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Aerospace Propulsion

Introduction

Lecture 1

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Good afternoon note in this course we will be talking about propulsion systems.

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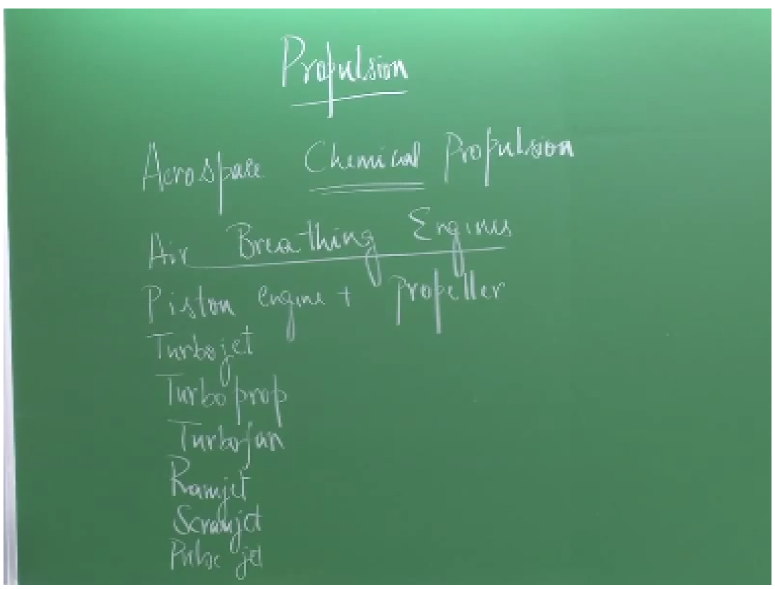

So this course deals with propulsion and in this course we will be restricting ourselves to aerospace propulsion only, so I said propulsion now have introduced a new term chemical propulsion chemical aerospace chemical propulsion is what we are going to discuss in this so in this course chemical propulsion I mean the energy that is converted by burning a fuel is what I am looking at so if you look at the chemical propulsion the energy stored in the bonds of the fuel and the oxidizer and when they are broken and fresh bonds are made energy is released which leads to high temperature gases which can then be expanded through nozzles which we will discover as we go along in this course.

So this course deals with aerospace chemical propulsion now let us firstly look at what are all the systems that are available for aerospace chemical propulsion let us familiarize ourselves with some names of systems in this we also have something known as everything and non air breathing propulsion in an air-breathing propulsion system what we have is the fuel is only carried onboard the oxidizer we get from the air has 21% oxygen and we use that for as the oxidizer.

So air is used as the oxidizer in everything propulsion which is why it is known as air breathing engine here we have a turbojet then we also have something known as pulse-jet which is very scarcely used so these are the systems that we have in air-breathing propulsion let us look at the non air breathing propulsion systems.

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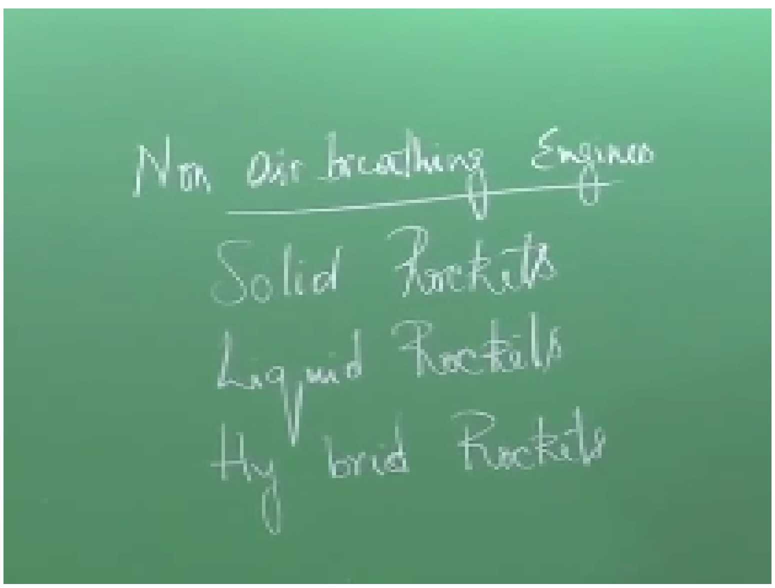

Here these are also known as rocket engines so you have solid rockets, liquid rockets and hybrid rockets now solid Rockets is named so because both the fuel and oxidizer are in a solid phase so hence the name solid rockets whereas in a liquid rocket you have the fuel and oxidizer being in a liquid phase and lastly the hybrid you have the fuel and solid phase and oxidizer being liquid so that is why the name hybrid because it is essentially a combination of these two systems.

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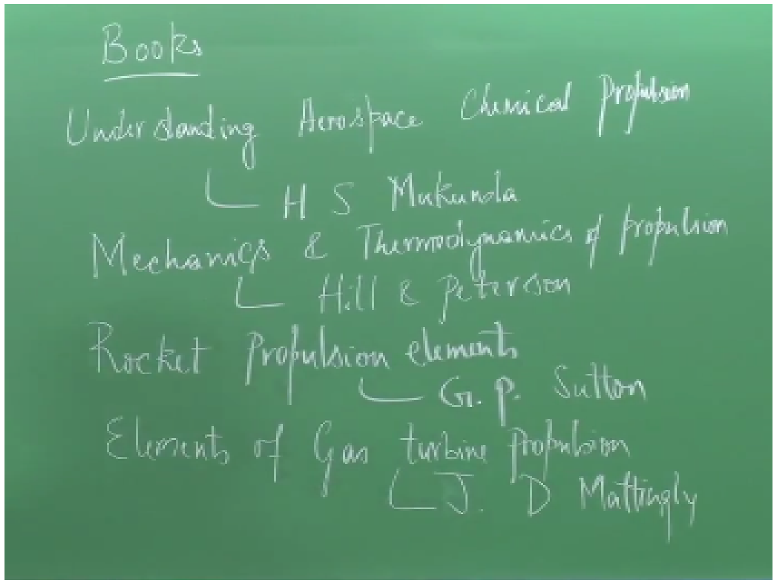

So these are basically the systems that we are going to study in this course and the textbooks that I am going to use or the reference books that I am going to use are as follows understanding aerospace chemical propulsion by H.S. Mukunda then mechanics and thermodynamics of propulsion by Hill and Peterson then you have rocket propulsion elements by GP Sutton then elements of gas turbine propulsion by JD Mattingly.

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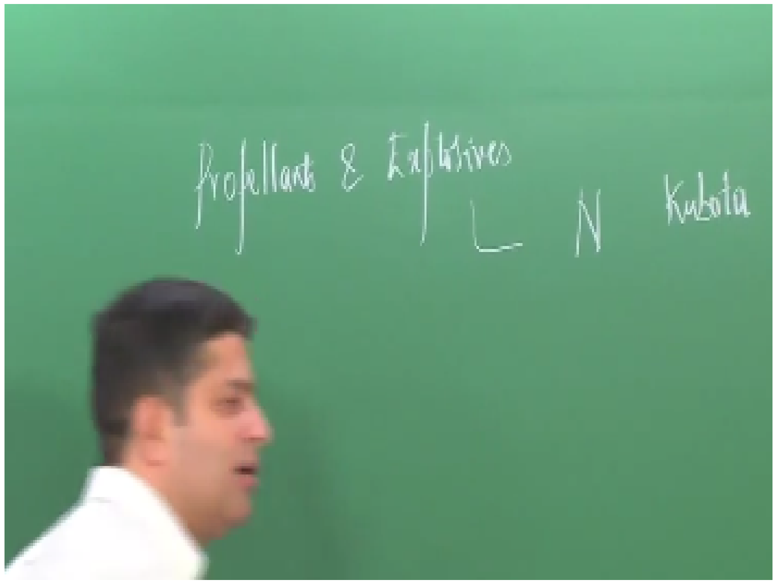

And lastly propellants and Explosives by N. Kubota these are the books that I will be following in this course and some of them are exclusively rocket propulsion textbooks like rocket propulsion elements and propellants and explosives these are exclusively raw deal with exclusively rockets while the rest of them are deal with both rockets and everything propulsion now firstly we need to understand that propulsion means to move oneself forward or to move oneself from one place to another that is to propel oneself.

So you need energy to do that and you need a system to take care of this and that is what is a propulsion system and as we have described there are two kinds of systems air breathing air breathing engines and non air breathing engines let us firstly look at when do you use which one whenever we require a very large thrust for a very short duration like in rockets or and missiles we use the non air breathing engines or the Rockets whenever we use we need a large thrust for a very long duration like in aircrafts that go from one place to another across continents.

We then you will use air breathing systems because in air breathing systems you have the advantage of not needing to carry the oxidizer so therefore it makes sense to make use of the atmospheric oxygen and propel yourself rather than carry the oxidizer also which is what is done in these rocket engines and the other application of rockets is in interplanetary missions wherein you actually do not have any oxygen available.

So therefore you will have to carry your own oxygen on board to make sure that you can reach your destination so these are used for interplanetary missions and for missions wherein you require a very large thrust for a very small duration of time whereas this system you use for large thrust long duration you use everything else okay so let us first look at some history of how these air breathing engines evolved and then we will go to the rockets.

So historically man has been looking at nature for inspiration to do things like we do look at birds flying and we wanted to fly that was our first attempts at flight so a lot of the earlier designs always try to mimic the bird so people built what is known as Ornithopters.

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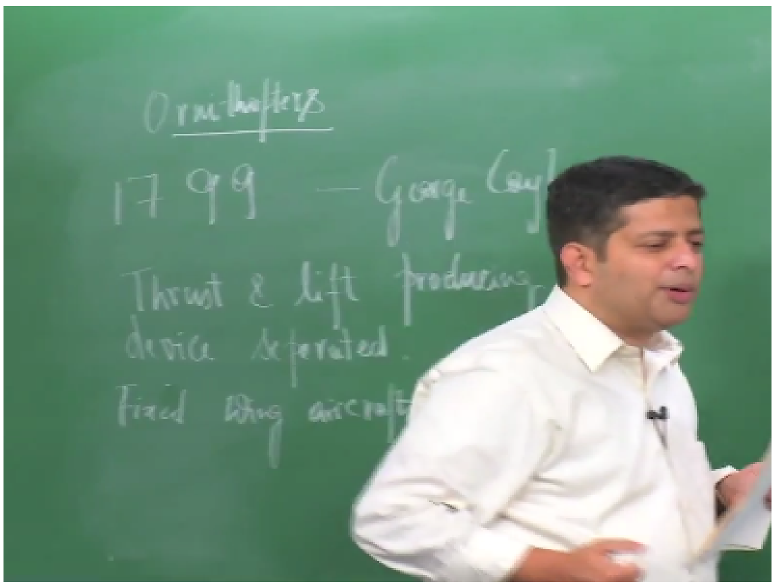

Ornithopters are essentially flapping wing devices which will help us stay afloat in the air ontology or to fly they were never really successful primarily because both the thrust and the lift had to be generated by the wings as done by the birds and given the weight of the human body and the power we could generate by flapping the wings we were never able to do both that is take care of lift as well as propelling ourselves forward so both this was not possible and it took a long time for people to realize this that it is not possible to do so and somewhere in the 11 1799 George Cayley he was the first one to come up with a system wherein the lift and the thrust producing devices would be separated.

So till that time people were having lift and the thrust producing device the same he was the first one to suggest that they should be different so trust came the idea of fixed-wing aircraft but this was only a conceptual stuff and the actual flight happened somewhere in 1903.

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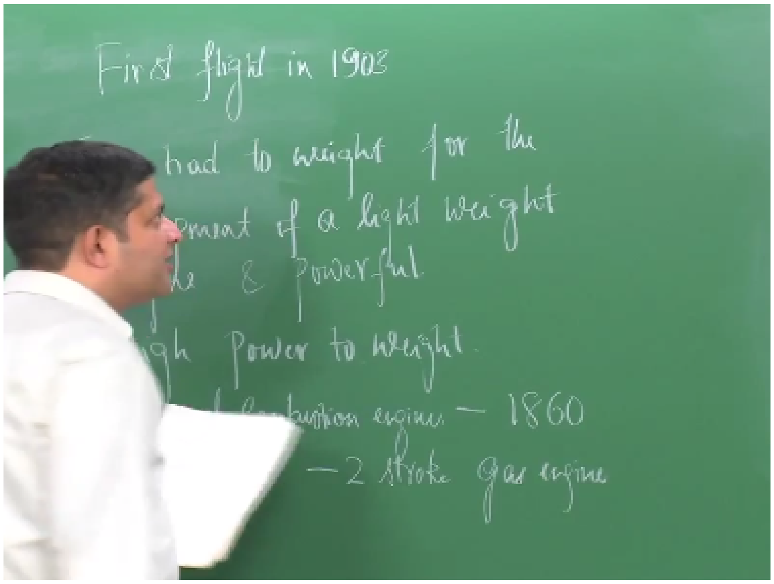

So it took almost a 100 years from the time we conceptualized flying that is separating the lift producing device and the thrust producing device to actually fly and the reason for that was although we said that the last thrust producing and lift producing devices are different they had to come up with a thrust producing device that was the engine so they had to wait they have to wait for a light weight engine which was also powerful so essentially they were looking for a engine which had a good thrust to weight or power-to-weight our internal combustion engines began to be developed in the Year 1960, 1860 and Leno have developed a two-stroke gas engine.

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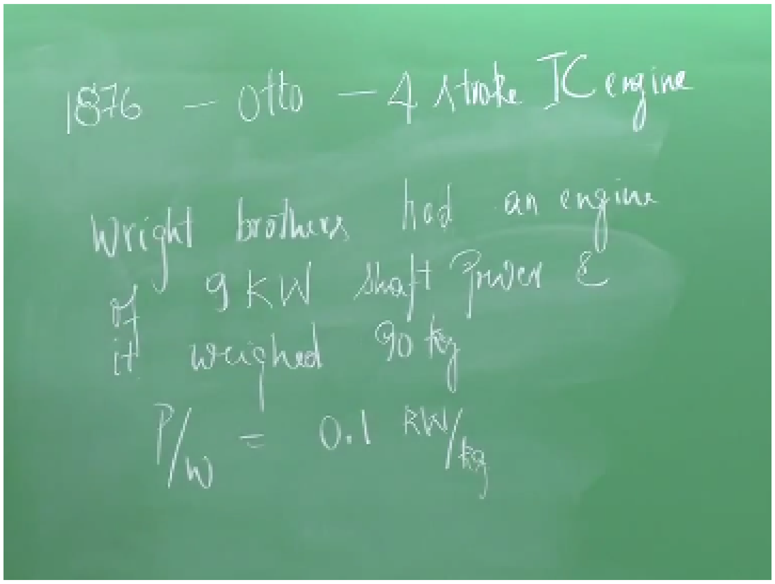

And later our in the year 1876 otto designed a 4-stroke internal combustion engine or IC engine and in the year nineteen not three the wright brothers had an engine of 9KW shaft power and it weighed something like 90 kgs so essentially a power-to-weight ratio of 0.1 so very small power-to-weight ratios of the engines that were developed later on towards the 40s you had engines of the order of power-to-weight ratio of the order of 0.4 to 0.6 and in the later years it did improve a little.

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Reciprocating engine propeller

Engine	Power, kW	Mass, kg	sfc kg/kWhr	P/M kW/kg	P/Vol. W/m^3
Al -14 R, Poland	242	245	0.36	0.98	0.31
Lycoming R-7755 (36 cyl)	3730	2745	0.43	1.36	----
Teledyne - Continental	324	290	--	1.1	0.4

If you look at this table here I have put together some of the engines here you have a reciprocating engine plus propeller some of these engines produce something like 3,700 kilowatt and had a power-to-weight ratio of 1.36 and a power to volume ratio of somewhere around 0.3 to 0.4 we will see how this engine works here.

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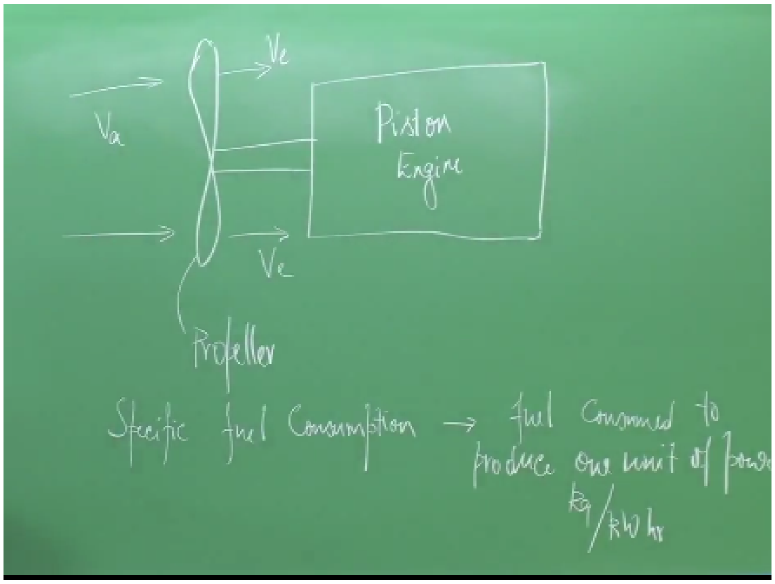

So if you look at the engine the engine would be having a propeller couple- a piston engine, so this is the propeller and this is the piston engine so the propeller is the thrust producing device and the piston is the power producing device so what happens well is when air comes in here let us say it has a velocity Va because of the propeller action the velocity of the air behind the propeller increases to Ve and because of this there is a change in momentum which leads to the thrust being produced.

So you have here the piston being the power producing device and propeller being the thrust producing device so with this they were able to propel themselves and as I said power-to-weight ratios of the order of 1.3 were also realized and if you look at the other performance parameter namely specific impulse sorry in this case specific fuel consumption what we mean by specific fuel consumption is that it indicates fuel consumed to produce one unit of power so it is units in SI units SI units would be kg per kilowatt hour ah kg per hour being the fuel flow rate and kilowatt being the power that is produced.

So it essentially indicates what is the amount of what is the fuel flow rate required to produce one kilo watt so this was about the engines now as I said you had engines that was producing a lot of power.

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Reciprocating engine propeller

Engine	Power, kW	Mass, kg	sfc kg/kWhr	P/M kW/kg	P/Vol. W/m^3
Al -14 R, Poland	242	245	0.36	0.98	0.31
Lycoming R-7755 (36 cyl)	3730	2745	0.43	1.36	----
Teledyne - Continental	324	290	--	1.1	0.4

And if you look at the like of an engine that I have shown here in this table you see that it had thirty six cylinders.

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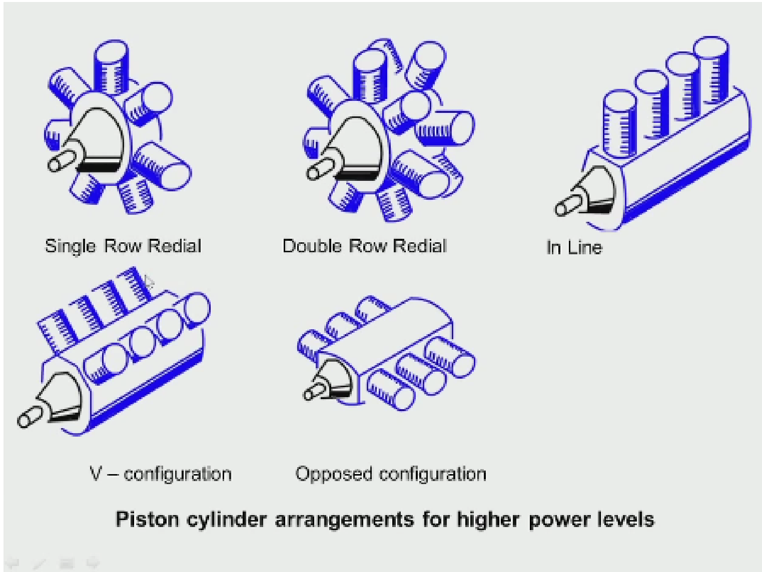

So if you look at the configuration there were various configurations that were possible like the single row radial or the double row radial wherein cylinders were arranged along the radius of a circle so all of them used to power only one shaft that is shown here and as a consequence you had a phenomenally large power because there were too many cylinders contributing towards the power then you had the double row radial Lycoming engine was a double row radial engine and then you had the in-line engine.

Now the one great advantage that the radial engines have in comparison to the inline engine sees balancing of the engines is very easy in this case whereas it is very difficult in the case of inline engines we configuration also takes care of the balancing part partially while the opposed configuration takes care of it completely so in terms of balancing one would look for single row radial double row radial or opposed configuration so these were the kind of configurations people used in order to ensure that they got enough power so let us firstly look at an expression as to how to obtain the power of such engines.

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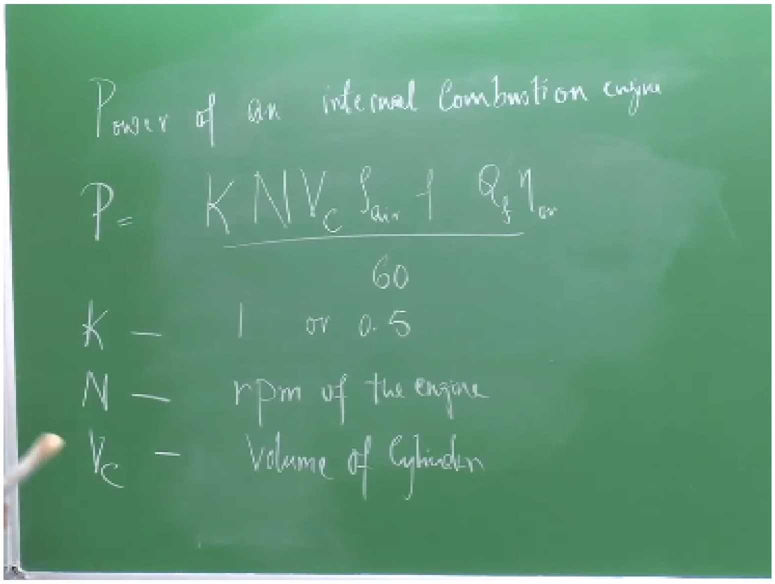

So power P use give is given us I will write this expression and then explain it now K here represents a constant which is either 1 or 0.5 depending on whether the engine is a two-stroke engine or a four-stroke engine remember in a four-stroke engine there is only one power cycle in two revolutions of the crankshaft so you have n being 0.5 here whereas in a two-stroke engine you have 1 power cycle for every rotation of the crankshaft so that is 1 here now N is the RPM of the engine that is how fast is the engine operate typically the RPMs of the engines that we see in regular life are between 5,000 to 9,000 revolutions per second per minute.

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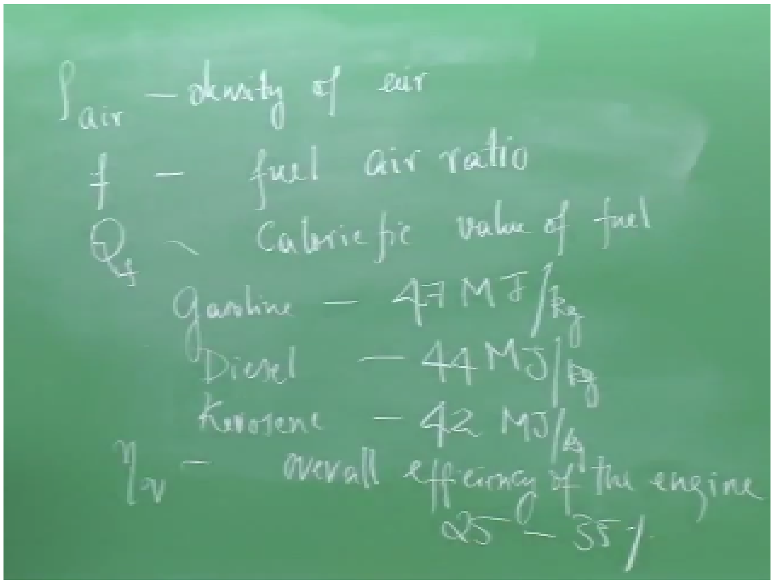

Then we have Vc which is nothing but volume of the cylinder and then we have δ air which is nothing but density of air and F is fuel air ratio I will explain this in a minute Qf is the calorific value of the fuel if you are using gasoline or petrol is the fuel it is around 47 MJ/kg and diesel would be something like 44 MJ/kg and kerosene which is an aviation fuel would be something like 42 MJ/kg and η overall is the overall efficiency of the engine and this varies between typically 25 to 35%.

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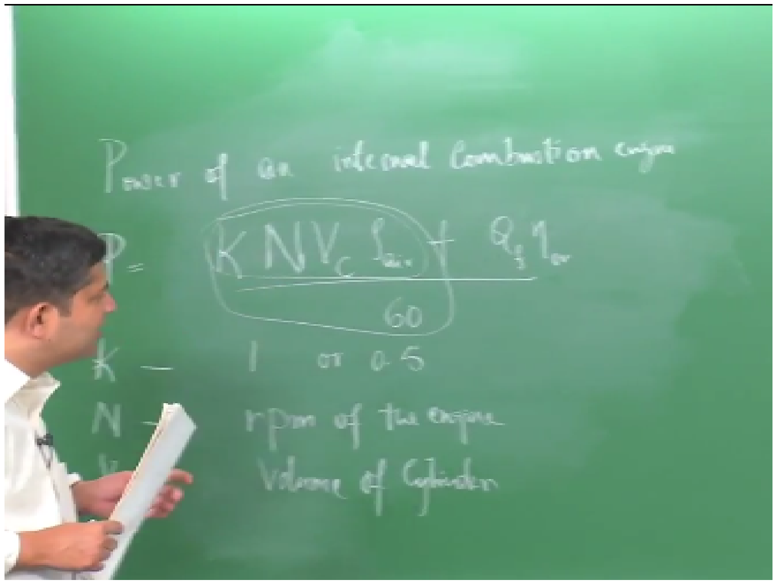

So if you look at this equation here this part here tells you what is the mass flow rate of air that is being ingested inside the cylinder so you have this being the volume and this being the flow rate this being the density so you have mass flow rate of air that is being ingested into the engine F as I said is the fuel a ratio so F here indicates the stoichiometric fuel a ratio that is the amount of air that is required to completely burn the fuel so if you're looking at any of the hydrocarbons it ranges between 13 to 15.

So the ratio for one part of fuel you need 13 parts of air to completely burn it so then if you multiply it by the fuel a ratio which is nothing but mass flow rate of fuel / mass flow rate of air as I had already said this part here indicates mass flow rate of air so you multiply it with F you get mass flow rate of fuel into Qf which is the calorific value of the fuel so if you multiply it by the calorific value you get the energy that is contained in the fuel and if you multiply it by the efficiency you get to know what is the energy that is or the power that is in the fuel that gets converted into useful work or useful power if you notice the overall efficiency is a very small number somewhere around 25 to 35.

A large part of this energy we lose out in terms of exhaust gas heat that or the heat that is carried by the exhaust gasses a significant portion of that of the energy of the that is stored in the fuel something to the tune of 50% goes in that as the exhaust gas energy now if you look at this equation one of the ways in which we could increase the power of the engine is by operating it at a higher rpm so if you operate the engine at a very high rpm then you can see that power goes directly as the rpm so the power would also increase.

So if you remember in India we had Bullitt motorcycles which used to run at somewhere around 4000 to 5000 rpm very low rpm engines whereas some of the more recent high-performance bikes run somewhere close to 8,000 to 9,000 rpm so when you increase the rpm you have higher power.

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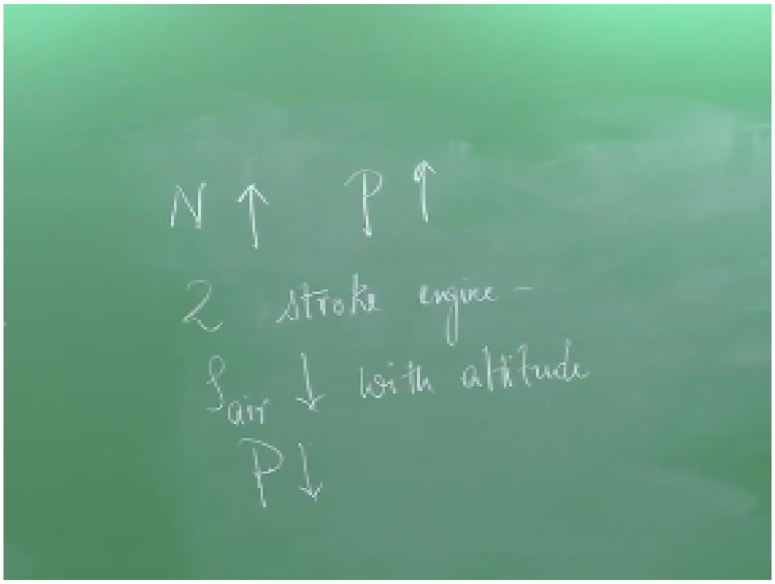

So as N increases power increases and then a two-stroke engine is better than a four-stroke engine in terms of power or then the other possibility of increasing power is if you look at density of air now the density of air at ground level is around 1.2 at sea level is around 1.2 one of the problems faced with by aircrafts operating with piston engine was that as the altitude increased the density of air decreases and as the density of air decreases we see that power also would decrease.

So as δ air decreases with altitude we have also power decreasing and this was one of the major problems faced by initial designers and they were able to overcome it overcome this problem by the use of something known as turbo super stretching which is explained in this figure here.

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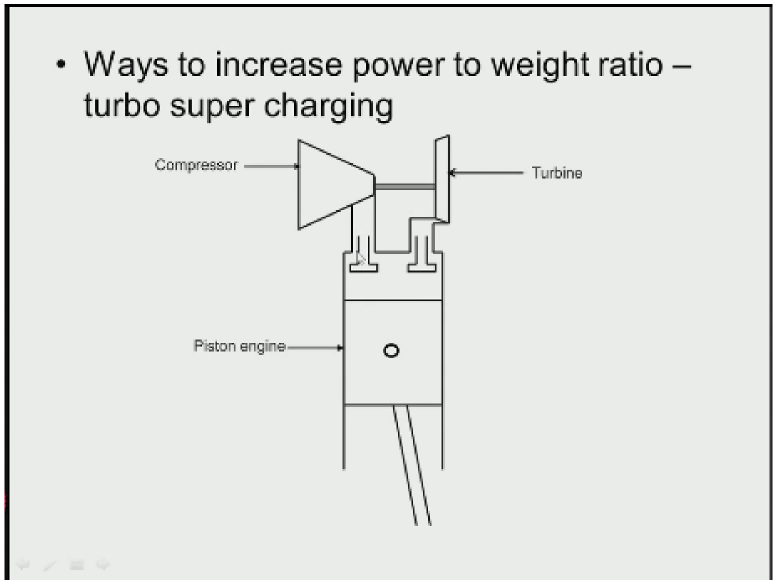

You have a piston engine this is the piston this is the top dead center and you have the valves here this is the air & fuel mixture coming in here so if you can compress the incoming mixture and supply it then the density of air that is coming in would be larger and the way to get the power for this was through the turbine so you use the exhaust to power a turbine which then runs a compressor and increases the density of air that is coming in so with the increase in density of air we see that with the increase in density of air we see power also increases.

The other way to increase is of course use gasoline which has a much higher calorific value than diesel or kerosene also if people were to come up with engines at a later date which have very good overall efficiencies the power produced per liter of engine volume would also increase now because of this problem that people had in terms of power being limited and therefore they had to go in for multi cylinder engines and other things people were really looking for another kind of engines which actually evolved from this piston engine plus propeller but before we go there let us look at all the applications of the piston engine.

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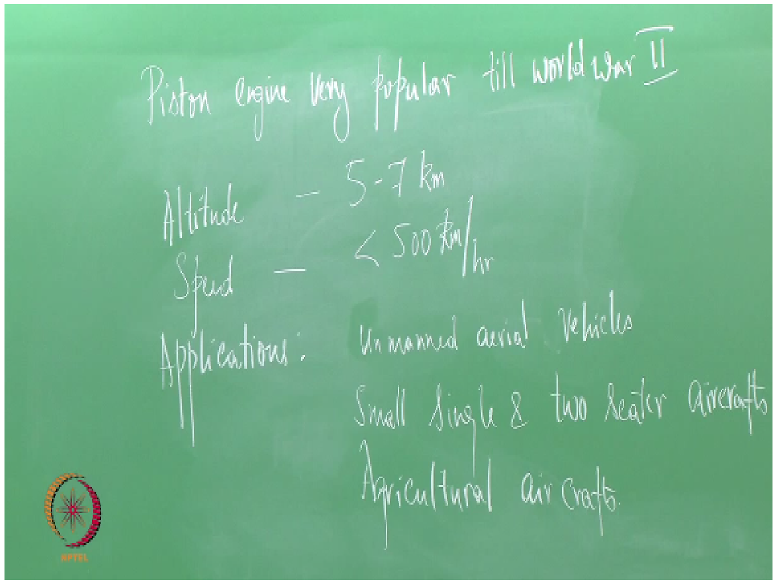

So piston engines very popular in World War two and their altitude that is the height at which they could fly was somewhere around 5 to 7 kilometers and the speed with which they were able to operate was somewhere less than 500 kilometers per hour so these applications of this have been limited to unmanned aerial vehicles basically for surveillance then you have small single or two-seater aircrafts and also agricultural aircraft that is aircraft used to spray pesticides and other chemicals.

Now because of these limitations of speed and height the piston engine plus propeller was slowly phased out to its next generation devices those are known as turbo jets we look at water these turbo Jets or.

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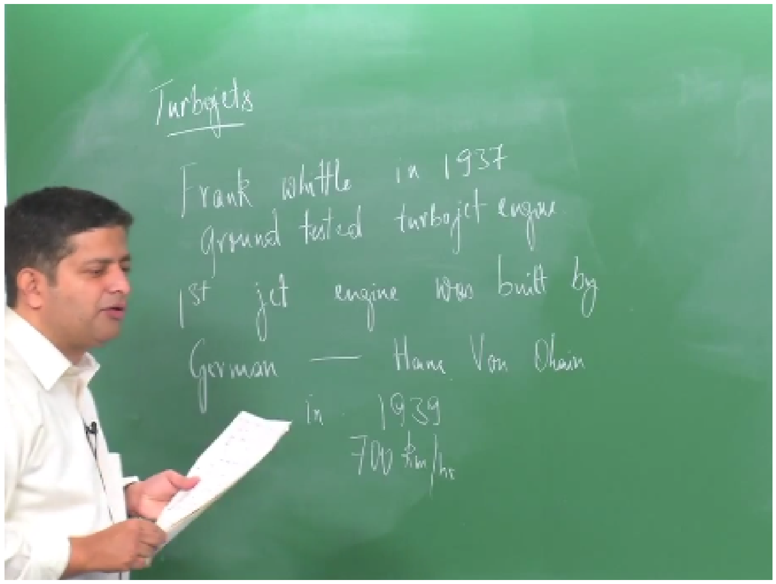

Turbo jets where things that evolved from the piston engine plus propeller let us look at the brief history of this device Frank Whittle was a pioneer who discovered this in 1937 ground tested the turbojet engine he was able to ground test them and he also had patents for compressors and turbines but although he was able to do this in 1937and remember the world war ii started in1939 the British did not really pay too much attention to his inventions he was a English national and British did not pay enough attention to his to his discoveries or inventions and it was the Germans who first flew a turbojet a aircraft an engine powered by a turbojet aircraft.

So first jet engine was built by a German hannes Von Ohain in 1939 and if you look at his engine his engine had a thrust of something that 4kN and it had a forward speed of something like 700 km/h the English then woke up to the situation and realized that they had to also do something because if you look at the speed that these engines were able to go at they were able to go at only 500 km/h the engines that were discovered by Ohain here was able to go at something like 700 km/h.

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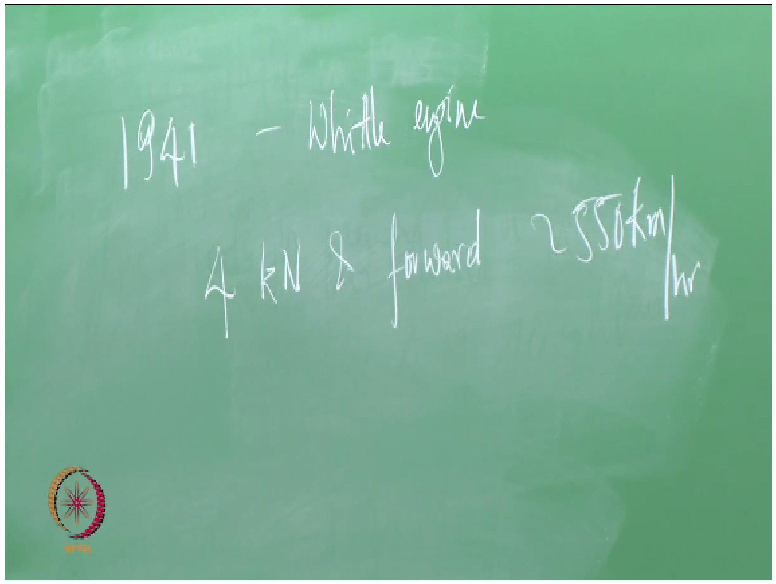

So therefore they were pressurized to discovering their own engines turbojet engines and in 1941 the British built their own engine called as Whittle engine so they had an aircraft built around it and it was also having a thrust of 4kN and a forward speed of around 550km/h and first developed the turbo jet engines in the next class we look at what these turbojet engines are thank you.

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