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GAS TURBINE ENGINES (CASA ATPL)

CHAPTER 1 – GAS TURBINE PRINCIPLES

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INTRODUCTION

The method by which a jet engine achieves the objective of propelling the aircraft through the air, relates directly to Newton's law's of motion. Newton's Second Law deals with the relationship between force, mass and acceleration in that, the acceleration of a mass, by a given force, is directly proportional to the force and inversely proportional to the mass. This is usually expressed as *F=MA or the Law of Momentum.* To use a comparison we can apply a force to a propeller and the same force to a jet engine. The propeller will move a large mass of air rearward, whereas a jet engine will move a relatively small mass of air but at a much faster acceleration. Both types of acceleration produce thrust.

As the body of air is propelled rearwards, a reactive force is applied to the aircraft to move forwards. This is consistent with *Newton's Third Law, which states that for every action there is an equal and opposite reaction. This is called the Law of Reaction.*

As the aircraft actually changes from a steady state or from one attitude to another, we can say this change is consistent with *Newton's First Law, which states that a body at rest will tend to remain at rest, and a body in motion will continue in uniform motion unless acted upon by an external force. This is called the Law of Inertia.*

A jet engine achieves the acceleration of air internally. Atmospheric air is drawn into the engine through an intake by a compressor. The air passes through the compressor, which increases the pressure and the temperature of the air at a relatively stable velocity. The compressed air passes into the combustion chamber, where it is mixed with fuel. The mixture is then ignited. The introduction of heat causes the compressed air to increase in volume and temperature, and accelerate through the turbine nozzle guide vanes. The turbine extracts sufficient energy to drive the compressor, which, as a consequence is reduced in pressure and temperature. The primary function of the turbine is to drive the compressor. It also provides the mechanical energy for accessory drives, and for the propeller shaft in turbo-propeller engines. After leaving the turbine, the gas flow passes into the exhaust system. Although the turbine has caused some loss of pressure, the gas retains sufficient energy to produce the required thrust. The gas then leaves the engine by way of the exhaust nozzle as a propulsive jet.

The jet efflux causes the thrust reaction.

NEWTON' LAWS AND THRUST

As we can see all of Newton's laws are used in jet propulsion. *To quantify thrust we must use Newton's Second Law, F= MA.*

1. Substitute T (thrust) for force.

2. Mass Flow is the amount of air entering the compressor or the propeller arc, per unit time.

3. A or acceleration, is the difference in velocity between the air entering the engine (V_v) and the exhaust gas velocity (V_j).

4. Therefore; $T = M (V_j – V_v)$ Refer to Figure 1-1 and 1-2 for examples.

400 kgs of air/sec enters the propeller arc with a velocity of zero

400 kgs of air is accelerated to a velocity of 65 m/s

$T = M (V_j - V_v)$ $\quad$ $T = 400 \times 65$

Thrust = 26000 Newtons

5820 lbs

Figure 1-1 Turboprop Thrust Calculation

40 kgs of air/sec enters the engine with a velocity of zero

40 kgs of air is accelerated to a velocity of 650 m/s

$T = M (V_j - V_v)$ $\quad$ $T = 40 \times 650$

Thrust = 26000 Newtons

5820 lbs

Figure 1-2 Turbojet Thrust Calculation

As is apparent, both types of engines produce the same amount of *Static Thrust*, that is, the amount of thrust produced when V_v is zero. *The turboprop accelerates a **Large Mass** of air to a relatively **Low Velocity** and the turbojet accelerates a **Small Mass** of air to a relatively **High Velocity**.*

The Newton (symbol: N) is the International System of Units (SI) derived unit of force. It is named after Isaac Newton in recognition of his work on classical mechanics, specifically Newton's second law of motion(4.45 Newtons of thrust equals 1 pound of thrust).

MOMENTUM DRAG

What happens to our thrust when the aircraft accelerates and the value of V_v rises? The amount of thrust produced falls as the aircraft accelerates. This is called *Net Thrust.*

This phenomenon is called Momentum Drag. Momentum drag is caused by work done by the intake slowing down the airflow (necessary to maintain a stable operating condition). Refer to Figure 1-3

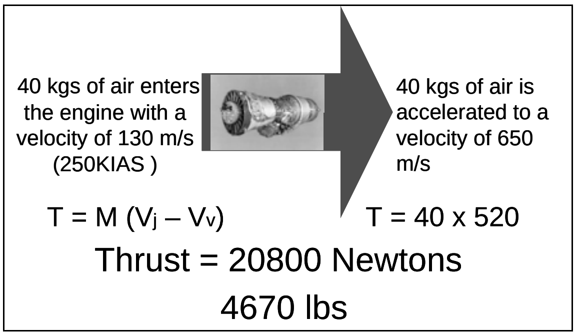

Figure 1-3 Net Thrust

RAM RECOVERY

As the aircraft continues to accelerate the static pressure increases in the intake which in turn will Increase the Mass Flow thereby increasing thrust. At speeds over 250KIAS the rise in ram effect will overcome the momentum drag. This effect is called *RAM RECOVERY.* Refer to Figure 1-4.

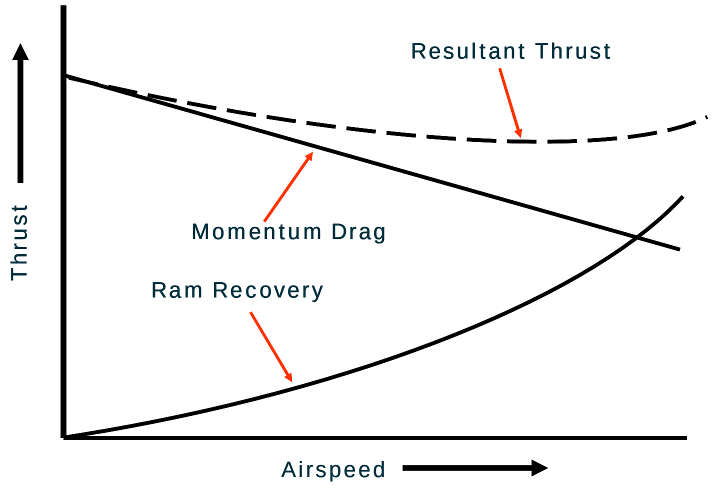

Figure 1-4 Ram Recovery

FACTORS AFFECTING THRUST

As we can see from the thrust formula, thrust can only be increased by adjusting the mass, of the air, or the acceleration of the airflow.

As we will see when we discuss ***Propulsive Efficiency***, increasing the acceleration of the airflow decreases the efficiency, increasing the amount of fuel used.

To increase thrust therefore, we need to increase the mass flow of the air through the engine. Factors affecting the ***Mass Flow*** include;

- The diameter of the Fan or Propeller,
- Air temperature,
- Air pressure,
- RPM/fuel flow, and
- Forward speed (ram recovery).

THRUST AND POWER

Gas turbine engines produce thrust and are rated by the amount of static thrust they produce. Turboprops are rated by the amount of shaft horse-power (SHP) generated together with the equivalent horse power generated by the residual gas velocity (EHP). This is called the *Total Equivalent Horse Power (TEHP).*

Thrust

As we have seen, thrust is the result of passing a mass of gas through an engine and comparing the exit velocity of the gas with the TAS of the aircraft. Clearly the higher the Mass Flow and/or the exit velocity compared with the TAS, the higher the thrust.

Jet thrust and power must not be confused. ***Power*** *is the rate of doing work and is calculated by multiplying force x speed. If the aircraft is stationary, then the engines are producing thrust, but not power.*

Power

The power of turboprop engines is measured in shaft horse power (SHP) to which is added the equivalent horse power (EHP) derived from the residual jet efflux. However there is no direct comparison between thrust and SHP, other than by converting one to the other. *For a Turboprop engine the total equivalent power (TEHP) is as follows;*

$$TEHP = SHP + \frac{\text{jet thrust (lb)}}{2.6}$$

The static thrust of a turbojet is measured on a test bench. Equivalent HP can be found as above by dividing the thrust by 2.6 but this is not an accurate procedure.

GAS TURBINE EFFICIENCY

Two efficiencies are relevant to gas turbine engines they are;

- Thermal Efficiency, and
- Propulsive Efficiency.

THERMAL EFFICIENCY

The thermal efficiency of an engine expresses the ability of that engine to convert the heat energy available in the fuel, to the kinetic energy of the gas flow. The main factor affecting the thermal efficiency is the compressor *Compression Ratio*. As the compression ratio increases, so does the thermal efficiency of the engine.

Other factors are the operating gas temperatures and the efficiency of the combustion system. These are mostly limited by engine design and so thermal efficiency cannot be enhanced by the engine operators. It should be noted that the thermal efficiency will, to a certain extent, be influenced by the ambient atmospheric temperature.

PROPULSIVE EFFICIENCY

The Propulsive or Mechanical Efficiency expresses the amount of kinetic energy which is converted to propulsive power. A jet engine operating at a *Low forward speed has a very Low Propulsive Efficiency*, as much of the high speed exhaust gas is wasted to atmosphere. As the aircraft gains momentum, the difference between the aircraft forward speed or TAS, and the speed of the jet efflux decreases.

This results in an increase in propulsive efficiency. A theoretical 100% propulsive efficiency would be expressed as the velocity of the exhaust gas rearward being equal to the forward speed of the aircraft. Propulsive efficiency may be calculated by use of the following formula:

Propulsive Efficiency $PE = \frac{2V}{V + V_j} \times \frac{100}{1}$

Where, V is the true air speed of the aircraft, and V_j is the jet efflux speed.

Relative propulsive efficiencies between different engine configurations are described in more detail in Chapter 2.

TOTAL EFFICIENCY

Total efficiency of an engine is the efficiency with which fuel energy is converted to kinetic energy and then the efficiency with which that kinetic energy is translated into a propulsive force.

GAS LAWS

The air, which is the working fluid of the gas turbine engine, experiences various changes in its pressure, temperature and volume due to its receiving and giving up heat during the working cycle of the engine.

These changes conform to the principles inherent in a combination of Boyle's Law and Charles' Law.

Boyle's Law states that, the volume of a given mass of gas at a constant temperature is inversely proportional to its pressure. Refer to Figure 1-5.

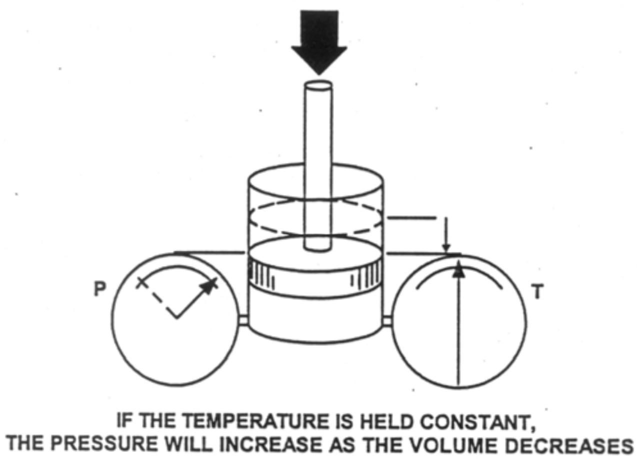

Figure 1-5 Boyle's Law

Charles' Law states that the volume of a given mass of gas at a constant pressure is proportional to its absolute temperature. Refer to Figure 1-6.

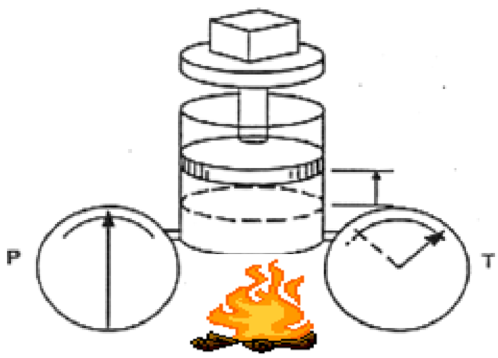

Figure 1-6 Charles' Law

To simplify these laws, assume a container of gas is exposed to 10 units of pressure. Boyle's law states that if the pressure was increased and the temperature remained the same, the gas volume would decrease. Charles' law states that if the pressure of the gas was maintained at 10 units, but the gas heated, the result would be an increase in the volume of the gas. Refer to Figure 1-7.

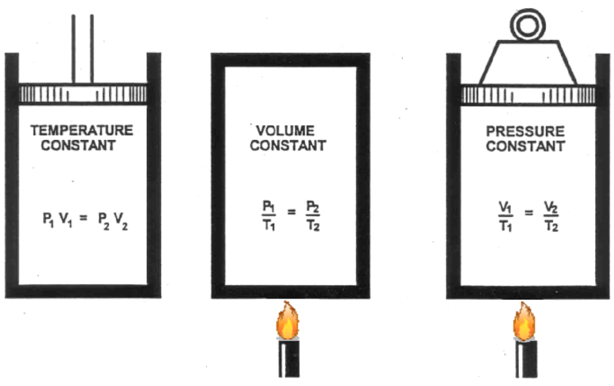

Figure 1-7 General Gas Laws

The two laws combined suggest that the absolute temperature of a gas is proportional to the product of the volume and the pressure of that gas. This applies at three distinct points in the working cycle of a jet engine. These are the;

- ***Compressor Section*** where the intake air is compressed, which increases the pressure and reduces the volume, causing a temperature rise,
- ***Combustion Section*** where the compressed air is mixed with fuel and ignited, causing an increase in temperature and volume, while the *pressure remains virtually constant,* and
- ***Turbine Section*** where the heated gas from the combustion chamber is guided onto the turbine, which removes heat energy. The temperature and pressure decrease but the gas *increases in volume and velocity.*

An example of these laws at work is shown in Figure 1-8. The most dramatic being the turbine section, where velocity varies through each turbine stage but there is a constant rapid pressure drop across the whole turbine section.

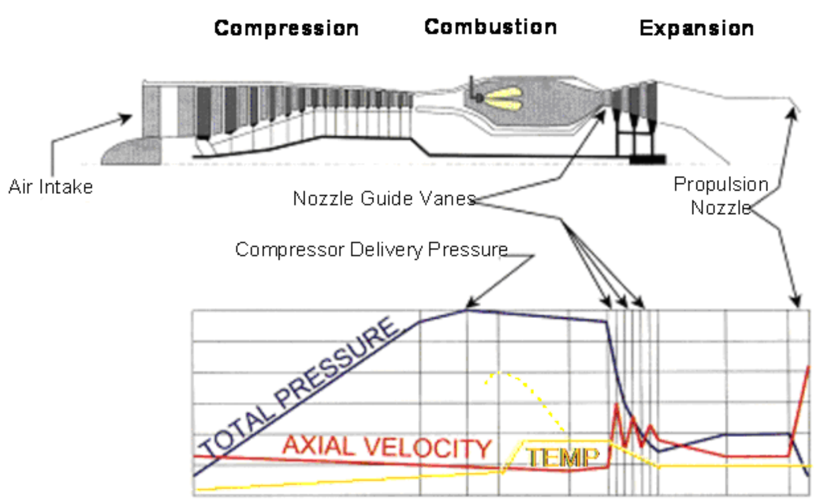

Figure 1-8 Internal Pressure, Temperature and Velocity

TEMPERATURE, VOLUME AND PRESSURE

Air passing through a jet engine will undergo changes in pressure and temperature within various sections of the engine. The changes that occur in the intake, diffuser and tailpipe are consistent with “Duct Theory”, while the changes that occur in the compressor, combustion and turbine sections are explained by “Charles” and “Boyle’s” laws.

To understand these changes, we must look at the properties of the air, and the laws which apply to a gas turbine engine.

AIRFLOW MUST BE SUBSONIC

The air entering all gas turbine engines must be subsonic. Supersonic air inside the compressor would have a dramatic effect on the airflow, as shock waves, (which are essentially pressure waves), would develop and may even result in damage to the compressor itself.

Aircraft travelling at a supersonic speed are able to reduce the relative velocity of the air entering the intake, by the use of variable geometry intakes, and/or shock wave generators. *The air behind a normal shock wave is always subsonic.*

BERNOULLI’S PRINCIPLE

This relates to pressure and velocity in moving fluid. The principle is based on the fact that subsonic air acts as an incompressible fluid. Gas flowing at a constant rate through a duct will possess a dynamic pressure component (kinetic), and a static pressure component (potential). *The combination of these, results in a total pressure value which remains unchanged as long as the mass flow rate of the air remains unchanged*. If the shape or diameter of the duct changes, the dynamic and static pressure values will each change, but they will still add up to the same combined total pressure value. Refer to Figure 1-9.

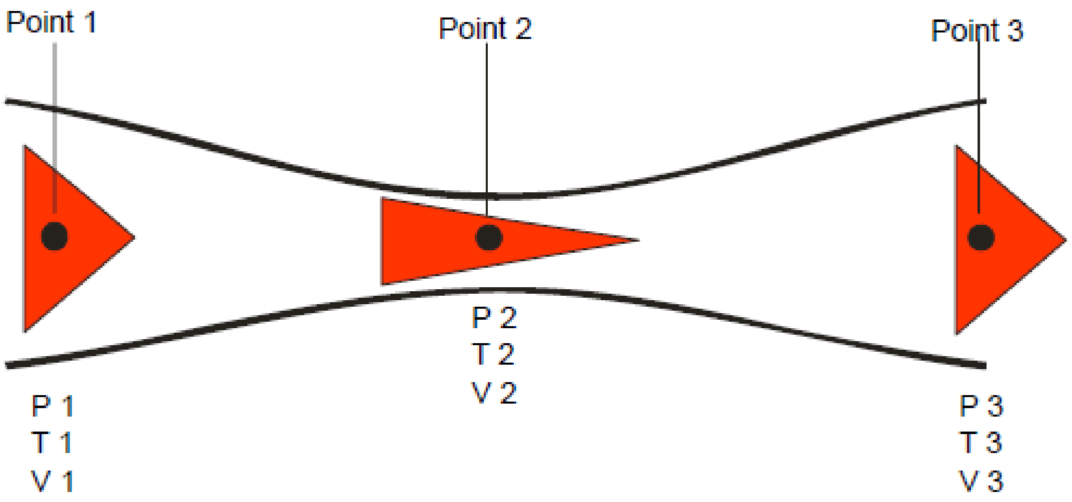

Figure 2-10 Bernoulli’s Principle

DUCT THEORY

A convergent duct is one where the cross-sectional area of the duct becomes smaller, and a divergent duct will increase in cross-sectional area relative to the flow through the duct, refer to Figures 1-10 and 1-11. If the mass flow rate remains unchanged, the velocity of a gas passing through a convergent duct will increase, and the static pressure will decrease, and, alternatively, the velocity of a gas passing through a divergent duct will decrease, and the static pressure will increase.

If we now include the basic principle of physics, that pressure and temperature are proportional, (increasing the pressure of a gas, will result in a corresponding increase in temperature), we can say that airflow through a convergent duct will experience an increase in velocity, with a decrease in pressure and temperature. Alternatively, airflow through a divergent duct will experience a decrease in velocity, with an increase in pressure and temperature.

This explanation applies to the airflow through the inlet, diffuser and tailpipe sections of the jet engine. In the compressor, combustion and turbine sections of the engine, there is an exchange of energy with the airflow, and is therefore subject to other laws of physics.

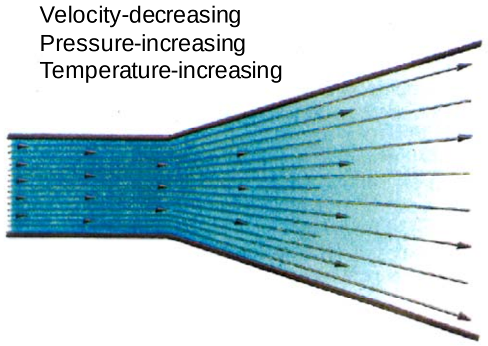

Figure 1-10 Divergent Duct

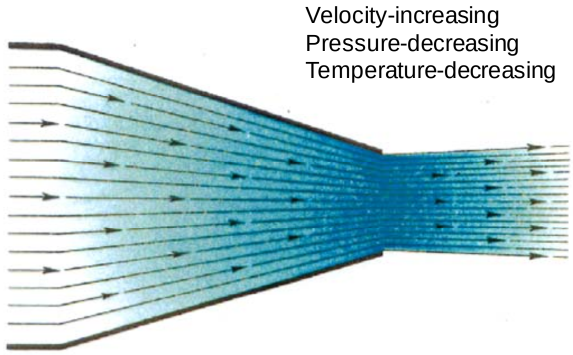

Figure 1-11 Convergent Duct

AIRFLOW AND VELOCITY

To show the importance of duct design in relation to the operation of the engine, the duct between the compressor stage and the combustion chamber is divergent in cross section, which causes the speed of the airflow to decrease, but the pressure and temperature to increase. This reduction in airflow velocity allows the flame to burn efficiently in the combustion chamber. Conversely, the cross section of the exhaust nozzle reduces in diameter, causing the gas flow to accelerate, while pressure and temperature reduce, enhancing the jet efflux.

GAS TURBINE WORKING CYCLE

Gas turbine engines may initially be compared to piston engines, in that they are both internal combustion units. They both also follow the process of induction, compression, combustion and exhaust, but there the similarity ends. The piston engine operates on the four stroke Otto cycle, which is referred to as the *Constant Volume Cycle,* because the energy added to the air causes almost no change in volume. All the events in the Otto cycle take place inside the engine cylinder, but at different times.

The gas turbine engine operates on the Brayton cycle, which is referred to as *a Constant Pressure Cycle*, because the air passing through the combustion chamber remains at the same pressure, while increasing in volume and temperature, thereby producing a continuous power output.

The Brayton Cycle is continuous, and like the Otto Cycle has four distinct operations. They are;

Induction Ambient air is induced into the engine through the air intake, drawn in by the compressor. If the aircraft is in flight, the intake air is already partly compressed.

Compression The intake air is progressively compressed by the rotating compressor stages. It should be noted that there are several different types of compressor. The diagram below shows a single spool compressor. As the air is compressed, it increases in pressure and temperature, though its speed through this stage remains virtually the same.

Combustion The compressed air is moved on into the combustion chamber by way of a divergent passage or diffuser, which increases the pressure further. In the combustion chamber it is mixed with fuel via spray nozzles. The mixture is ignited by igniter plugs and then burns, causing the gas to increase in volume. The greater the temperature rise, the greater the expansion of the gas, producing a higher thermal efficiency. The upper limit will be specified by the manufacturer to safely protect the structural integrity of the engine. This in turn causes an increase in temperature and in velocity. Combustion is continuous, and during this stage the high pressure of the gas remains more or less constant.

Expansion and Exhaust The heated high pressure gas from the combustion stage is next directed through nozzle guide vanes which, as restrictors, increase the speed of the gas and direct it onto the turbine blades. The turbine extracts energy from the hot gas which causes it to rotate and drive the compressor.

The energy left over is directed through the exhaust, a convergent duct, which increases the velocity of the gas to produce thrust. Refer to Figure 1-12.

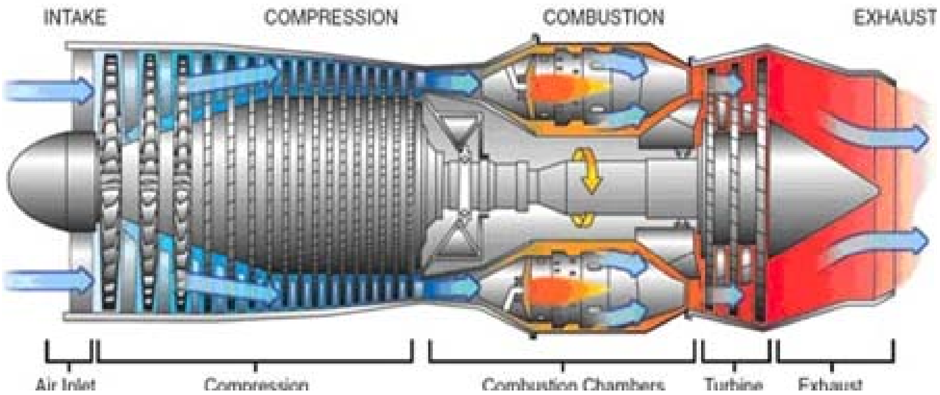

Figure 1-12 Turbojet Working Cycle

OTTO VS BRAYTON

Otto Cycle or piston engine failure rates are proportional to the power they produce. The higher the horsepower output the higher the failure rate. To produce more power an Otto Cycle engine requires more cylinders and more size, with higher pressures and more moving parts. As Brayton Cycle engines have the same amount of moving parts no matter the thrust output, there is no link between power and failure rates.

As the Brayton Cycle is continuous, unlike the Otto Cycle, which only produces power on the power stroke, it has a much higher power to weight ratio. Refer to Figure 1-13.

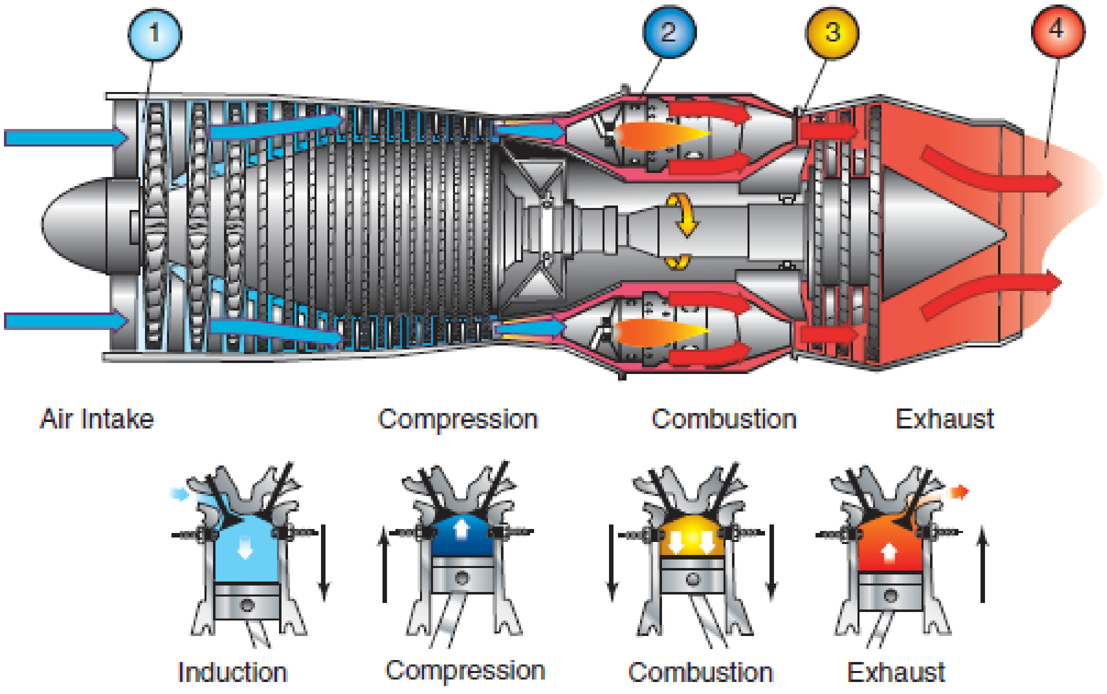

Figure 1-13 Otto Cycle Vs Brayton Cycle