3.1 INTRODUCTION:

The basic operation of the gas turbine is similar to that of the steam power plant except that air is used instead of water. Fresh atmospheric air flows through a compressor that brings it to higher pressure. Energy is then added by spraying fuel into the air and igniting it so the combustion generates a high-temperature flow. This high-temperature and high-pressure gas enters a turbine, where it expands down to the exhaust pressure, producing a shaft work output in the process. The turbine shaft work is used to drive the compressor and other devices such as an electric generator that may be coupled to the shaft. The energy that is not used for shaft work comes out in the exhaust gases, so these have either a high temperature or a high velocity. The purpose of the gas turbine determines the design so that the most desirable energy form is maximized. Gas turbines are used to power aircraft, trains, ships andelectrical generators.

3.2 THE IDEAL BRAYTON-JOULE CYCLE

The thermodynamic cycle of a simple gas turbine is described by the Brayton-Joule cycle. It consists in the ideal case of four processes: two is isentropic and two isobaric ones. In this cycle, depicted in figure 1, the working fluid undergoes an isentropic compression from the state 1 to the state 2. then it is heated isobarically in the combustion chamber to the state 3. An isentropic expansion leads to the state 4 and an isobaric cooling to the initial state 1.

In figure 3.1 the heat supplied to the cycle in the combustion chamber is denoted as Q_{2-3} and the heat carried away by the ambient air (for open cycle) or by heat exchanger (for closed cycle) is denoted asQ_{4-1}.

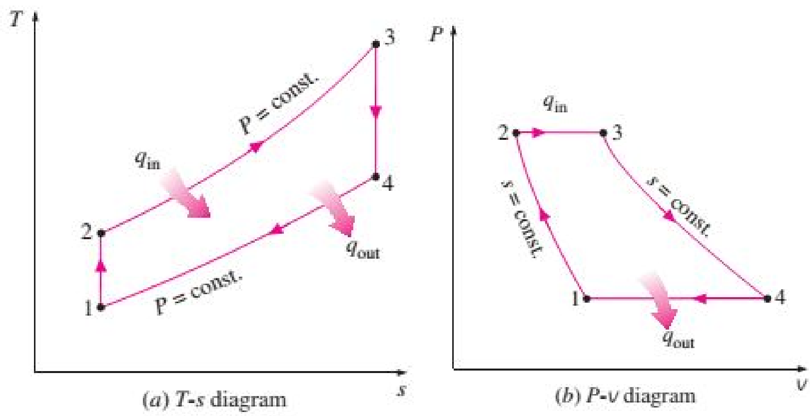

Fig. 3.1: *T-s&P-v* diagrams for ideal Brayton cycle

Thermal efficiency for Brayton cycle is:

$$\eta_{th,Brayton} = 1 - \frac{q_{out}}{q_{in}} = 1 - \frac{T_4 - T_1}{T_3 - T_2} = 1 - \frac{T_1(T_4/T_1 - 1)}{T_2(T_3/T_2 - 1)}$$

$$\frac{T_2}{T_1} = \left(\frac{P_2}{P_1}\right)^{\frac{\gamma-1}{\gamma}} = \left(\frac{P_3}{P_4}\right)^{\frac{\gamma-1}{\gamma}} = \frac{T_3}{T_4}$$

Thus

$$\eta_{th,Brayton} = 1 - \frac{1}{(r_p)^{\frac{\gamma-1}{\gamma}}} \qquad \ldots\ldots(3-1)$$

The basic indicator which describes the cycle and which is a measure of its thermodynamic perfection is the thermal efficiency η_{th}. It's the ratio between the net output powers to the thermal energy supplied to the system.

3.3. TYPES OF GAS TURBINE CYCLES

3.3.1. OPEN CYCLE GAS TURBINE

Gas turbines usually operate on an open cycle. Fresh air at ambient conditions is drawn into the compressor, where its temperature and pressure are raised. The high-pressure air proceeds ito the combustion chamber, where the fuel is burned at constant pressure. The resulting high-temperature gases then enter the turbine, where they expand to the atmospheric pressure through a row of nozzle vanes. Expansion causes the turbine blade to spin, which then turns a shaft. The shaft work thus generated drives the auxiliaries which includes compressor, generators etc. if electricity is to be produced. The exhaust gases leaving the turbine in the open cycle are not re-circulated. The schematic diagram of the open cycle gas turbine is shown in figure 3.2 .

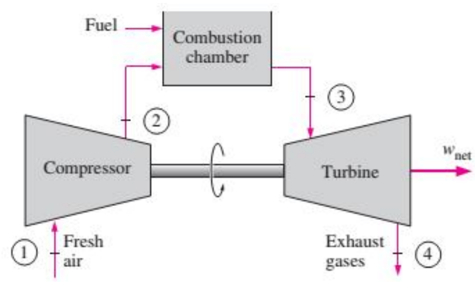

Fig. 3.2: An open cycle gas turbine

3.3.2. CLOSED CYCLE GAS TURBINE

The open gas-turbine cycle can be modelled as closed cycle by utilizing the air standard assumptions. Here the compression and expansion process remain the same, but a constant-pressure heat-rejection process to the ambient air replaces the combustion process. The ideal cycle that the working fluid undergoes in this closed loop is the Brayton cycle, which is made up of four internally reversible processes. Using a closed cycle for the gas turbine develops the possibility of using a high pressure (and hence a high gas density) throughout the cycle, which would result in a reduced size of turbo-machinery for a given output. The schematic diagram of the closed cycle gas turbine is shown in figure 3.3.

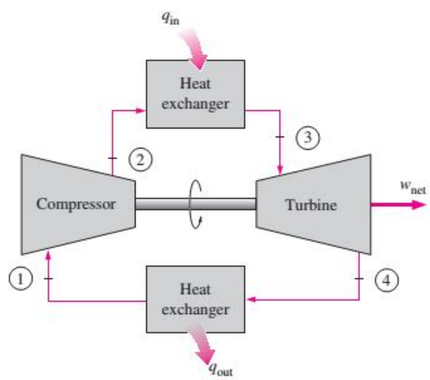

Fig. 3.3: A closed cycle gas turbine

3.4MAIN GAS POWER CYCLE COMPONENTS

Gas turbine engine are, theoretically, extremely simple. They have three parts as shown in figure 3.2:

1. Compressor: compresses the incoming air to high pressure.
2. Combustion chamber: burns the fuel and produces high- pressure, high – velocity gas.
3. Turbine: extracts the energy from the high-pressure, high-velocity gas flowing from the combustion chamber.

3.4.1 COMPRESSOR:

Efficient compression of large volumes of air is essential for a successful gas turbine engine. This has been achieved in tow types of compressors, the axial-flow compressor and the centrifugal compressor. Most power plant compressors are axial-flow compressors because they are able to handle large mass flow rates. The objective of a good compressor design is to obtain the most air through a given diameter compressor with a minimum number of stages while retaining relatively high efficiencies and aerodynamic stability over the operating range. Compressors contain a row of rotating blades followed by a row of stationary (stator) blades. A stage consists of a row of rotor and a row of stator blades. All work done on the working fluid is done by the rotating rows, the stators converting the fluid kinetic energy to pressure and directing the fluid into the next rotor. The fluid enters with an initial velocity relative to the blade and leaves with a final relative velocity at a different angle.

3.4.1.1 CENTRIFUGAL AIR COMPRESSOR

The impeller, which consists of large number of blades, is mounted on the compressor shaft, inside the stationary casing. As the impeller rotates the pressure in suction region falls and hence the air enters through the eye and flows radically outwards through impeller blades. As a result velocity and pressure of air increases. Later this air enters and flows through the divergent passages formed by the diffuser blades. At this stage the velocity of air is decreases but the pressure increases still further. We may say that, during this stage the kinetic energy is converted into pressure energy. Finally this high pressure air escapes from the compressor delivery portion. By this method we can obtain high pressure ratios by arranging the number of air compressor in series. The schematic diagram of the centrifugal compressor is shown in the figure 3.4.

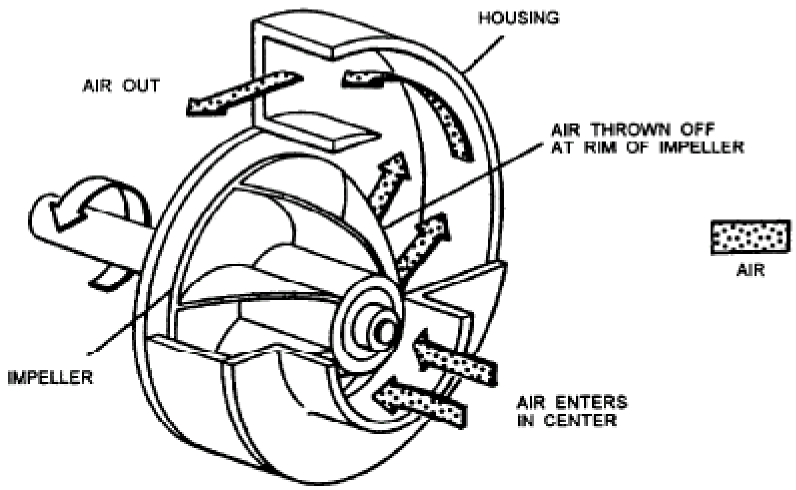

Fig. 3.4: Centrifugal air compressor

3.4.1.2 AXIAL-FLOW AIR COMPRESSOR:

These types of compressors are more commonly used now a day. In axial compressor, the air flows in an axial direction right from intake to the discharge. The stator, which has stator blades, encloses the rotor, which is provided with rotor blades. As the air enters from suction region, it flows through the alternately arranged stator and rotor blade rings. In flowing through each pair of blade rings formed up of one rotor blade ring and one stator blade ring, the air gets compressed successively. The air is finally delivered from delivery region, which is smaller in size compare to suction side.

Axial flow compressors produce a continuous flow of compressed gas, and have the benefits of high efficiencies and large mass flow capacity, particularly in relation to their cross-section. The do, however, require several rows of airfoils to achieve large pressure rises making them complex and expensive relative to other designs.

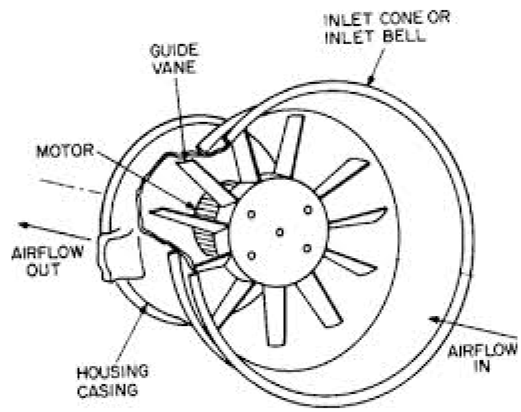

Fig. 3.5:Axial-flowair compressor

The figure 3.5 shows a cross-section of an axial-flow compressor with multiple impellers. The gas flows axially along the shaft of the compressor from one impeller to another, directed by the stationary vanes.

Each impeller/stationary vane set represent one stage of compression. The fluid is accelerated by impeller vanes and subsequently it is decelerated in the stator vanes which then guide it into next stage of impeller vanes.

Axial compressors are widely used in gas turbines, such as jet engines, high speed ship engines, and small scale power stations. They also used in industrial applications such as large volume air separation plants, but furnace air, fluid catalytic cracking air, and propane dehydrogenation. Axial compressors, known as superchargers, have also been used to boost the power of automotive reciprocating engines by compressing the intake air, through these are very rare.

3.4.2 COMBUSTION CHAMBER (COMBUSTOR)

Combustion is the chemical reaction of a substance with certain elements, usually oxygen, accompanied by the production of a high temperature or transfer of heat. The function of the combustion chamber is to accept the air from the compressor and to deliver it to the turbine at the required temperature, ideally with no loss of pressure. Essentially, it is a direct-fired air heater in which fuel is burned with less than one-third of the air after which the combustion products are then mixed with the remaining air. For the common open-cycle gas turbine, this requires the internal combustion of fuel. This means the problem of fuel operation, mixing and burning, must be addressed. Fuel is commonly gaseous or liquid. Gaseous or liquid fuels are usually hydrocarbons. Gases usually being natural gas, mostly methane, and butane. Liquids may range from highly refined gasoline through kerosene and light diesel oil to a heavy residual oil. Combustion itself possesses great difficulties. The difficulty arises because of pressure loss in combustion chamber. Almost any fuel can be burnt successfully if sufficient pressure drop is available to provide the necessary turbulence for mixing of air and fuel and if sufficient volume is available to give the necessary time for combustion to be completed.

The high-pressure air then enters the combustion area, where a ring of fuel injectors injects a steady stream of fuel. The fuel is generally kerosene, jet fuel, propane or natural gas.

Figure 3.6 show one of the combustion chamber types.

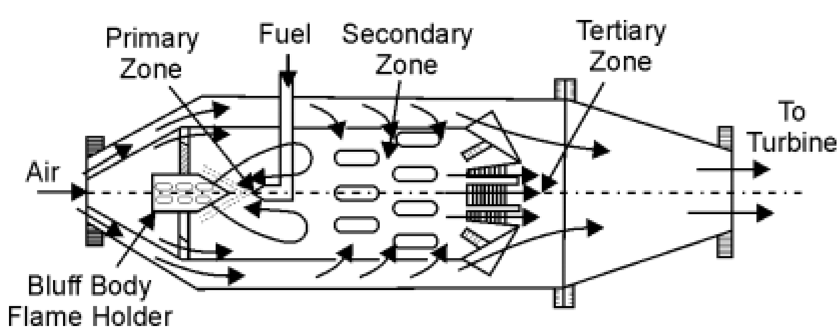

Fig. 3.6:Combustion chamber

3.4.3 GAS TURBINE:

The gas turbine in its most common from is a heat engine operating through a series of processes. These processes consist of compression of air taken from the atmosphere, increasing of gas temperature by the constant-pressure combustion of fuel in the air, expansion of the hot gases, and finally, discharging of the gases to atmosphere, in a continuous flow process. It is similar to gasoline and diesel engines in its working medium and internal combustion, but is like the steam turbine in the steady flow of the working medium. The compression and expansion processes are both carried out by means of rotating elements in which the energy transfer between fluid and rotor is affected by means of kinetic action, rather than by positive displacement as in reciprocating machinery.

Energy is added to the gas steam in the combustor, where air is mixed with fuel and ignited. Combustion increases the temperature, velocity and volume of the gas flow. This is directed through a nozzle over the turbine's blade, spinning the turbine and powering the compressor. Energy is extracted in the form of shaft power, compressed air and thrust, in any combination, and used to power aircraft, trains, ships, generators, and even tanks.

Gas turbines move relatively large quantities of air through the cycle at very high velocities. Among the mechanical characteristics of gas turbine engines are very smooth operation and absence of vibration due to reciprocating action. The high rotational speeds utilized require very accurate rotor balancing to avoid damaging vibration. Rotor parts are highly stressed with low factors of safety. Blades are very finely turned to avoid resonant vibration. Gas turbines have relatively few moving (and no sliding) parts and are not subjected to vibratory forces. As result, they are highly reliable when properly designed and developed.

3.5AUXILIARY GAS POWER CYCLE COMPONENTS

3.5.1 HEAT EXCHANGER:

The temperature of gases leaving the turbine at the end of expansion is very high. Part of this heat content can be utilized to preheat the compressed air before it reaches the combustion chamber. This reheating is done in counter-flow heat exchanger. With heat-exchanger, there is no change in the compressor work, turbine work and network done. However, there is substantial reduction in the quantity of fuel required and this aspect results in the increase in the thermal efficiency. The efficiency of regenerator is defined as:

$$\boldsymbol{H.E.E} = \frac{\textbf{Actual heat transfer}}{\textbf{Maximum possible heat transfer from gasses}} \quad \dots\dots(\mathbf{3-2})$$

The effectiveness of most regenerators used in practice is below 0.85.

3.5.2 INTER-COOLER:

The power output of gas turbine can be increased by inter-cooling. The compressed air from low pressure compressor during delivery to high pressure compressor is cooled in the inter-cooler. Therefore the compression is preformed in tow stages. The compressed cooled air has lesser volume, enabling air to be compressed in smaller compressor with less expenditure of energy.

Clearly the work required for compression is reduced with inter-cooler. The heat supplied with inter-cooling is more than that with the heat supplied in single stage compression. The net output is also increased but thermal efficiency falls due to increased heat supply.

3.6DESCRIPTION OF THE THERMODYNAMIC PROCESS

The conversion of thermal energy to mechanical one is possible only by means of a thermodynamic cycle. It can be defined as a succession of thermodynamic processes in which the working fluid undergoes a series of state changes and finally returns to its initial state. The character of the thermodynamic cycle, together with its details,influences significantly the design of the engine and its parameters. That is why the relations of the cycle parameters need to be precisely analyzed.

3.7 DEVELOPMENT MODIFICATIONS ON GAS POWER CYCLE

3.7.1BRAYTON CYCLE WITH REGENERATION

In gas-turbine engines, the temperature of the exhaust gas leaving the turbine is oftenconsiderably higher than the temperature of the air leaving the compressor. Therefore, the highpressureair leaving the compressor can be heated by transferring heat to it from the hot exhaustgases in a counter-flow heat exchanger, which is also known as a regenerator or a recuperator.A sketch of the gas-turbine engine utilizing a regenerator and the T-s diagram of the new cycler are shown in Figurs 3.7 and 3.8, respectively.

The thermal efficiency of the Brayton cycle increases as a result of regeneration since the portionof energy of the exhaust gases that is normally rejected to the surroundings is now used to preheatthe air entering the combustion chamber. This, in turn, decreases the heat input (thus fuel)requirements for the same net work output. Note, however, that the use of a regenerator isrecommended only when the turbine exhaust temperature is higher than the compressor exittemperature. Otherwise, heat will flow in the reverse direction (to theexhaust gases), decreasingthe efficiency. This situation is encountered in gas-turbine engines operating at very highpressure ratios.

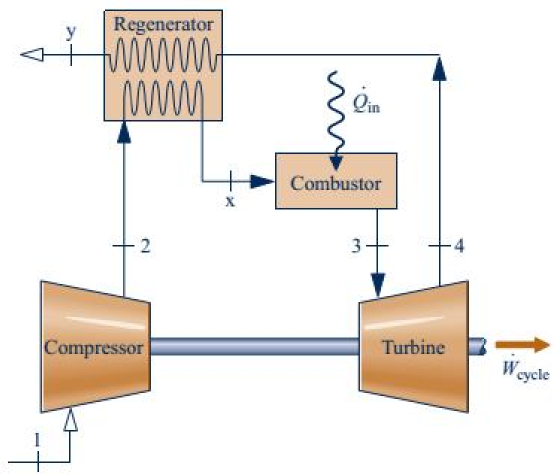

Fig. 3.7: A gas-turbine engine with regenerator.

The highest temperature occurring within the regenerator is T_4, the temperature of the exhaustgases leaving the turbine and entering the regenerator. Under no conditions can the air bepreheated in the regenerator to a temperature above this value. Air normally leaves theregenerator at a lower temperature, T_5. In the limiting (ideal) case, the air exits the regenerator atthe inlet temperature of the exhaust gases T_4.

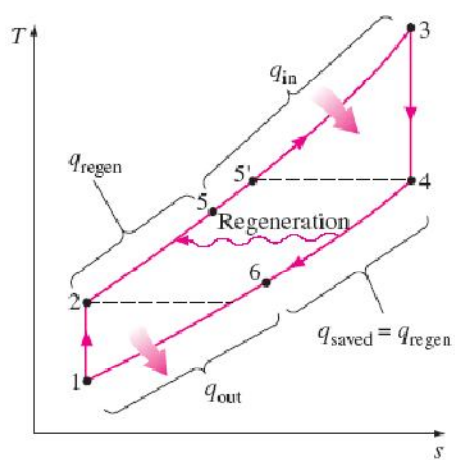

Fig. 3.8:*T-s* diagram of a Brayton cycle with regenerator.

3.7.2BRAYTON CYCLE WITH REHEATING

This process aims to reduce losses of expansion to become possibly close to isothermalexpansion process. This can be done by continuous heating of the gas as it expandsthrough the turbine. The continuous heating is not practical and so it is done in stages.In this case, the gases are allowed to expand partially before they enter the combustionchamber, where heat is added at constant pressure until the limiting temperature isreached. The use of reheat increases the turbine work output without changing thecompressor work or the maximum limiting temperature. Using the turbine reheatincrease the whole cycle output.

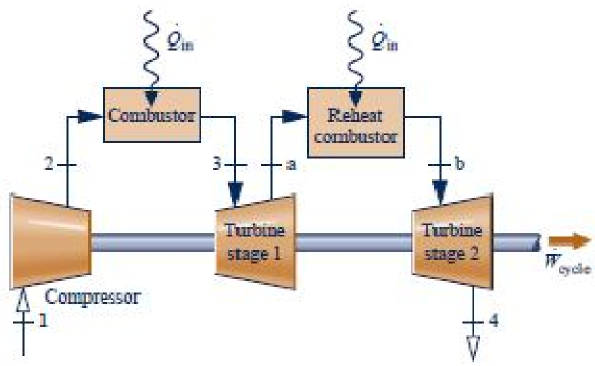

Fig. 3.9: A gas-turbine engine with reheating.

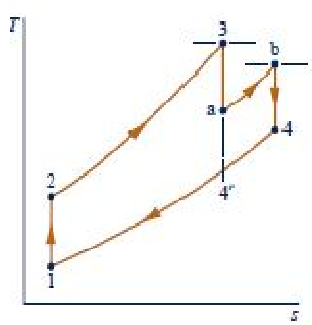

Fig. 3.10:*T-s* diagram of a Brayton cycle with reheating.

3.7.3BRAYTON CYCLE WITH INTERCOOLING

Another method of increasing the overall efficiency of a gas turbine cycle is to decreasethe work input to the compression process. These effects in an increase of the net workoutput. In this process the fluid is compressed in the first compressor to someintermediate pressure and then it is passed through an intercooler, where it is cooleddown to a lower temperature at essentially constant pressure. It is desirable that thelower temperature is as low as possible. The cooled fluid is directed to anothercompressor, where its pressure is further raised and then it is directed to the combustionchamber and later to the expander. A multistage compression processes is also possible.

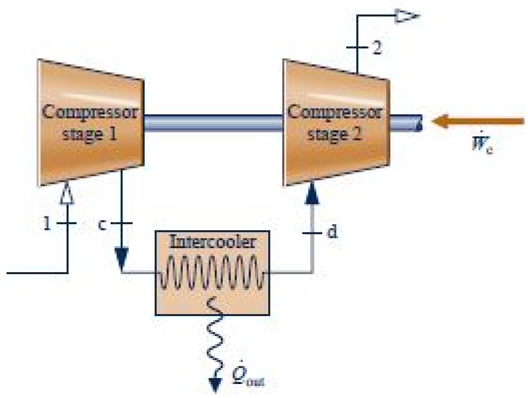

Fig. 3.11:Two stage compressors with intercooler.

3.7.4 COMBINATION OF ALL DEVELOPMENT MODIFICATIONS

The net work of a gas-turbine cycle is the difference between the turbine work output and thecompressor work input, and it can be increased by either decreasing the compressor work orincreasing the turbine work, or both. As mentioned before that the work required to compress agas between two specified pressures can be decreased by carrying out the compression process instages and cooling the gas in between —that is, using multistage compression with intercooling.

As the number of stages is increased, the compression process becomes nearly isothermal at thecompressor inlet temperature, and the compression work decreases. Likewise, the work output ofa turbine operating between two pressure levels can be increased by expanding the gas in stagesand reheating it in between—that is, utilizing multistage expansion with reheating. This isaccomplished without raising the maximum temperature in the cycle. As the number of stages isincreased, the expansion process becomes nearly isothermal. The foregoing argument is based ona simple principle: The steady-flow compression or expansion work is proportional to the specificvolume of the fluid. Therefore, the specific volume of the working fluid should be as low aspossible during a compression process and as high aspossible during an expansion process. This is precisely what intercooling and reheatingaccomplish.

Combustion in gas turbines typically occurs at four times the amount of air needed for completecombustion to avoid excessive temperatures. Therefore, the exhaust gases are rich in oxygen, andreheating can be accomplished by simply spraying additional fuel into the exhaust gases betweentwo expansion states.

The working fluid leaves the compressor at a lower temperature, and the turbine at a highertemperature, when intercooling and reheating are utilized. This makes regeneration moreattractive since a greater potential for regeneration exists. Also, the gases leaving the compressorcan be heated to a higher temperature before they enter the combustion chamber because of thehigher temperature of the turbine exhaust.

A schematic of the physical arrangement and the *T-s* diagram of an ideal two-stage gas-turbinecycle with intercooling, reheating, and regeneration are shown in Figurs 3.9 and 3.10. The gasenters the first stage of the compressor at state 1, is compressed isentropically to an intermediatepressure P_2, is cooled at constant pressure to state 3 ($T_3 = T_1$), and is compressed in the secondstage isentropically to the final pressure P_4. At state 4 the gas enters the regenerator, where it isheated to T_5 at constant pressure. In an ideal regenerator, the gas leaves the regenerator at thetemperature of the turbine exhaust, that is, $T_5 = T_9$. The primary heat addition (or combustion)process takes place between states 5 and 6. The gas enters the first stage of the turbine at state 6and expands isentropically to state 7, where it enters the reheater. It is reheated at constantpressure to state 8 ($T_8 = T_6$), where it enters the second stage of the turbine. The gas exits theturbine at state 9 and enters the regenerator, where it is cooled to state 10 at constant pressure.The cycle is completed by cooling the gas to the initial state (or purging the exhaust gases).

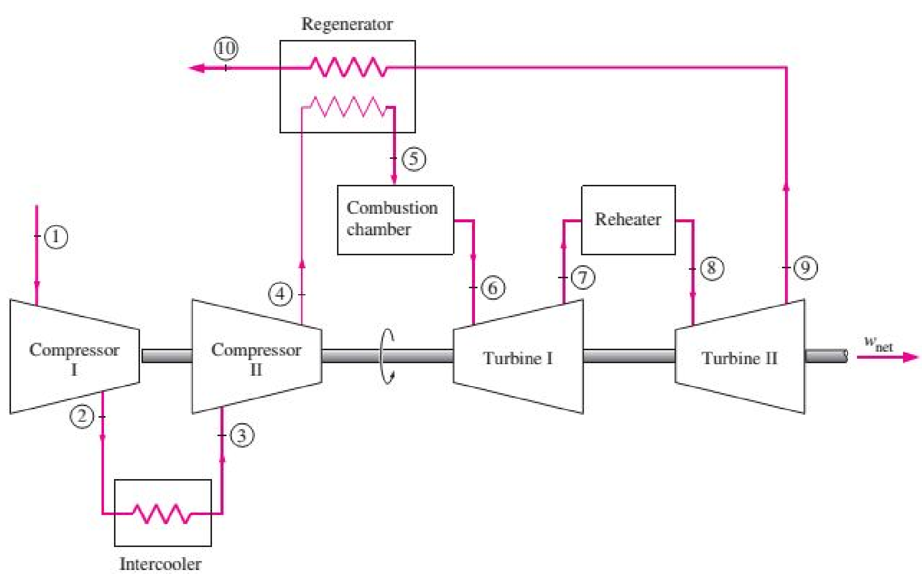

Fig. 3.12:Schmatic diagram for all development modifications

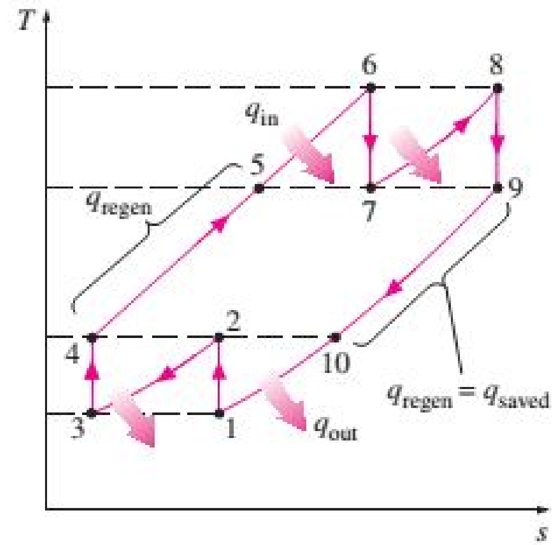

Fig. 3.13:*T-s* diagram of a Brayton cycle with all modifications.