**INTRODUCTION TO AEROSPACE PROPULSION**

**LECTURE NO – 23**

Today we shall see about the various types of engines that power the aircraft for flight. We have already had good exposure to various laws of physics like the Newton’s Laws of Motion, the Thermodynamic Laws. Most of these engines or all of these engines conform to these laws and they cannot operate without these laws. These are the fundamental laws on which the Engines are built and operated. So they are also called as Heat Engines. As these engines create motion, they are also necessary to satisfy the Laws of Motion.

Today we shall see about Piston-Prop Engine.

**PISTON – PROP ENGINE:**

This is the engine that powered the 1st flight of the Wright Brothers. 50 years later the 1st flight almost all aircrafts flew with the piston prop engine. Even today 1000’s of aircrafts fly with this type of engine. The working of this type of engine will be discussed today.

There are two components of the Piston Prop Engine. They are:

1. **Piston Engine**: It is also known as the **Internal Combustion Engine (ICE).** This type of engine creates the power for the engine which is used by the propellers to provide the thrust.
2. **Propellers:** They are known as the Thrusters. They create the thrust by using the Power provided by the Piston Engine. They convert the power of the piston engine to the thrust which assists in aircraft moving forward.

Piston Engine is created from the concept of Energy, Work from the laws of thermodynamics. These laws again help to convert this work into the power.

**PISTON – PROP POWER PLANTS:**

This type of engine is based on the Otto Cycle. This Otto cycle is one of the cycles upon which the heat engines are generally based on. There is the Ideal Otto Cycle and the Actual Otto Cycle. The Piston Engines work upon the Actual Otto Cycle.

These Piston Prop Power plant engines are the ICE. The combustion is the method by which the energy is supplied to the system. The system is nothing but the Engine itself. Input from outside the system is supplied into the system. This energy is converted to work. This conversion uses the Thermodynamic laws. This is the principle which is used in creating Engines.

Energy from outside the system which is the process of burning the fuel known as the **Combustion Process** is to be converted to Work Output. The mechanism by which this is converted produces the Mechanical Work upon which the whole engine is built. We shall see that all the thermodynamic concepts are used in this conversion and the thrust is thereby obtained which makes the aircraft fly.

The heat engines that are developed should be based on one or the other thermodynamic cycle so that a continuous process of control is there over the various legs or stages of the cycle. The main advantage of using these thermodynamic laws is that the we can predict how the engine will perform at various legs or processes of the cycle along with the mathematics that goes into the thermodynamic laws. Therefore it is necessary for the creator of the engine that the engine conforms to the Thermodynamic Laws so that the final performance is very closely predicted. A **Thermodynamic Cycle is made up of different processes or legs**. These processes can be constant volume process, constant pressure process, isentropic process..etc. All these processes might combine to form a cycle. So a thermodynamic cycle performance can be predicted. All the processes of the cycle have a definite path. The cycle uses or re-cycles the working medium which is nothing but the Air from the atmosphere. The main purpose of using air as a working medium is that, it is available in bulk quantity. So all the engines which we will be seeing in this course will be the **Air Breathing Engines (ABE).** Towards the end of this course we will be seeing the **Rocket Engines** which are the **Non- Air Breathing Engines**.

Now let us see about the Ideal Otto cycle.

**IDEAL OTTO CYCLE:**

This cycle is shown in the Picture 1 of the plot of Specific Volume (v) vs Pressure. This cycle has6 processes. The air is taken in freshly which is shown by the point ‘a’. The air intake is from ‘a-b’. Then the air is compressed from ‘b-c’ in which the pressure and the temperature increase. The combustion process is shown from ‘c-d’ where the fuel is added. In this combustion process, the temperature of the air mixed with the fuel increases. So as the temperature increases, pressure also increases. Then from‘d-e’ is the expansion of the air or the **power stroke**. This is the stroke that produces the power to the entire engine. From ‘e-b’ there is some heat rejection through various heat transfers. The process ‘b-a’, the exhaust of the hot gas is exhaled. Then again the fresh air comes in through ‘a-b’ into the system. This is a continuous process.

**SCHEMATIC OF THE ENGINE:**

The schematic of the Piston is shown horizontally below the Plot and vertically at the right of the plot. The **Stroke Length LP** is the displacement of the Piston from the **Top Dead Centre (TDC)** to the **Bottom Dead Centre (BDC)** which is held upright in vertical position. The piston can also be horizontally placed and need not be vertical alone. When air is inhaled from ‘a-b’, the piston moves from the TDC to the BDC forming a large space of opening for the air to come in. Air is sucked in to the piston and fills up the entire space. Then during the Compression stroke from ‘b-c’ the piston moves from the BDC to TDC compressing the air to a very small space. Air is trapped in this small space. In this small space where the air is trapped, the combustion process takes place where the fuel is injected into the air. This process raises the temperature as well as the Pressure of the air trapped. This pressure acting on the piston head is forced to move the piston from the TDC to BDC. This stroke is called the **Power Stroke or Expansion** stroke from‘d-e’. Then the exhaust stroke starts. The burnt gas exhaust is exhaled out of the port at the TDC through a valve. The opening and closing of the valve is controlled by a timing port. And at the same time the gases are exhaled, the fresh air comes in again. These ports are timed to open and close.

The various processes involving these compression and expansion are as follows:

1. **‘a-b’:** the air intake takes place at Constant Pressure Process.
2. **‘b-c’:** the compression process is Isentropic in nature in ideal cycle. It means that the entropy is conserved.
3. **‘c-d’:** the combustion occurs at Constant Volume Process. There is no change in Volume.
4. **‘d-e’:** the expansion or the power stroke occurs at Isentropic again.
5. **‘e-b’:** the heat rejection is at Constant Volume Heat Rejection from the exhaust gases.
6. **‘b-a’:** the exhaust stroke is occurring in a Constant Pressure Process. The exhaust of the burnt gas takes place in this stroke.

In the Isentropic process above for an ideal cycle, it means that there are no losses occurring in each stroke and the process is adiabatic in nature. Therefore an **Isentropic process** can be said to be a **Reversible Adiabatic Process**.

All these legs can be done in various thermodynamic processes. So all these processes can be put together to find out the work output of the engine. All these processes should be such that they conform to the various Thermodynamic Laws and say how an entire works.

**AREA OF THE PV DIAGRAM:**

It can be noted from the PV diagram that, as the Net Area of the Cycle Diagram Increases, then the Power output also increases. The **area under‘d-c’ is the output Power** available and the **area under ‘b-c’ is the input** power given. The useful amount of Work available to generate the Thrust is the **area of ‘b-c-d-e’ curve**. This is the **Net Work or useful work available.**

**Network = Output Work – Input Work**

The engine designer tends to increase the area of the cycle if there is a need to increase the Power Output. To **increase the Power Output to a maximum** value, then there are some ways:

1. **Increasing Specific Volume (v):** by increasing the Stroke Length, the Specific Volume can be increased so that the ‘a-b’ line increases.
2. **Increasing Pressure (p):** by increasing the pressure the‘d-e’ line increases such that ‘d’ is at higher pressure and ‘e’ is at low pressure.

The large change in volume causes the engine size to increase. And the large change in pressure causes the volume to change. Large change in temperature requires the large input of fuel or fuel of high heat release capacity. Therefore, these are some of the troubles that are faced when the power is to be increased. Because when volume changes then the engine size also changes which means the Engine weight goes up which is not desired when used to power the aircraft.

**Ideal Otto Cycle Analysis:**

To quantify our needs, let us mathematically develop the Otto Cycle.

The line ‘c-d’ is the region where the heat input (Q1) is given to the cycle. The line ‘e-b’ is the region where the heat goes out (Q2) of the cycle. Therefore, if no compression and expansion took place then Q1 & Q2 are the input and output given to the cycle.

**Heat Input, Q1 = Cv ( T3-T2)**

**Heat Output, Q2 = Cv ( T4-T1)**

Taking the points ‘b-c-d-e’ as ‘1-2-3-4’, it gives the Heat Input and Heat output to and out of the system. The Power Stroke Converts the heat of energy released by the fuel burnt and the pressure increase obtained through the compression process into a mechanical work or mechanical motion. Therefore, the Net Work is:

**Net Work = Q1-Q2**

= Work done by power stroke – work done by Compression Stroke

= area bcde

= available useful work from the cycle to produce the Thrust.

**CHARACTERISTIC PARAMETERS OF THE CYCLE:**

There are number of parameters that characterize a cycle. They are called the Characteristic Parameters. There are 3 such parameters:

1. **Compression Ratio (ε) :** Vb/Vc. It is the Volume Ratio of the Inlet Stroke ‘a-b’ and the Compression Stroke ‘b-c’.
2. **Pressure Ratio (п) :** Pc / Pb . It is the Pressure Ratio between the Compression and the Power line.
3. **Temperature Ratio (τ):** Td / Tb. It is the Temperature Ratio of the Maximum Temperature of the cycle to the Minimum Temperature of the cycle.

Every cycle is sensitive to these ratios because these parameters decide the work capacity and efficiency with which the work is accomplished in the cycle. Cycles are mentioned often in terms of these ratios. In fact, the Open Cycles are mentioned in terms of the Pressure Ratios.

The Compression and Expansion are Isentropic. So we can use the isentropic laws. The Combustion and Heat Rejection processes are Iso-choric (constant volume process). We can use these laws also. Using these laws, if we put a simple derivation we get the **Thermal Efficiency** of the system to be:

**ηth= 1- 1/(ε^(k-1))**

where,

k –specific heat ratio of the working medium (air in our cycle)

ε – Compression ratio of the cycle.

If we have the ε and k value for a cycle, then the thermal Efficiency can be found out. Therefore thermal efficiency of the cycle can be found out quickly. This allows an engine designer to configure a cycle before it is even built.

**Using this equation from above for example:** taking the values as shown in Table-1, Picture 2. Calculating the Efficiency of the cycle for various compression ratios, and two different ‘k’ values of 1.35 for hot gas and 1.4 for air, we can see that the efficiency of the cycle with pure air is greater than that for a hot gas. But for us to produce power, hot gas is used. Therefore, as the compression ratio increases, the Efficiency of the cycle also increases. This gives the designer an idea so as to obtain efficiency for the cycle, what has to be the compression ratio and the ‘k’ value.

**T-S DIAGRAM OF OTTO CYCLE:**

The P-V diagram can also be recast as the T-S diagram as shown in Picture 3. The Thermal Efficiency in the TS diagram can be found out as follows. The Work Input to the System is the Area ‘6-2-3-5’ and the Work Output from the system is the Area ‘6-1-4-5’. Therefore the Thermal efficiency is given as

ηth = (Q1-Q2)/Q1

= (area ‘6-2-3-5’ – area ‘6-1-4-5’) / area ‘6-2-3-5’

= Net Area / area ‘6-2-3-5’

**ηth = area ‘1-2-3-4’ / area ‘6-2-3-5’**

Consider another cycle plaed in the TS diagram which has the same net area as the 1st cycle. Area ‘1-2-3-4’ = Area ‘1-7-8-9’. It implies that 2 different people have designed these 2 different cycles with the net area being the same. In the **2nd cycle the ηthis higher than the 1st** cycle because the Heat Rejection in the 2nd cycle shown by the area ‘6-1-9-10’ is lesser than the 1st cycle heat rejection which is shown by the area ‘6-1-4-5’. Therefore the Area ‘6-7-8-10’ is also lesser than the area ‘6-2-3-5’.

The line ‘7-8’ is the heat input of the 2nd cycle at constant volume which makes the efficiency of the 2nd cycle higher than the 1st cycle. The cycle designer plays an important role in choosing these values and a lot of thought is be done before creating the Otto cycle to create the Piston Engine which is used to generate the Thrust.

**DIFFERENCE BETWEEN IDEAL AND ACTUAL CYCLES:**

The picture of ideal and actual cycle is plotted together in Picture 4. The actual engine will have some losses and will work on the actual cycle. We shall see in what ways the real cycle of the engine differs from the ideal cycle.

**Difference:**

1. Net Area of the actual cycle is lesser than the Ideal cycle Net Area because the Work done during the expansion and compression process is not Isentropic. There are some losses in the form of energy loss. Therefore the Isentropic process is not reversible. It still though remains closely Adiabatic. Therefore the **Net Work out of the system** for an **Actual cycle is lesser than the Ideal cycle**.
2. The Intake and Exhaust stroke are not on the same pressure line as the ideal. They both differ from the ideal cycle.
3. **Intake:** the intake stroke occurs at a Pressure Line ‘1-2’ which is lesser than the Ideal cycle Pressure line ‘a-b’
4. **Compression:** the pressure at compression is starting at ‘2’ which is lesser than the ideal cycle pressure ‘b’. Therefore, the actual cycle pressure of compression starting is lower than the Ideal cycle. This is because the process is not isentropic and has some losses due to the Piston Motion. The end of the compression does not reach ‘c’ as the ideal cycle, but reaches a lesser pressure value ‘3’.
5. **Combustion:** the combustion process starts even before the compression process has ended at ‘3-4’. The Pressure and temperature rises for the gas. An incomplete combustion occurs, which is why the piston never reaches the ideal cycle position of ‘4’ for the combustion process.
6. **Expansion:** the expansion starts at ‘4’ even before the combustion has completed. The power stroke moves the piston to ‘5’ which is at a pressure lower than the ideal cycle pressure‘d’. The expansion completes at a lower pressure. The Power stroke appears to be rounded because there is no time to complete the entire process as the exhaust gas has to be taken out of the system. The gases are exhausted out very quickly.
7. **Exhaust:** the exhaust occurs at ‘5-6’ which is a higher pressure than the ideal cycle pressure. There is a slight difference between the exhaust stroke and the intake stroke which causes a loss of energy and the Thrust also Reduces. The exhaust completes off at ‘6’. The cycle then starts off once again. It is a continuous process.

**TWO STROKE ENGINES:**

This type of engine is shown in the Picture 5. The Otto cycle was earlier used to develop the 2 Stroke engines. They are not used in aircraft engines anymore. Modern aircrafts uses 4 stroke engines.

The Working of the 2 Stroke engines is the whole cycle is completed within the 2 legs of processes. The **Intake and the Power stroke** are combined together in this cycle. This happens when the Piston moves downward from the TDC to BDC; the fresh intake of air comes in from the side of the engine. Then when the Piston moves top to TDC where the air gets compressed and combustion takes place at TDC itself. The **Combustion and the Exhaust Stroke are put together** in this engine.

The cycles that we will be looking from now onwards will be four stroke engines.

**FOUR STROKE ENGINE:**

This type of engine is shown in Picture 6. These types of engines are used in modern aircrafts. The thermodynamic processes are converted into the strokes.

**Operation of Four Stroke Engines:**

The Intake Valve (A) or the intake port opens through which the Fresh air comes into the engine cylinder. These opening of the ports are timed properly. The piston moves to the BDC and the air fills the entire cylinder. The Compression Stroke starts which compresses the air to a small place in which the piston moves from BDC to the TDC. The combustion Process starts at the TDC in which a Spark Plug (K) initiates the ignition. The combustion produces a high pressure, temperature and high internal energy hot gas. This pressure moves the piston downward to the BDC which is the Power or Expansion Stroke. In this stroke the Power is obtained and extracted. What remains is the burnt gas which is exhausted out of the cylinder by the inertial movement of the piston to the TDC. The burnt gases are sent out through the exhaust valve (J) which is timed properly to open. Almost entire amount of burnt gases are exhausted. Only some quantity of the burnt gases remains in the TDC when the inlet port opens and the fresh air comes in. So the **air that gets compressed from the 2nd time is not a fresh air but a mixture of fresh air and burnt gases.** This is the **reason why the Real cycle differs from an Actual cycle.**

The power has already been taken by the Crankshaft to which the Piston is attached. The crankshaft provides a Rotary motion from the reciprocating motion, which powers any working body. In our case, the rotary motion is used to rotate the Propellers. So this is the working of the four stroke engine.

In the next lecture we will be seeing as to how an engine of this kind is converted to aircraft power plants. We shall be looking at the arrangements of the various components so that the Thrust is obtained.