plot(pr,eeffov1,'r.','markersize',20)
%p2(1).Marker = 'o';
%p2(2).Marker = 'o';
end
if t4==700
    plot(pr,eeffov1,'b.','markersize',20)
%p2(1).Marker = '.';
%p2(2).Marker = '.';
end
if t4==750
    plot(pr,eeffov1,'k.','markersize',20)
%p2(1).Marker = 'p';
%p2(2).Marker = 'p';
end
legend({' T4=600^{o}C',' T4=650^{o}C',' T4=700^{o}C','
T4=750^{o}C'},'location','best','fontsize',13)

%legend({'Energy efficiency of Hybrid cycle','Exergy efficiency of
Hybrid cycle'},'location','best','fontsize',13)
xlabel('Pressure Ratio','fontsize',13)
ylabel('Exergy Efficiency of combined system(%) ','fontsize',13)
%axis([1 5 0.8 0.88])
axis square
ax = gca;
c = ax.FontSize;
ax.FontSize = 13;
hold on
if t4==750
figure(3)
fig = figure(3);
u = fig.Color;
fig.Color = 'w';
plot(pr,Effov1,'r.',pr,Efff1,'b.',pr,Effb1,'k.','markersize',20)
legend({'Combined Cycle (Fuel Cell + Reheat & Regenerative
Braysson)','Fuel cell','Reheat & Regenerative Braysson
cycle'},'location','best','fontsize',13)
xlabel('Pressure Ratio','fontsize',13)
ylabel('Energy Efficiency (%) ','fontsize',13)
%axis([1 5 0.1 0.88])
axis square
ax = gca;
c = ax.FontSize;
ax.FontSize = 13;
hold on
end
figure(4)
```

```
fig = figure(4);
u = fig.Color;
fig.Color = 'w';
%p4=plot(pr,WR,'k.','markersize',8)
if t4==600
    plot(pr,WR,'r.','markersize',20)
%p4(1).Marker = '*';

end
if t4==650
    plot(pr,WR,'b.','markersize',20)
%p4(1).Marker = 'o';

end
if t4==700
    plot(pr,WR,'g.','markersize',20)
%p4(1).Marker = '.';
end
if t4==750
    plot(pr,WR,'k.','markersize',20)
%p4(1).Marker = 'p';
end
%legend({'Powerratio of Fuel cell Vs Reheat & Regenerative Braysson
cycle'},'location','best','fontsize',13)
xlabel('Pressure Ratio','fontsize',13)
ylabel('Power Ratio    (Fuel cell/ Braysson)','fontsize',13)
legend({' T4=600^{o}C',' T4=650^{o}C',' T4=700^{o}C','
T4=750^{o}C'},'location','best','fontsize',13)
%axis([1 5 0.1 0.88])
axis square
ax = gca;
c = ax.FontSize;
ax.FontSize = 13;
hold on
figure(5)
fig = figure(5);
u = fig.Color;
fig.Color = 'w';
%p5=plot(pr,SFC1,'k.','markersize',8)
if t4==600
    plot(pr,SFC1,'r.','markersize',20)
%p5(1).Marker = '*';

end
if t4==650
    plot(pr,SFC1,'b.','markersize',20)
%p5(1).Marker = 'o';

end
if t4==700
    plot(pr,SFC1,'g.','markersize',20)
%p5(1).Marker = '.';
end
if t4==750
    plot(pr,SFC1,'k.','markersize',20)
%p5(1).Marker = 'p';
end
%legend({'Powerratio of Fuel cell Vs Reheat & Regenerative Braysson
cycle'},'location','best','fontsize',13)
xlabel('Pressure Ratio','fontsize',13)
```

```
ylabel('Specific Fuel Consumption of combined system (Kg/KW-
hr)','fontsize',13)
legend({' T4=600^{o}C',' T4=650^{o}C',' T4=700^{o}C','
T4=750^{o}C'},'location','best','fontsize',13)
%axis([1 5 0.1 0.88])
axis square
ax = gca;
c = ax.FontSize;
ax.FontSize = 13;
hold on
%pause

figure(7)
fig = figure(7);
u = fig.Color;
fig.Color = 'w';
%p7=plot(pr,Wopf1,'g.',pr,NWB1,'r.','markersize',8)
if t4==600
    plot(pr,Wopf1,'g.','markersize',20)
%p7(1).Marker = '*';
%p7(2).Marker = '*';
end
if t4==650
    plot(pr,Wopf1,'r.','markersize',20)
%p7(1).Marker = 'o';
%p7(2).Marker = 'o';
end
if t4==700
    plot(pr,Wopf1,'b.','markersize',20)
%p7(1).Marker = '.';
%p7(2).Marker = '.';
end
if t4==750
    plot(pr,Wopf1,'k.','markersize',20)
%p7(1).Marker = 'p';
%p7(2).Marker = 'p';
end
%legend({'Energy efficiency of Hybrid cycle','Exergy efficiency of
Hybrid cycle'},'location','best','fontsize',13)
xlabel('Pressure Ratio','fontsize',13)
ylabel('Power Output of Fuel cell(KW) ','fontsize',13)
legend({' T4=600^{o}C',' T4=650^{o}C',' T4=700^{o}C','
T4=750^{o}C'},'location','best','fontsize',13)
axis([1 6 6000 15000])
%axis square
ax = gca;
c = ax.FontSize;
ax.FontSize = 13;
hold on
figure(8)
%plot(pr,NWB1,'r.','markersize',8)
fig = figure(8);
u = fig.Color;
fig.Color = 'w';
%p9=plot(pr,Efff1,'k.','markersize',8)
if t4==600
%p9(1).Marker = '*';
plot(pr,NWB1,'r.','markersize',20)
end
if t4==650
%p9(1).Marker = 'o';
```

```
plot(pr,NWB1,'b.','markersize',20)
end
if t4==700
%p9(1).Marker = '.';
plot(pr,NWB1,'g.','markersize',20)
end
if t4==750
%p9(1).Marker = 'p';
plot(pr,NWB1,'k.','markersize',20)
end
%legend({'Powerratio of Fuel cell Vs Reheat & Regenerative Braysson
cycle'},'location','best','fontsize',13)
xlabel('Pressure Ratio','fontsize',13)
ylabel('Power Output of Reheat & Regenerative
Braysson(KW)','fontsize',13)
legend({' T4=600^{o}C',' T4=650^{o}C',' T4=700^{o}C','
T4=750^{o}C'},'location','best','fontsize',13)
%axis([1 5 0.1 0.88])
axis square
%axis([1 6 .7 .8])
ax = gca;
c = ax.FontSize;
ax.FontSize = 13;
hold on
figure(9)
fig = figure(9);
u = fig.Color;
fig.Color = 'w';
%p9=plot(pr,Efff1,'k.','markersize',8)
if t4==600
%p9(1).Marker = '*';
plot(pr,Efff1,'rp','markersize',15)
end
if t4==650
%p9(1).Marker = 'o';
plot(pr,Efff1,'b*','markersize',15)
end
if t4==700
%p9(1).Marker = '.';
plot(pr,Efff1,'go','markersize',15)
end
if t4==750
%p9(1).Marker = 'p';
plot(pr,Efff1,'y^','markersize',15)
end
%legend({'Powerratio of Fuel cell Vs Reheat & Regenerative Braysson
cycle'},'location','best','fontsize',13)
xlabel('Pressure Ratio','fontsize',13)
ylabel('Energy efficiency of Fuel Cell','fontsize',13)
legend({' T4=600^{o}C',' T4=650^{o}C',' T4=700^{o}C','
T4=750^{o}C'},'location','best','fontsize',13)
%axis([1 5 0.1 0.88])
%axis square
axis([1 6 .7 .8])
ax = gca;
c = ax.FontSize;
ax.FontSize = 13;
hold on
figure(10)
fig = figure(10);
u = fig.Color;
```

```
fig.Color = 'w';
%p10=plot(pr,eefffc11,'k.','markersize',8)
if t4==600
%p10(1).Marker = '*';
plot(pr,eefffc11,'rp','markersize',15)
end
if t4==650
%p10(1).Marker = 'o';
plot(pr,eefffc11,'bo','markersize',15)
end
if t4==700
%p10(1).Marker = '.';
plot(pr,eefffc11,'g*','markersize',15)
end
if t4==750
%p10(1).Marker = 'p';
plot(pr,eefffc11,'y^','markersize',15)
end
%legend({'Powerratio of Fuel cell Vs Reheat & Regenerative Braysson
cycle'},'location','best','fontsize',13)
xlabel('Pressure Ratio','fontsize',13)
ylabel('Exergy efficiency of Fuel Cell','fontsize',13)
 legend({' T4=600^{o}C',' T4=650^{o}C',' T4=700^{o}C','
T4=750^{o}C'},'location','best','fontsize',13)
%axis([1 5 0.1 0.88])
%axis square
axis([1 6 .9 1])
ax = gca;
c = ax.FontSize;
ax.FontSize = 13;
hold on
figure(11)
fig = figure(11);
u = fig.Color;
fig.Color = 'w';
%p10=plot(pr,eefffc11,'k.','markersize',8)
if t4==600
%p10(1).Marker = '*';
plot(pr,Effb1,'r.','markersize',20)
end
if t4==650
%p10(1).Marker = 'o';
plot(pr,Effb1,'b.','markersize',20)
end
if t4==700
%p10(1).Marker = '.';
plot(pr,Effb1,'g.','markersize',20)
end
if t4==750
%p10(1).Marker = 'p';
plot(pr,Effb1,'y.','markersize',20)
end
%legend({'Powerratio of Fuel cell Vs Reheat & Regenerative Braysson
cycle'},'location','best','fontsize',13)
xlabel('Pressure Ratio','fontsize',13)
ylabel('Energy efficiency of Reheat and Regenerative Braysson
cycle','fontsize',13)
 legend({' T4=600^{o}C',' T4=650^{o}C',' T4=700^{o}C','
T4=750^{o}C'},'location','best','fontsize',13)
%axis([1 5 0.1 0.88])
axis square
```

```
%axis([1 6 .9 1])
ax = gca;
c = ax.FontSize;
ax.FontSize = 13;
hold on
figure(12)
fig = figure(12);
u = fig.Color;
fig.Color = 'w';
%p10=plot(pr,eefffc11,'k.','markersize',8)
if t4==600
%p10(1).Marker = '*';
plot(pr,eeffb1,'r.','markersize',20)
end
if t4==650
%p10(1).Marker = 'o';
plot(pr,eeffb1,'b.','markersize',20)
end
if t4==700
%p10(1).Marker = '.';
plot(pr,eeffb1,'g.','markersize',20)
end
if t4==750
%p10(1).Marker = 'p';
plot(pr,eeffb1,'y.','markersize',20)
end
%legend({'Powerratio of Fuel cell Vs Reheat & Regenerative Braysson
cycle'},'location','best','fontsize',13)
xlabel('Pressure Ratio','fontsize',13)
ylabel('Exergy efficiency of Reheat and Regenerative Braysson
cycle','fontsize',13)
 legend({' T4=600^{o}C',' T4=650^{o}C',' T4=700^{o}C','
T4=750^{o}C'},'location','best','fontsize',13)
%axis([1 5 0.1 0.88])
axis square
%axis([1 6 .9 1])
ax = gca;
c = ax.FontSize;
ax.FontSize = 13;
hold on
figure(13)
fig = figure(13);
u = fig.Color;
fig.Color = 'w';
%p10=plot(pr,eefffc11,'k.','markersize',8)
if t4==600
%p10(1).Marker = '*';
plot(pr,ted1,'r.','markersize',20)
end
if t4==650
%p10(1).Marker = 'o';
plot(pr,ted1,'b.','markersize',20)
end
if t4==700
%p10(1).Marker = '.';
plot(pr,ted1,'g.','markersize',20)
end
if t4==750
%p10(1).Marker = 'p';
plot(pr,ted1,'y.','markersize',20)
end
```

```
%legend({'Powerratio of Fuel cell Vs Reheat & Regenerative Braysson
cycle'},'location','best','fontsize',13)
xlabel('Pressure Ratio','fontsize',13)
ylabel('Total Exergy Destruction (KW)','fontsize',13)
 legend({' T4=600^{o}C',' T4=650^{o}C',' T4=700^{o}C','
T4=750^{o}C'},'location','best','fontsize',13)
%axis([1 5 0.1 0.88])
axis square
%axis([1 6 .9 1])
ax = gca;
c = ax.FontSize;
ax.FontSize = 13;
hold on
figure(14)
fig = figure(14);
u = fig.Color;
fig.Color = 'w';
if t4==600
    plot(pr,NW1,'g.','markersize',20)
%p2(1).Marker = '*';
%p2(2).Marker = '*';
end
if t4==650
    plot(pr,NW1,'r.','markersize',20)
%p2(1).Marker = 'o';
%p2(2).Marker = 'o';
end
if t4==700
    plot(pr,NW1,'b.','markersize',20)
%p2(1).Marker = '.';
%p2(2).Marker = '.';
end
if t4==750
    plot(pr,NW1,'k.','markersize',20)
%p2(1).Marker = 'p';
%p2(2).Marker = 'p';
end
legend({' T4=600^{o}C',' T4=650^{o}C',' T4=700^{o}C','
T4=750^{o}C'},'location','best','fontsize',13)

%legend({'Energy efficiency of Hybrid cycle','Exergy efficiency of
Hybrid cycle'},'location','best','fontsize',13)
xlabel('Pressure Ratio','fontsize',13)
ylabel('Net Power output of combined system(KW) ','fontsize',13)
%axis([1 5 0.8 0.88])
axis square
ax = gca;
c = ax.FontSize;
ax.FontSize = 13;
hold on

end

clear all
```

Programme for exergy efficiency and exergy destruction at different maximum cycle temperatures:

```
T=800+273.15;
T1=300;
%t4=700;
j=1;
for t4=600:50:750
T4=t4+273.15;
p7=0.4;
pat=1.013;
eta1c=0.8;
N=4;
deltaG=10483.33; % value at 800 degreecelcius (KJ/kg);
deltaH=13788.8;% value at 800 degree celcius (KJ/kg);
cesh2=116557;%chemical exergy supplied for H2 (KJ/kg);
ceso=123.3;%chemical exergy supplied for O2 (KJ/kg);
Cph=5.19;%CP of helium in KJ/kgK;
mf=1;%mf is mass flow rate of braysson = 1kg/s;
qh=(deltaH-deltaG); % qh is heat from fuel cell;
etareg=0.8;
etat=0.8;
etac=0.8;
%rp=4;
gama=1.667;
T6=T4;
T9=T1;
T0=T1;
%for N=1:1:100
i=1;
%for rp=1:.1:100
rp=1.4;
    p4=rp*pat;
    rp1=sqrt(p4/p7);
rpo=pat/p7;
T2=T1+T1*(rp^((gama-1)/gama)-1)/etac;

T5=T4+etat*T4*(rp1^((1-gama)/(gama))-1);
if T2<T5
pr(i,1)=rp;
T7=T5;
T3=etareg*(T7-T2)+T2;
T8=T7-T3+T2;
%if T3<T8
Ta=T9+(T9*((rpo^((gama-1)/(N*gama)))-1)/eta1c);
mfh2o1=mf*Cph*((T4-T3))/(qh*0.8);
mfh2o2=mf*Cph*((T6-T5))/(qh*0.8);
mfh21=(1/9)*mfh2o1;
mfh22=(1/9)*mfh2o2;
mfo1=8*mfh21;
mfo2=8*mfh22;

esc=Cph*(T2-T1);%Exergy supplied for compressor;
erc=Cph*(T2-T1)-T0*Cph*(log(T2/T1)-((gama-1)*log(rp)/gama));%Exergy
recovered;
edc=esc-erc;%Exery destroyed;
eeffc=erc/esc;%Exergy efficiency of compressor;

%Exergy efficiency of regenerator;
eeffr=((T3-T2)-T0*log(T3/T2))/((T7-T8)-T0*log(T7/T8));
```

```
edr=Cph*((T7-T8)-T0*log(T7/T8))-Cph*((T3-T2)-T0*log(T3/T2));

%Exergy efficiency of fuel cell;

eefffc1=(mfh2o1*((qh)*(1-
(T0/T))+deltaG))/((mfh21*cesh2)+(mfo1*ceso));
eefffc2=(mfh2o2*((qh)*(1-
(T0/T))+deltaG))/((mfh22*cesh2)+(mfo2*ceso));
eeffwoqhfc1=(mfh2o1*(deltaG))/((mfh21*cesh2)+(mfo1*ceso));
eeffwoqhfc2=(mfh2o2*(deltaG))/((mfh22*cesh2)+(mfo2*ceso));
edfc1=((mfh21*cesh2)+(mfo1*ceso))-(mfh2o1*((qh)*(1-(T0/T))+deltaG));
edfc2=((mfh22*cesh2)+(mfo2*ceso))-(mfh2o2*((qh)*(1-(T0/T))+deltaG));
edfwoqhc1=((mfh21*cesh2)+(mfo1*ceso))-(mfh2o1*(deltaG));
edfwoqhc2=((mfh22*cesh2)+(mfo2*ceso))-(mfh2o2*(+deltaG));
edwh1=mfh2o1*0.2*(qh)*(1-(T0/T));%exergy destruction by gases(waste
heat) in fuel cell
edwh2=mfh2o2*0.2*(qh)*(1-(T0/T));
%Exergy efficiency of Turbine;
est=2*(Cph*(T4-T5)-Cph*T0*(log(T4/T5)-((gama-1)*log(rp1)/gama)));
ert=2*(Cph*(T4-T5));

edt=est-ert;
eefft=ert/est;


%Exergy efficiency of multistage compressor with intercooling;
first=N*Cph*T9*(rpo^((gama-1)/(gama*N))-1)/eta1c;
sec=-N*Cph*T0*(log(1+((rpo^((gama-1)/(gama*N))-1)/eta1c)));
thir=(N*Cph*T0*(gama-1)*log(rpo))/(gama*N);
ermc=first+sec+thir;
%ermc=N*Cph*((T9*(rpo^((gama-1)/(gama*N))-1))/eta1c)-
T0*log(1+((rpo^((gama-1)/(gama*N))-1))/eta1c)+T0*((gama-
1)*log(rpo)/(gama*N)));
ermi=(N-1)*Cph*((Ta-T9)-T0*log(1+((rpo^((gama-1)/(gama*N))-
1))/eta1c));
ermct=ermc-ermi;
esmct=N*Cph*(Ta-T9);
edmct=esmct-ermct;
eeffmct=ermct/esmct;
%exergy in heating of the fluid (3-4)& (5-6) process
erhf34=Cph*((T4-T3)-T0*(log(T4/T3)));
eshf34=mfh2o1*(qh)*(1-(T0/T));
edhf34=eshf34-erhf34;
eehf34=erhf34/eshf34;

erhf56=Cph*((T6-T5)-T0*(log(T6/T5)));
eshf56=mfh2o2*(qh)*(1-(T0/T));
edhf56=eshf56-erhf56;
eehf56=erhf56/eshf56;
edcool=Cph*((T8-T9)-T0*log(T8/T9));

Wopb=Cph*(T4-T5)+Cph*(T6-T7);

Winb=Cph*(T2-T1)+N*Cph*(Ta-T9);

Wopf=(mfh2o1+mfh2o2)*deltaG;

Qin=deltaH*(mfh2o1+mfh2o2);
%Effb=Wopb/qh;
%p=Wopb-Winb;
```

```
Efff=deltaG/deltaH;
%Effb=(Wopb-Winb)/Qin;
%Effov=(Wopb+Wopf-Winb)/Qin;
Effb=(Wopb-Winb)/(qh*(mfh2o1+mfh2o2));
Effov=(Wopb+Wopf-Winb)/Qin;
%Total Exergy efficiency of Braysson and Fuel cell cycle;
tes=((mfh21*cesh2)+(mfo1*ceso))+((mfh22*cesh2)+(mfo2*ceso));%total
exergy supplied;
NW=Wopb+Wopf-Winb;
NWB=Wopb-Winb;
TFC=(mfh21+mfh22)*3600;
SFC=TFC/NW;
Workratio=Wopf/NWB;
eeffov=(Wopb+Wopf-
Winb)/(((mfh21*cesh2)+(mfo1*ceso))+((mfh22*cesh2)+(mfo2*ceso)));
Texd=(1-eeffov)*tes;%Total Exergy Destroyed;

ted=edc+edr+edfc1+edfc2+edt+edmct+edhf34+edhf56+edcool;%sum of
exergy destruction of individual;

difference=Texd-ted;
percentage=difference*100/tes;
%plot(rp,Effov,'b.',rp,Efff,'r.',rp,Effb,'g.')
%plot(rp,eeffov,'m.')
%plot(rp,eeffov,'r.',rp,Effov,'b.')

%hold on
tesb=eshf34+eshf56;
erb=NWB;
eeffb=erb/tesb;

ted1(i,1)=ted;
eeffb1(i,1)=eeffb;
eefffc11(i,1)=eefffc1;
eefffc21(i,1)=eefffc2;

Effov1(i,1)=Effov;
eeffov1(i,1)=eeffov;
Efff1(i,1)=Efff;
Effb1(i,1)=Effb;
WR(i,1)=Workratio;
SFC1(i,1)=SFC;
Wopf1(i,1)=Wopf;
NWB1(i,1)=NWB;
i=i+1;
else
%end
%else
%end
end
edc1(j,1)=edc;
edr1(j,1)=edr;
edfc11(j,1)=edfc1;
edfc21(j,1)=edfc2;
edt1(j,1)=edt;
edmct1(j,1)=edmct;
edhf341(j,1)=edhf34;
edhf561(j,1)=edhf56;
edcool1(j,1)=edcool;
eeffc1(j,1)=eeffc;
```

```
eeffr1(j,1)=eeffr;
eefffc11(j,1)=eefffc1;
eefffc21(j,1)=eefffc2;
eefft1(j,1)=eefft;
eeffmct1(j,1)=eeffmct;
eehf341(j,1)=eehf34;
eehf561(j,1)=eehf56;
eecool(j,1)=0;
j=j+1;

figure(14)
fig = figure(14);
u = fig.Color;
fig.Color = 'w';

end
figure(14)
fig = figure(14);
u = fig.Color;
fig.Color = 'w';
bar([edc1(1,1),edr1(1,1),edfc11(1,1),edfc21(1,1),edt1(1,1),edmct1(1,
1),edhf341(1,1),edhf561(1,1),edcool1(1,1);edc1(2,1),edr1(2,1),edfc11
(2,1),edfc21(2,1),edt1(2,1),edmct1(2,1),edhf341(2,1),edhf561(2,1),ed
cool1(2,1);edc1(3,1),edr1(3,1),edfc11(3,1),edfc21(3,1),edt1(3,1),edm
ct1(3,1),edhf341(3,1),edhf561(3,1),edcool1(3,1);edc1(4,1),edr1(4,1),
edfc11(4,1),edfc21(4,1),edt1(4,1),edmct1(4,1),edhf341(4,1),edhf561(4
,1),edcool1(4,1)])
legend({'Main compressor','Regenerator','Fuel Cell-1','Fuel Cell-
2','Turbines','Multi-stage Compressor','Heat exchanger-34','Heat
exchanger-56','Cooler'},'location','best','fontsize',13)
set(gca,'XTickLabel',{'T4=600^{o}C','T4=650^{o}C','T4=700^{o}C','T4=
750^{o}C'});
ylabel('Exergy Destruction (KW)');
axis square
set(gca,'Ygrid','on')
set(gca,'Yminorgrid','on')
set(gca,'MinorGridLineStyle','-');
figure(15)
fig = figure(15);
u = fig.Color;
fig.Color = 'w';

bar([eeffc1(1,1),eeffr1(1,1),eefffc11(1,1),eefffc21(1,1),eefft1(1,1)
,eeffmct1(1,1),eehf341(1,1),eehf561(1,1),eecool(1,1);eeffc1(2,1),eef
fr1(2,1),eefffc11(2,1),eefffc21(2,1),eefft1(2,1),eeffmct1(2,1),eehf3
41(2,1),eehf561(2,1),eecool(2,1);eeffc1(3,1),eeffr1(3,1),eefffc11(3,
1),eefffc21(3,1),eefft1(3,1),eeffmct1(3,1),eehf341(3,1),eehf561(3,1)
,eecool(3,1);eeffc1(4,1),eeffr1(4,1),eefffc11(4,1),eefffc21(4,1),eef
ft1(4,1),eeffmct1(4,1),eehf341(4,1),eehf561(4,1),eecool(4,1)])
legend({'Main compressor','Regenerator','Fuel Cell-1','Fuel Cell-
2','Turbines','Multi-stage Compressor','Heat exchanger-34','Heat
exchanger-56','Cooler'},'location','best','fontsize',13)
set(gca,'XTickLabel',{'T4=600^{o}C','T4=650^{o}C','T4=700^{o}C','T4=
750^{o}C'});
ylabel('Exergy Efficiency');
axis square
set(gca,'Ygrid','on')
set(gca,'Yminorgrid','on')
set(gca,'MinorGridLineStyle','-');
%hold on
```

```
clear all
```

Programme to find the optimum number of stages in the multistage compressor:

```
T=800+273.15;
T1=300;
t4=750;
j=1;
%for t4=600:50:750
T4=t4+273.15;
p7=0.4;
pat=1.013;
eta1c=0.8;
%N=4;
deltaG=10483.33; % value at 800 degreecelcius (KJ/kg);
deltaH=13788.8;% value at 800 degree celcius (KJ/kg);
cesh2=116557;%chemical exergy supplied for H2 (KJ/kg);
ceso=123.3;%chemical exergy supplied for O2 (KJ/kg);
Cph=5.19;%CP of helium in KJ/kgK;
mf=1;%mf is mass flow rate of braysson = 1kg/s;
qh=(deltaH-deltaG); % qh is heat from fuel cell;
etareg=0.8;
etat=0.8;
etac=0.8;
%rp=4;
gama=1.667;
T6=T4;
T9=T1;
T0=T1;
i=1;
for N=1:1:100

N1(i,1)=N;
%for rp=1:.1:100
rp=1.4;
    p4=rp*pat;
    rp1=sqrt(p4/p7);
rpo=pat/p7;
T2=T1+T1*(rp^((gama-1)/gama)-1)/etac;

T5=T4+etat*T4*(rp1^((1-gama)/(gama))-1);
if T2<T5
pr(i,1)=rp;
T7=T5;
T3=etareg*(T7-T2)+T2;
T8=T7-T3+T2;
%if T3<T8
Ta=T9+(T9*((rpo^((gama-1)/(N*gama)))-1)/eta1c);
mfh2o1=mf*Cph*((T4-T3))/(qh*0.8);
mfh2o2=mf*Cph*((T6-T5))/(qh*0.8);
mfh21=(1/9)*mfh2o1;
mfh22=(1/9)*mfh2o2;
mfo1=8*mfh21;
mfo2=8*mfh22;

esc=Cph*(T2-T1);%Exergy supplied for compressor;
erc=Cph*(T2-T1)-T0*Cph*(log(T2/T1)-((gama-1)*log(rp)/gama));%Exergy
recovered;
```

```
edc=esc-erc;%Exery destroyed;
eeffc=erc/esc;%Exergy efficiency of compressor;

%Exergy efficiency of regenerator;
eeffr=((T3-T2)-T0*log(T3/T2))/((T7-T8)-T0*log(T7/T8));
edr=Cph*((T7-T8)-T0*log(T7/T8))-Cph*((T3-T2)-T0*log(T3/T2));

%Exergy efficiency of fuel cell;

eefffc1=(mfh2o1*((qh)*(1-
(T0/T))+deltaG))/((mfh21*cesh2)+(mfo1*ceso));
eefffc2=(mfh2o2*((qh)*(1-
(T0/T))+deltaG))/((mfh22*cesh2)+(mfo2*ceso));
eeffwoqhfc1=(mfh2o1*(deltaG))/((mfh21*cesh2)+(mfo1*ceso));
eeffwoqhfc2=(mfh2o2*(deltaG))/((mfh22*cesh2)+(mfo2*ceso));
edfc1=((mfh21*cesh2)+(mfo1*ceso))-(mfh2o1*((qh)*(1-(T0/T))+deltaG));
edfc2=((mfh22*cesh2)+(mfo2*ceso))-(mfh2o2*((qh)*(1-(T0/T))+deltaG));
edfwoqhc1=((mfh21*cesh2)+(mfo1*ceso))-(mfh2o1*(deltaG));
edfwoqhc2=((mfh22*cesh2)+(mfo2*ceso))-(mfh2o2*(+deltaG));
edwh1=mfh2o1*0.2*(qh)*(1-(T0/T));%exergy destruction by gases(waste
heat) in fuel cell
edwh2=mfh2o2*0.2*(qh)*(1-(T0/T));
%Exergy efficiency of Turbine;
est=2*(Cph*(T4-T5)-Cph*T0*(log(T4/T5)-((gama-1)*log(rp1)/gama)));
ert=2*(Cph*(T4-T5));
%A=-Cph*T0*(log(T4/T5))
%B=+Cph*T0*((gama-1)*log(rp1)/gama)
%A+B

edt=est-ert;
eefft=ert/est;

%Exergy efficiency of multistage compressor with intercooling;
first=N*Cph*T9*(rpo^((gama-1)/(gama*N))-1)/eta1c;
sec=-N*Cph*T0*(log(1+((rpo^((gama-1)/(gama*N))-1)/eta1c)));
thir=(N*Cph*T0*(gama-1)*log(rpo))/(gama*N);
ermc=first+sec+thir;
%ermc=N*Cph*((T9*(rpo^((gama-1)/(gama*N))-1))/eta1c)-
T0*log(1+((rpo^((gama-1)/(gama*N))-1))/eta1c)+T0*((gama-
1)*log(rpo)/(gama*N)));
ermi=(N-1)*Cph*((Ta-T9)-T0*log(1+((rpo^((gama-1)/(gama*N))-
1))/eta1c));
ermct=ermc-ermi;
esmct=N*Cph*(Ta-T9);
edmct=esmct-ermct;
eeffmct=ermct/esmct;
%exergy in heating of the fluid (3-4)& (5-6) process
erhf34=Cph*((T4-T3)-T0*(log(T4/T3)));
eshf34=mfh2o1*(qh)*(1-(T0/T));
edhf34=eshf34-erhf34;
eehf34=erhf34/eshf34;

erhf56=Cph*((T6-T5)-T0*(log(T6/T5)));
eshf56=mfh2o2*(qh)*(1-(T0/T));
edhf56=eshf56-erhf56;
eehf56=erhf56/eshf56;
edcool=Cph*((T8-T9)-T0*log(T8/T9));

Wopb=Cph*(T4-T5)+Cph*(T6-T7);
```

```
Winb=Cph*(T2-T1)+N*Cph*(Ta-T9);

Wopf=(mfh2o1+mfh2o2)*deltaG;

Qin=deltaH*(mfh2o1+mfh2o2);
%Effb=Wopb/qh;
%p=Wopb-Winb;
Efff=deltaG/deltaH;
%Effb=(Wopb-Winb)/Qin;
%Effov=(Wopb+Wopf-Winb)/Qin;
Effb=(Wopb-Winb)/(qh*(mfh2o1+mfh2o2));
Effov=(Wopb+Wopf-Winb)/Qin;
%Total Exergy efficiency of Braysson and Fuel cell cycle;
tes=((mfh21*cesh2)+(mfo1*ceso))+((mfh22*cesh2)+(mfo2*ceso));%total
exergy supplied;
NW=Wopb+Wopf-Winb;
NWB=Wopb-Winb;
TFC=(mfh21+mfh22)*3600;
SFC=TFC/NW;
Workratio=Wopf/NWB;
eeffov=(Wopb+Wopf-
Winb)/(((mfh21*cesh2)+(mfo1*ceso))+((mfh22*cesh2)+(mfo2*ceso)));
Texd=(1-eeffov)*tes;%Total Exergy Destroyed;

ted=edc+edr+edfc1+edfc2+edt+edmct+edhf34+edhf56+edcool;%sum of
exergy destruction of individual;

%hold on
tesb=eshf34+eshf56;
erb=NWB;
eeffb=erb/tesb;



Effov1(i,1)=Effov;
eeffov1(i,1)=eeffov;
i=i+1;
else

end
end
figure(1)
fig = figure(1);
u = fig.Color;
fig.Color = 'w';
plot(N1,Effov1,'r.',N1,eeffov1,'b.','markersize',8);
axis square
%axis([1 100 0.815 0.835])
set(gca,'ytick',0.81:.004:.95)

grid on
xlabel('Number of stages in multi-stage compressor','fontsize',13)
ylabel('Efficiency of combined system','fontsize',13)
legend({' Energy efficiency',' Exergy
efficiency'},'location','best','fontsize',13)
```

Programme to find optimum back pressure of low pressure turbine:

```
T=800+273.15;
```

```
T1=300;
%t4=750;


for t4=600:50:750
T4=t4+273.15;
j=1;
for p7=0.1:0.1:0.8;

pat=1.013;
eta1c=0.8;
%N=4;
deltaG=10483.33; % value at 800 degreecelcius (KJ/kg);
deltaH=13788.8;% value at 800 degree celcius (KJ/kg);
cesh2=116557;%chemical exergy supplied for H2 (KJ/kg);
ceso=123.3;%chemical exergy supplied for O2 (KJ/kg);
Cph=5.19;%CP of helium in KJ/kgK;
mf=1;%mf is mass flow rate of braysson = 1kg/s;
qh=(deltaH-deltaG); % qh is heat from fuel cell;
etareg=0.8;
etat=0.8;
etac=0.8;
%rp=4;
gama=1.667;
T6=T4;
T9=T1;
T0=T1;

N=4;
%for N=1:1:100

p71(j,1)=p7;
i=1;
forrp=1:.1:100
%rp=1.4;
    p4=rp*pat;
    rp1=sqrt(p4/p7);
rpo=pat/p7;
T2=T1+T1*(rp^((gama-1)/gama)-1)/etac;

T5=T4+etat*T4*(rp1^((1-gama)/(gama))-1);
if T2<T5
pr(i,1)=rp;
T7=T5;
T3=etareg*(T7-T2)+T2;
T8=T7-T3+T2;
%if T3<T8
Ta=T9+(T9*((rpo^((gama-1)/(N*gama)))-1)/eta1c);
mfh2o1=mf*Cph*((T4-T3))/(qh*0.8);
mfh2o2=mf*Cph*((T6-T5))/(qh*0.8);
mfh21=(1/9)*mfh2o1;
mfh22=(1/9)*mfh2o2;
mfo1=8*mfh21;
mfo2=8*mfh22;

esc=Cph*(T2-T1);%Exergy supplied for compressor;
erc=Cph*(T2-T1)-T0*Cph*(log(T2/T1)-((gama-1)*log(rp)/gama));%Exergy
recovered;
edc=esc-erc;%Exery destroyed;
eeffc=erc/esc;%Exergy efficiency of compressor;
```

```
%Exergy efficiency of regenerator;
eeffr=((T3-T2)-T0*log(T3/T2))/((T7-T8)-T0*log(T7/T8));
edr=Cph*((T7-T8)-T0*log(T7/T8))-Cph*((T3-T2)-T0*log(T3/T2));

%Exergy efficiency of fuel cell;

eefffc1=(mfh2o1*((qh)*(1-
(T0/T))+deltaG))/((mfh21*cesh2)+(mfo1*ceso));
eefffc2=(mfh2o2*((qh)*(1-
(T0/T))+deltaG))/((mfh22*cesh2)+(mfo2*ceso));
eeffwoqhfc1=(mfh2o1*(deltaG))/((mfh21*cesh2)+(mfo1*ceso));
eeffwoqhfc2=(mfh2o2*(deltaG))/((mfh22*cesh2)+(mfo2*ceso));
edfc1=((mfh21*cesh2)+(mfo1*ceso))-(mfh2o1*((qh)*(1-(T0/T))+deltaG));
edfc2=((mfh22*cesh2)+(mfo2*ceso))-(mfh2o2*((qh)*(1-(T0/T))+deltaG));
edfwoqhc1=((mfh21*cesh2)+(mfo1*ceso))-(mfh2o1*(deltaG));
edfwoqhc2=((mfh22*cesh2)+(mfo2*ceso))-(mfh2o2*(+deltaG));
edwh1=mfh2o1*0.2*(qh)*(1-(T0/T));%exergy destruction by gases(waste
heat) in fuel cell
edwh2=mfh2o2*0.2*(qh)*(1-(T0/T));
%Exergy efficiency of Turbine;
est=2*(Cph*(T4-T5)-Cph*T0*(log(T4/T5)-((gama-1)*log(rp1)/gama)));
ert=2*(Cph*(T4-T5));
%A=-Cph*T0*(log(T4/T5))
%B=+Cph*T0*((gama-1)*log(rp1)/gama)
%A+B

edt=est-ert;
eefft=ert/est;


%Exergy efficiency of multistage compressor with intercooling;
first=N*Cph*T9*(rpo^((gama-1)/(gama*N))-1)/eta1c;
sec=-N*Cph*T0*(log(1+((rpo^((gama-1)/(gama*N))-1)/eta1c)));
thir=(N*Cph*T0*(gama-1)*log(rpo))/(gama*N);
ermc=first+sec+thir;
%ermc=N*Cph*((T9*(rpo^((gama-1)/(gama*N))-1))/eta1c)-
T0*log(1+((rpo^((gama-1)/(gama*N))-1))/eta1c)+T0*((gama-
1)*log(rpo)/(gama*N)));
ermi=(N-1)*Cph*((Ta-T9)-T0*log(1+((rpo^((gama-1)/(gama*N))-
1))/eta1c));
ermct=ermc-ermi;
esmct=N*Cph*(Ta-T9);
edmct=esmct-ermct;
eeffmct=ermct/esmct;
%exergy in heating of the fluid (3-4)& (5-6) process
erhf34=Cph*((T4-T3)-T0*(log(T4/T3)));
eshf34=mfh2o1*(qh)*(1-(T0/T));
edhf34=eshf34-erhf34;
eehf34=erhf34/eshf34;

erhf56=Cph*((T6-T5)-T0*(log(T6/T5)));
eshf56=mfh2o2*(qh)*(1-(T0/T));
edhf56=eshf56-erhf56;
eehf56=erhf56/eshf56;
edcool=Cph*((T8-T9)-T0*log(T8/T9));

Wopb=Cph*(T4-T5)+Cph*(T6-T7);

Winb=Cph*(T2-T1)+N*Cph*(Ta-T9);
```

```
Wopf=(mfh2o1+mfh2o2)*deltaG;

Qin=deltaH*(mfh2o1+mfh2o2);
%Effb=Wopb/qh;
%p=Wopb-Winb;
Efff=deltaG/deltaH;
%Effb=(Wopb-Winb)/Qin;
%Effov=(Wopb+Wopf-Winb)/Qin;
Effb=(Wopb-Winb)/(qh*(mfh2o1+mfh2o2));
Effov=(Wopb+Wopf-Winb)/Qin;
%Total Exergy efficiency of Braysson and Fuel cell cycle;
tes=((mfh21*cesh2)+(mfo1*ceso))+((mfh22*cesh2)+(mfo2*ceso));%total
exergy supplied;
NW=Wopb+Wopf-Winb;
NWB=Wopb-Winb;
TFC=(mfh21+mfh22)*3600;
SFC=TFC/NW;
Workratio=Wopf/NWB;
eeffov=(Wopb+Wopf-
Winb)/(((mfh21*cesh2)+(mfo1*ceso))+((mfh22*cesh2)+(mfo2*ceso)));
Texd=(1-eeffov)*tes;%Total Exergy Destroyed;

ted=edc+edr+edfc1+edfc2+edt+edmct+edhf34+edhf56+edcool;%sum of
exergy destruction of individual;

%hold on
tesb=eshf34+eshf56;
erb=NWB;
eeffb=erb/tesb;



Effov1(i,1)=Effov;
eeffov1(i,1)=eeffov;
pr(i,1)=rp;
i=i+1;
else

end
end
if t4==600
figure(1)
fig = figure(1);
u = fig.Color;
fig.Color = 'w';
if p7==0.1
    plot(pr,Effov1,'g-.',pr,eeffov1,'g-','markersize',8);
elseif p7==0.2
    plot(pr,Effov1,'b-.',pr,eeffov1,'b-','markersize',8);
elseif p7==0.3
    plot(pr,Effov1,'m-*',pr,eeffov1,'m-*','markersize',8);
elseif p7==0.4
    plot(pr,Effov1,'y-.',pr,eeffov1,'y-','markersize',8);
elseif p7==0.5
    plot(pr,Effov1,'c-.',pr,eeffov1,'c-','markersize',8);
elseif p7==0.6
    plot(pr,Effov1,'k-.',pr,eeffov1,'k-','markersize',8);
elseif p7==0.7
      plot(pr,Effov1,'g-*',pr,eeffov1,'g*','markersize',8);
else
```

```
    plot(pr,Effov1,'r-.',pr,eeffov1,'r-','markersize',8);

end
%pause
grid on
xlabel('Pressure ratio','fontsize',13)
ylabel('Efficiency of combined system','fontsize',13)
%legend({' P7=0.1','
P7=0.2','P7=0.3','P7=0.4','P7=0.5','P7=0.6','P7=0.7'},'location','be
st','fontsize',13)
axis square
%ax = gca;
%c = ax.FontSize;
%ax.FontSize = 13;
set(gca,'ytick',0.8:.004:0.94)
hold on
end
legend({' Energy efficiency for P7=0.1',' Exergy efficiency for
P7=0.1','Energy efficiency for P7=0.2','Exergy efficiency for
P7=0.2',' Energy efficiency for P7=0.3',' Exergy efficiency for
P7=0.3','Energy efficiency for P7=0.4','Exergy efficiency for
P7=0.4','Energy efficiency for P7=0.5','Exergy efficiency for
P7=0.5','Energy efficiency for P7=0.6','Exergy efficiency for
P7=0.6',' Energy efficiency for P7=0.7',' Exergy efficiency for
P7=0.7','Energy efficiency for P7=0.8','Exergy efficiency for
P7=0.8'},'location','best','fontsize',13)
max_Eeff(j,1)=max(Effov1);
max_eeff(j,1)=max(eeffov1);
%pause
j=j+1;
end
figure(2)
fig = figure(2);
u = fig.Color;
fig.Color = 'w';
if t4==600
    plot(p71,max_Eeff,'r-.',p71,max_eeff,'r-','markersize',8);
elseif t4==650
    plot(p71,max_Eeff,'b-.',p71,max_eeff,'b-','markersize',8);
elseif t4==700
    plot(p71,max_Eeff,'g-.',p71,max_eeff,'g-','markersize',8);
elseif t4==750
    plot(p71,max_Eeff,'k-.',p71,max_eeff,'k-','markersize',8);
end
axis square
set(gca,'ytick',0.8:.004:0.94)
grid on
xlabel('P7 value','fontsize',13)
ylabel('Maximum Efficiency of combined system','fontsize',13)
hold on

end
legend({' Energy efficiency for T4=600^{0}C',' Exergy efficiency for
T4=600^{0}C','Energy efficiency for T4=650^{0}C','Exergy efficiency
for T4=650^{0}C','Energy efficiency for T4=700^{0}C','Exergy
efficiency for T4=700^{0}C','Energy efficiency for
T4=750^{0}C','Exergy efficiency for T4=750^{0}C','Energy efficiency
for T4=750^{0}C'},'location','best','fontsize',13)

clear all
```