Fundamentals of Combustion for Propulsion

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Lecture - 02
Combustion processes in ICE and Gas turbine engines

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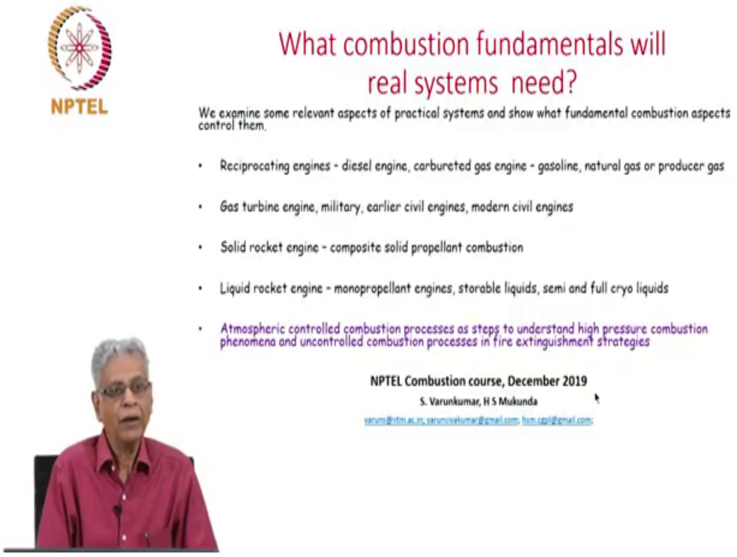

What we will do is to ask ourselves a question what combustion fundamentals will real systems need? We will examine some aspects of practical systems and show what fundamental aspects control them. To enable you to understand you know what fundamentals are really required. So, we look at reciprocating engines which means diesel engine, carbureted gas engine, gasoline, natural gas or producer gas.

A gas turbine engine which can be military or earlier civil engines and modern civil engines. Solid rocket engine which means composite solid propellant combustion. Liquid rocket engine, it could be mono propellant engines, storable liquids or semi and full cryo liquids. I just want to touch upon atmospheric controlled combustion processes, more a steps to understand high pressure combustion phenomena and uncontrolled combustion processes in fire extinguishment strategies.

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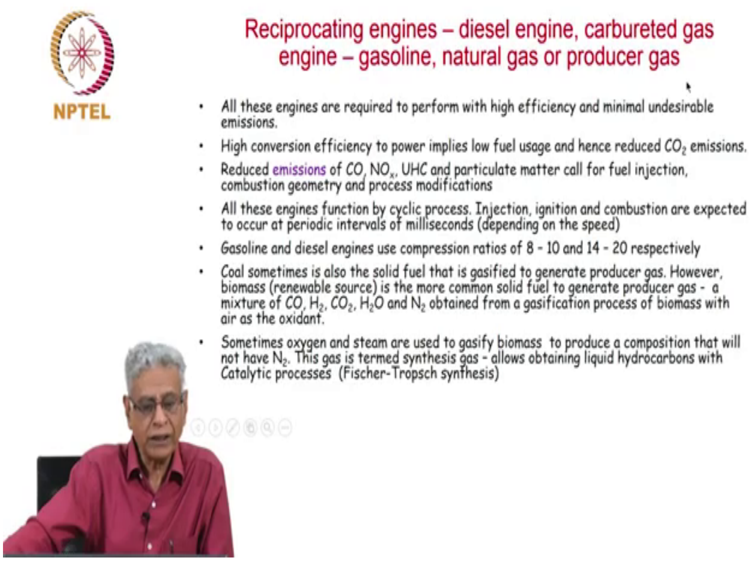

We look at reciprocating engines - diesel engine, carbureted gas engine – gasoline, natural gas or producer gas and we must know that all these engines are required to perform with high efficiency and minimal undesirable emissions. So, they must have high conversion efficiency to power which actually implies low fuel usage.

And therefore, reduce carbon dioxide emissions. Reduced emissions of carbon monoxide, oxide self nitrogen, unburned hydrocarbons and particulate matter call for fuel injection combustion geometry in process modifications which are actually not the same as obtaining high conversion efficiency. These are more complex.

All these engines function by a cyclic process. You have injection, ignition and combustion and there all expected to occur at periodic intervals of milliseconds and it depends on the speed of the engine, from a couple of thousand to several thousands. Gasoline and diesel engines use compression ratios of something like 8 to 10 and 14 to 20; that means, diesel engines have a high compression ratio.

Coal sometimes is also used as a solid fuel and that is gasified to generate what is called producer gas. However, biomass which is a renewable form of energy is the more common solid fuel to generate producer gas - a mixture of carbon monoxide, hydrogen carbon dioxide, water vapor and nitrogen from a process called gasification with using air as the oxidant.

Sometimes oxygen and steam are also used to gasify biomass to produce a composition that does not have nitrogen; this gas system synthesis gas. It allows you to obtain liquid hydrocarbons by using catalytic processes; something called Fischer - Tropsch Synthesis.

I just want to tell you for clarification, those which use air as oxidant are called the gas producers called producer gas. Those we use does not have nitrogen as the oxidant. You call a synthesis gas, because we can use it to synthesize liquid fuels.

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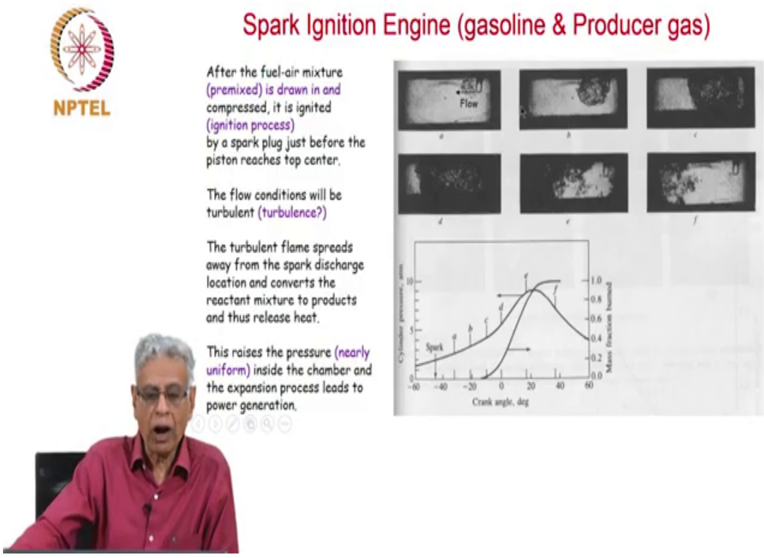

Let us look at Sparking Ignition Engine which is essentially either gasoline or producer gas. Producer gas is mixed with a and introduced into the a combustion chamber and then spark ignite engine. The air after the fuel-air mixture which is a pre mixed mixture is drawn in and compressed, it is ignited, it is called the ignition process. This is the fundamental property or premix is another feature which you must keep in mind by using a spark plug just before the piston reaches the top center.

The flow conditions will be turbulent. So, a fundamental issue is what is turbulence. The turbulent flame spreads away from the spark discharge location and converts the reactant mixture to products and of course, releasing heat. This raises the pressure which is nearly uniform inside the combustion chamber and the expansion process leads to power generation.

You see in these figures the spark plug and the flame begins propagating at various stages in its life and you see at the end that the flame has burned up, most of the composition at this stage, all the mass of the gas has been burned into products.

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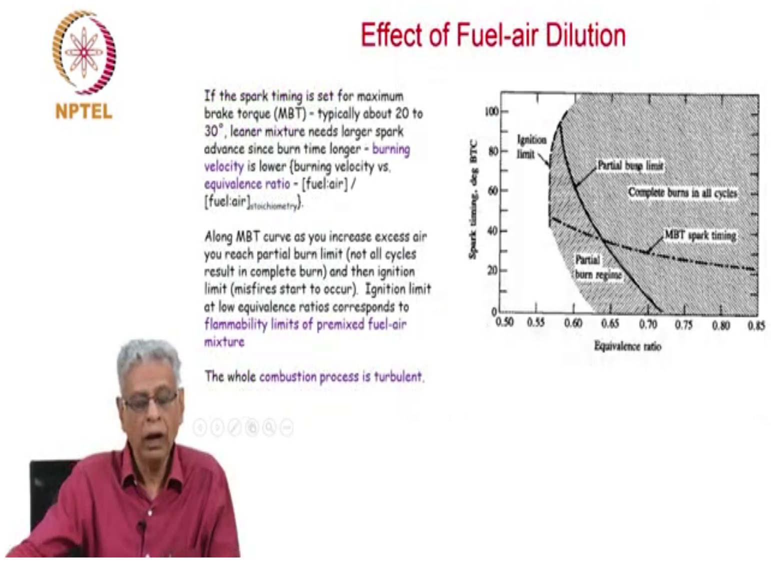

You look at the effect of fuel-air dilution in such mixtures and in the spark timing is setted for maximum brake torque as it is called in search engines. And this advance is typically about 20 to 30 degrees. A linear mixture meets leading a large larger spark advance, since the burn time is longer; that means, the burning velocity of the mixture is lower. So, we have aspect like burning velocity which must be understood as to what it is and this equivalence ratio which is essentially the fuel-air ratio divided by the fuel-air ratio is stoichiometry and sometimes, you may see in literature definitions of the universe, but you can't we keep track of that.

You see that in this curve, as you increase the exercise; that means, as you reduce as you come towards the leaner side that means reduce the equivalence ratio, you will you will find that the spark timing increases for the reasons which I just now mentioned. There is also an ignition limit at the lower equivalence ratios and this correspond to flammability limits of pre mixed fuel-air mixture. So, this is the subject which is normally taught in premium flames is relevant in this case. Of course, the coal combustion process inside is turbulent.

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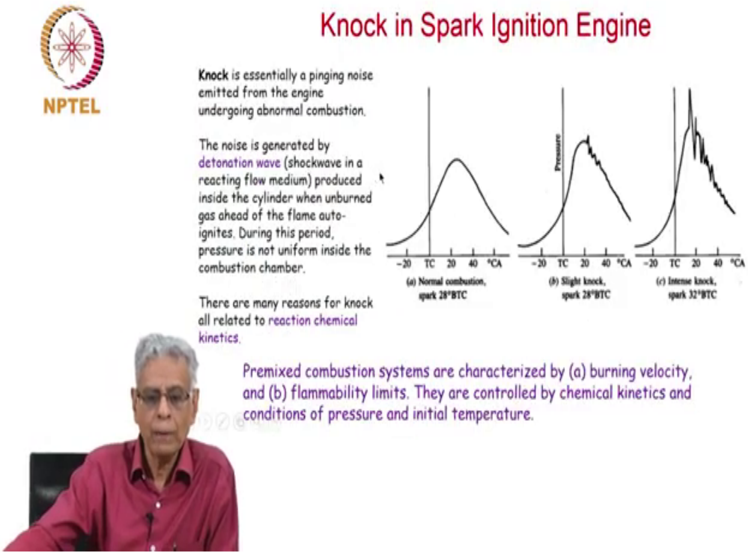

This is a feature called knock in spark ignition engines is essentially a pinging noise emitted from the engine undergoing abnormal combustion and you will find the pressure has lots of fluctuations during the process of combustion. The noise is actually generated by what is called a detonation wave, which we do not really discuss in this course. Its essentially a shock wave in a reacting flow medium which is produced inside the cylinder when unburned gas ahead of the flame auto ignites.

During this period the pressure is not uniform inside the combustion chamber and that many reasons for this knock are related to the reaction chemical kinetics. So, pre mixed combustion systems are therefore, characterized by burning velocity and flammability limits and these are controlled by chemical kinetics and the conditions of pressure and initial temperature. So, these are the features we should keep in mind.

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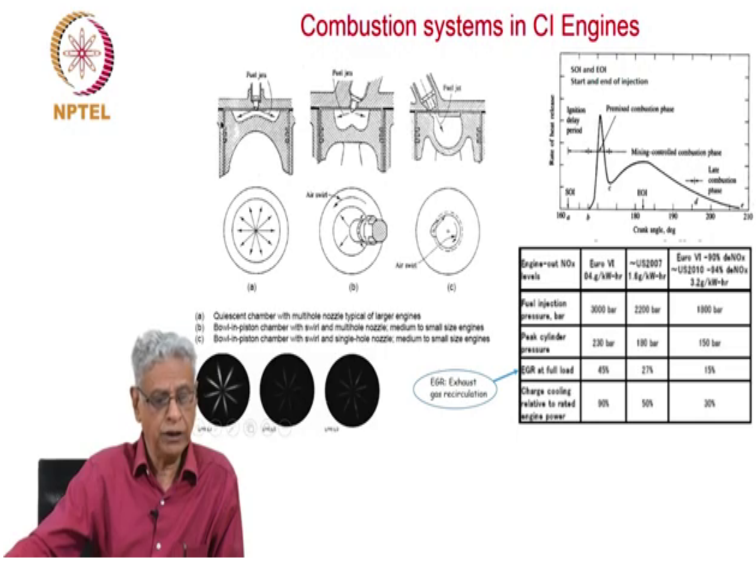

Let us go to compression ignition engines. We have variety of combustion systems in which the fuel is injected in variety of ways. You will see the three of them here. This combustion chamber is multi hole nozzle and typically used for larger engines. You radially inject the fuel.

Then, you have also Bowl-in-piston chamber with swirl and multi hole nozzle. Typically, using medium to small engines and as a Bowl-in-piston with swirl and a single hole injection. This is used in medium to small engines. You will see this picture contains the way the jets come out and burn inside the combustion chamber various times.

The actual process is briefly stated here. This is the start of injection and tip takes a couple of milliseconds are even less for injection process to be completed and then, these occur in modern engines injection occurs at extremely high pressures, 3000 bars and in earlier engines which used to be something like 2200, 1800 bars and we peak cylinder pressure itself varies from 230 bars in modern engines and then, earlier little bit lower.

That you see here something called Exhaust gas recirculation, essentially used to reduce the emissions improve the efficiency and their varying degrees of the exhaust gas recirculation inside the system. And you see the actual processes after injected at some point of time, ignition begins and because of the fact that after injection there is a delay, there is a pre mixing which occurs.

So, there is a first part which is essentially a pre mixed combustion phase. Subsequently, there is a diffusing combustion phase which is also mixing control combustion phase, till it ends at some point of time.

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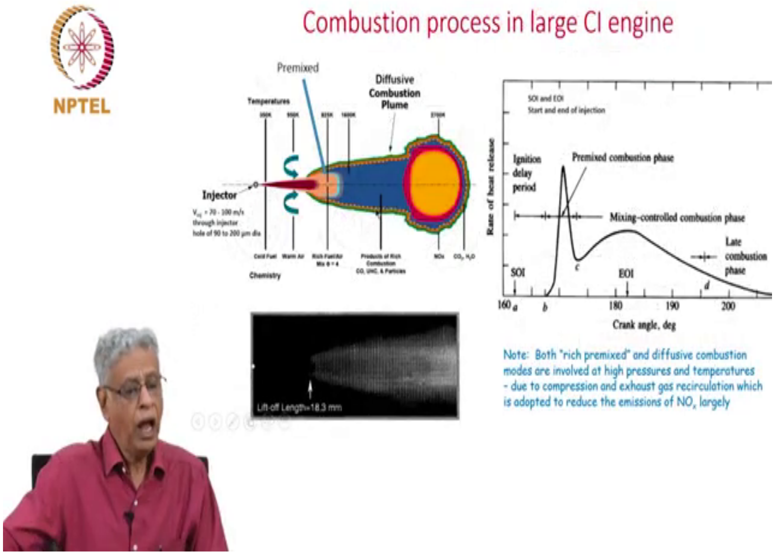

These are physically described here. You see the first part after the injection takes place and it occurs at extremely high velocities because they are large pressure difference through which the jet it gets introduced into extremely fine orifices; 150 to 200 microns and this injection velocity is typically 70 to 100 meters per second.

And as soon as introduced, it moves in and train some amount of oxidant here gets pre mixed in some domain and there is rich fuel-air combustion here because, fuel is still large. There is some amount of oxidant. There is a premix combustion. Those products come out, mix with again air and there is a diffusive combustion process. You will see that combustion process defined here and you will find fair amount of soot has to burn in this domain.

So, soot is in fact a critical element in the process of completion of the combustion process ok. So, both which pre-mixed and diffusive combustion modes are involved at high pressures in temperatures and due to compression and exhaust gas recirculation which is adopted to reduce the emissions of NOx largely. The switch to gas turbine combustion as military civil air engines and modern engines.

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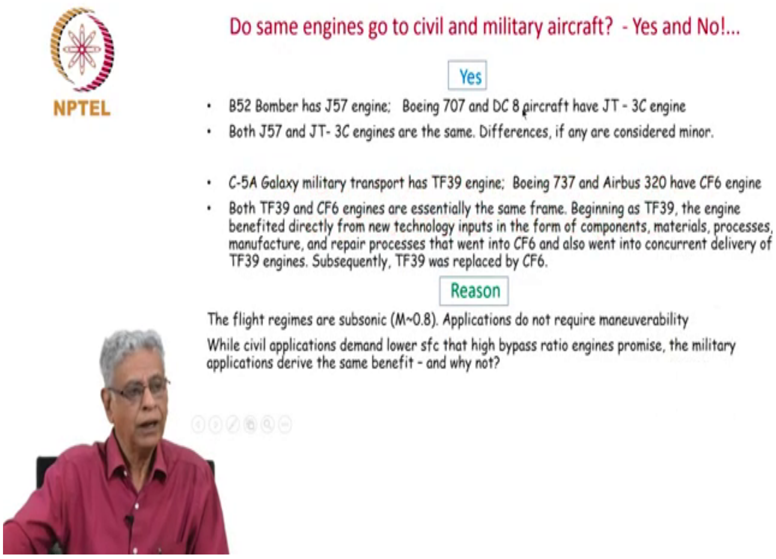

I will ask a question. Do the same engines go to civil and military aircraft is both yes and no; both yes and no? Yes, because you know you have something like a B52 Bomber it has any old time system still in practice has an engine called J57; Boeing 707 and DC 8 aircraft also have engine called JT - 3C engine. Both these are the same differences if any are very minor.

Next you have something are C-5A, it is a military transport. It has an engine called TF39; Boeing 737 and Airbus to 320 also have CF6 engine. Both TF39 and CF6 engines are essentially the same frame. In fact, it began as three TF39 and the engine benefited directly from the new technology inputs in the form of components, materials, processes, manufacture and repair that went into CF6 and also it went into concurrent delivery on of the TF39 engines.

Of course, later TF39 was replaced by CF6. Why is this so? Why do I say that the same engines go to solid military aircraft? That is because the flight regimes are subsonic the maximum of number is about 0.85 and applications do not require maneuverability.

So, while civil engines demand lower specific fuel consumption, that actually high bypass ratio engine promise, the military application derive the same benefit and surely, why not. Because the in flight regimes are not very different; operational procedures are not very different. In one case you would carry passengers, another case you carry cargo.

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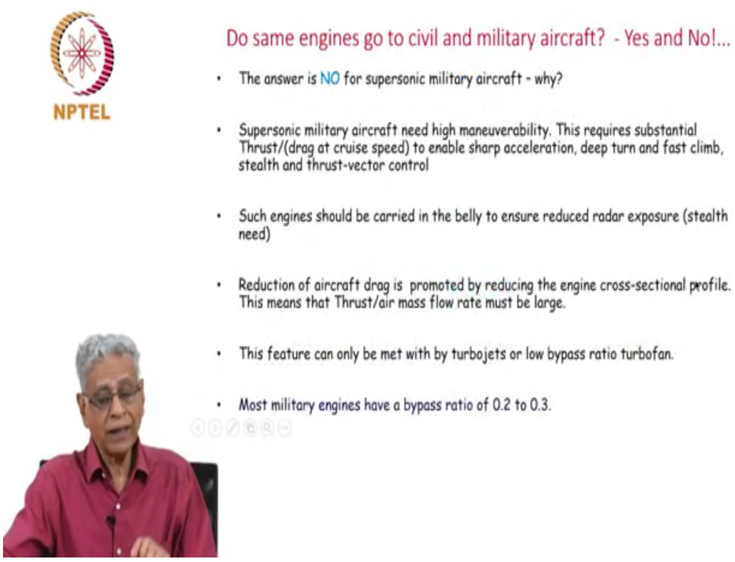

Now, let me ask the question and with respect to no. Its true with supersonic military aircraft and why supersonic military aircraft need high maneuverability. This require substantial thrust to drag at cruise; the cruise is to be defined carefully in military aircraft. The some regime which is considered at on speed and that is considered cruise and but you want sharp acceleration, deep turn, fast climb, stealth and thrust-vector control. All these are features of a supersonic aircraft meant for military applications.

Such engines should be carried in the belly to ensure reduce radon exposure called stealth need and reduction of aircraft drag is promoted by reducing the engine cross-sectional profile. This means that for the same amount of airflow that you ingest you must get a larger thrust. So, the thrust to airflow rate must be large. This feature can only be met with turbo jets or low bypass ratio turbo fans. Most military engines have a bypass ratio somewhere between 0.2 to 0.3.

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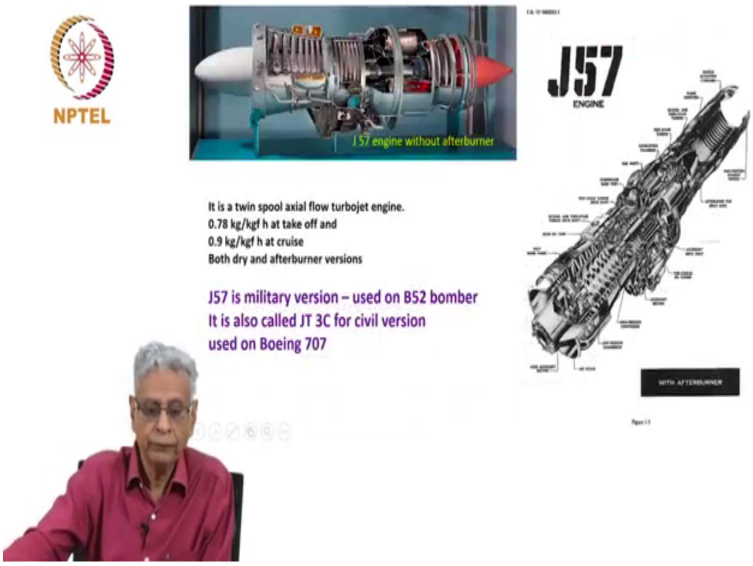

I just show you some pictures for this familiarity. This is the J71 57 engine and you will see all the components here. This the first part is the compressor, then you have the compressor, then the you have a combustion chamber turbine and exhaust goes into a afterburner which is where you get extra thrust for acceleration.

This engine which show cross section; I have shown here is we thought afterburner and this with afterburner. This is of course, some called twin spool, there high pressure fan and the low pressure fan; two of them are there. Only it has some performance which is shown here and when it goes on afterburner, the consumption rate is much higher. J57 is a military version used on B52 bomber as I said earlier. It is also called JT 3C for 707. These are things we can just now mentioned.

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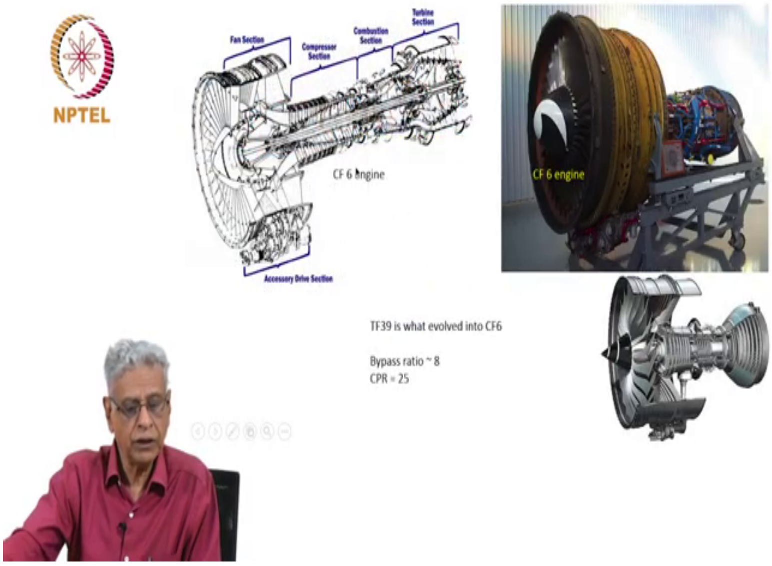

CF6 engine, you can see the difference. It is got a large fan; that means, bypass ratio is very large, large amount of mass logos co-resides. The core engine is powerful, it provides the power to run the fan as well. And this compressor pressure ratio therefore is my chair because you have to make it more compact, usually work power for running the fan as well.

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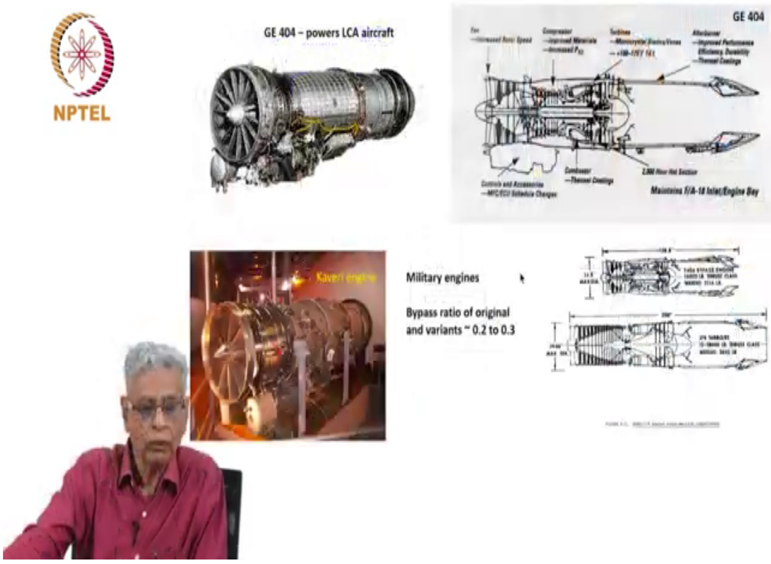

Well, you have GE 404, it you may know is powers to LCA aircraft it has again all the aspects here the fan, compressor, turbine and in fact, that GE 404 engine has many interesting properties that improve materials. It has single crystal blades veins that gives it life for the turbine blades and the afterburner which gives you the extra clutch whenever you demand and the bypass ratio of the original and the variance is typically 0.2 to 0.3.

You also see the engine being developed at GTRE a Kaveri engine which has gone through many stages of successes, may be needs needing the improvement it will go into service soon enough.

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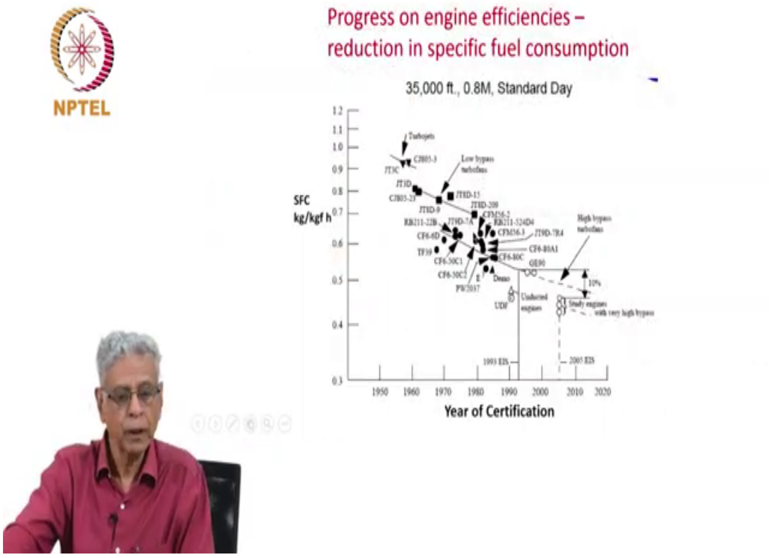

If you just look at the progress and engine efficiencies, look at reduction specific fuel consumption over here, you will see that you are looking at something like 0.9 for turbo jets. Then, low bypass the ratio turbo fans have typically around 0.7 to 0.8.

Then, as you go to higher bypass ratios the SFC has come down to anywhere between 0.5 and 0.6 and more time you see substantial reductions in the specific fuel consumption, that is all that you can see here, yeah.

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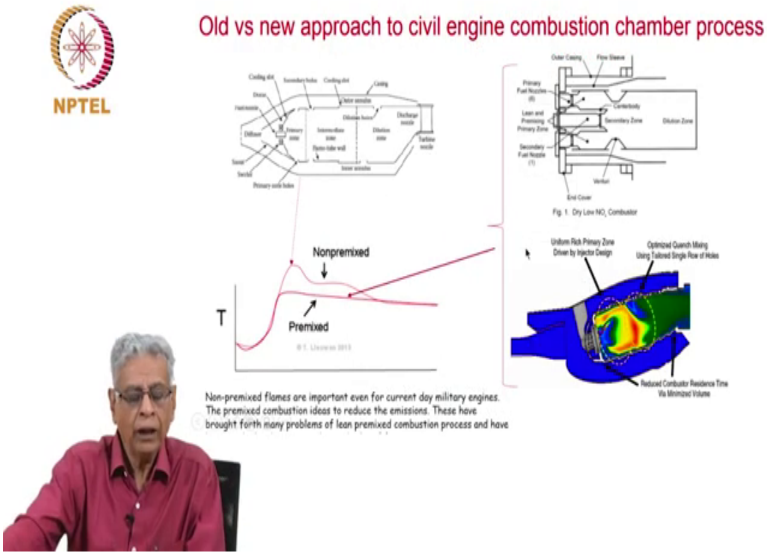

Now, there is an old approach which has which are gone on and a new approach to civil engine combustion chamber process. If you see the old system design, you will see the air flow comes from the compressor divides itself into some part which goes into directly into the combustion chamber to process. The smaller power fraction of the fuel in the primary zone, then you keep introducing air in various stages to complete the combustion process.

What this would do to the temperature profile of the gases is that would begin from at the end of the compression process, the temperature would be about 350 to 450 degree centigrade. Then, it goes it can go right up to 1700, 1800 degree centigrade in the combustion zone as you see here and this is so called nonpremixed mode, diffusing mode of combustion. As it goes through air is injected into various zones, temperature falls down to what the turbine blades will accept.

The modern day system is slightly different as you see it in these figures. You see there is a core which carries the diffusing mode of combustion there is also two and this two sides which is actually annular space, where you will discover that the fuel and air will get mixed here and you have got a combustion process which is premixed. So, both premixed combustion process and diffusing mode of combustion process dominate the total phenomenon here ok.

So, non-premixed flame in fact are important even for current day military engines because it produces a stability. But you want to reduce the emissions, the only way of reducing the emissions you do premixing and burning at as lean condition as possible. It helps you to reduce the specific fuel consumption as well that is the change between the old practice of diffusing mode of combustion and current day process of combustion process in civil engines.

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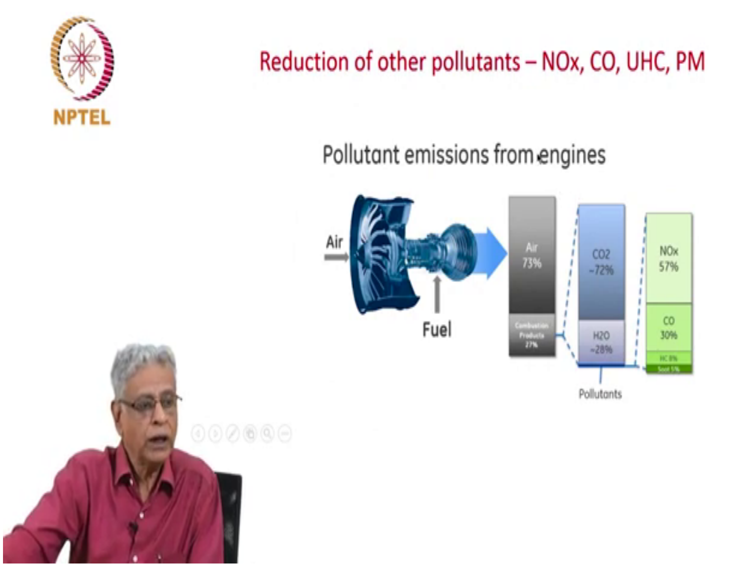

Well, let us look at this question of reduction of pollutant like NOx, carbon monoxide, unburned hydrocarbons in particulate matter. If you see any gas turbine engine, here it is about 73 percent; combustion products constitute about 27 percent. These combustion products will contain carbon dioxide to the extent above 72 percent, water vapor 28 percent and some amount of pollutants and this is the pollutant switch which is all we were concerned with.

You see the is the extreme end of the composition small ones and in that you find 57 percent typically about NOx, carbon monoxide about 30 percent, hydrocarbons 8 percent and soot about 5 percent. That is this fraction is in the pollutants which is a very small fraction, ppm levels.

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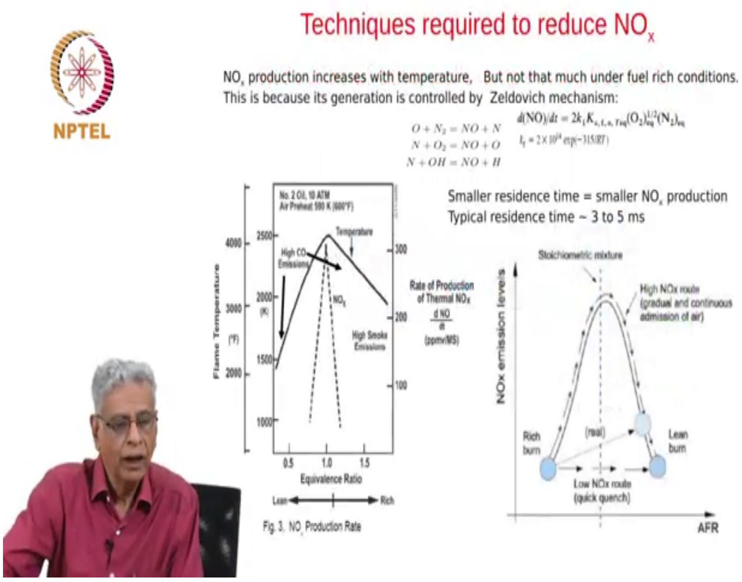

Now, I just want to bring to your attention what have been done to reduce the NOx to understand the fundamentals, which part of the fundamentals are important. It is been known for a long time that the production of NOx is related to temperature and when then, it is a fuel rich condition you will not find much NOx. This is because its generation is controlled by what is called a Zeldovich mechanism. You see oxygen atom reacting with nitrogen molecule leading to NO and N.

In the nitrogen molecule reacts with oxygen leading to NO and H and there is a third reaction N plus OH is equal to NO and H. This mechanism controls the NOx, it has been fairly well established over the last maybe 4 decades. And it is also known how NOx get generated with time. It is it is actually simple analysis; you will see the standard books including for example. And, any book of combustion will give you this detail.

So, you will find that is proportional to the oxygen fraction at equilibrium or to the power of half and nitrogen fraction in at equilibrium and you see that what is described is a rate which means given a rate is the time which controls the amount of NOx produced. So, smaller the residence time implies smaller nitric oxide production; nitric oxide N OH is the composition of NO NO2 and N2O, but the NO2 and N2 are very small fractions; about 90, 95 percent of it is contributed by NO itself and yet it is called NOx.

So, this strategy used if you see this diagram, you will find that the equilibrium flame temperature which is something which I told you will speak about little later, goes up to very high temperatures on the equivalence ratio. There is a lean side 0.5 to 1 is lean side; 1 to 1.5 rich side. You see the temperature falls on both sides of arrow zone near stoichiometry; typically, around 1.5, you will find the temperature peaks.

Then, you will find the NOx is low and the on the fuel lean side, it gets low because of temperature and fuel rich side, it goes low because oxygen fraction is very low. As you see here oxygen fraction controls it. So, if you are in lean side, this controls it. But temperature is low, it goes down. On the rich side, there is no fuel oxygen at all. Therefore, it goes down.

So, it goes down on either side and if you go to fuel two fuel dis conditions you have high smoke emissions, you will find CO being formed because of low temperature at lean conditions even though (Refer Time: 23:33) excess and it is not it is found in larger amount in rich conditions, because it does not have enough oxygen to get oxidized. So, this is the complex feature which controls the formation of NOx and CO.

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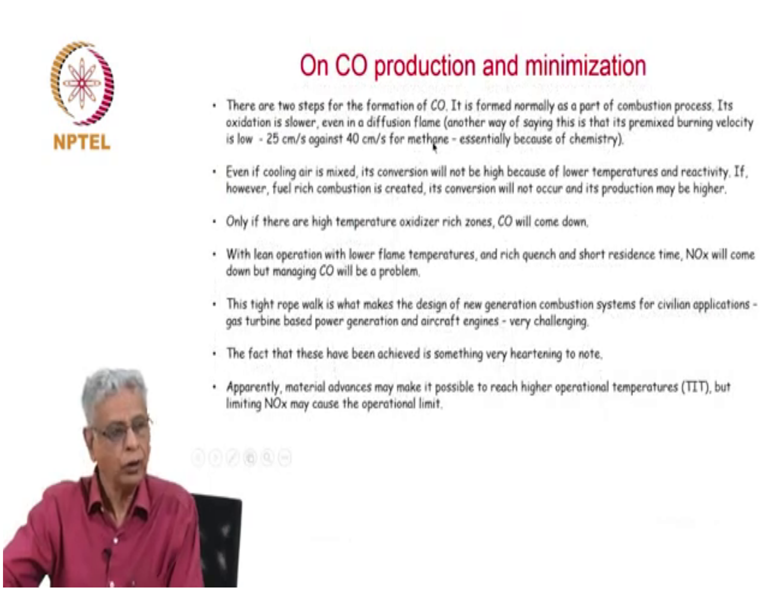

So, let us look at CO production and minimization itself. There are two steps for the formation of CO. Its form normal is a part of combustion process. Its oxidation slower even in a diffusion flame which means another way of saying that is that its premix burning velocity is low. In fact, is in true, you have 25 centimeter per second as against 40 centimeter per second for methane - essentially because of chemistry.

Even if cooling air is mixed, its conversion will not be high because the of lower temperatures and reactivity. If, however, fuel rich condition is created, this conversion will not occur at all it production may even be higher. Only if there are high temperature oxidizer rich zones will CO come down. With lean operation and lower flame temperatures and rich quench and short residence time, NOx will come down, but managing CO will be a problem.

Now, I have said many things here with lean operation, lower flame temperatures and so-called rich quench and short residence time, NOx will come down. So, this is a tight rope walk which makes the design of the new generation combustion system for civilian applications.

There is a gas turbine-based power generation and aircraft engines, very challenging. The fact that this have been achieved in the last 10 years has been very significant development in this area and very heartening to note. Also, material advances may take it possible to reach higher operational temperatures, when I say turbine blade you remember I said single critical blades. Yeah, go ahead.

Student: Sir, once (Refer Time: 25:30) which groups?

I will explain to you in the next slide. Yeah, but limiting NOx may actually become the operational limit that is you may you determine is the controlling element for limiting the temperature of the entry of the gasses into the turbine.

You may use advanced materials cooling techniques, thermal barrier coatings which are standard in this whole process to raise the inlet temperature. It will be possible to build an engine, but the emission may be so much more because the temperatures are really high that, that the NOx emission may become the limiting factor for the design not so much as a material and technology ok.

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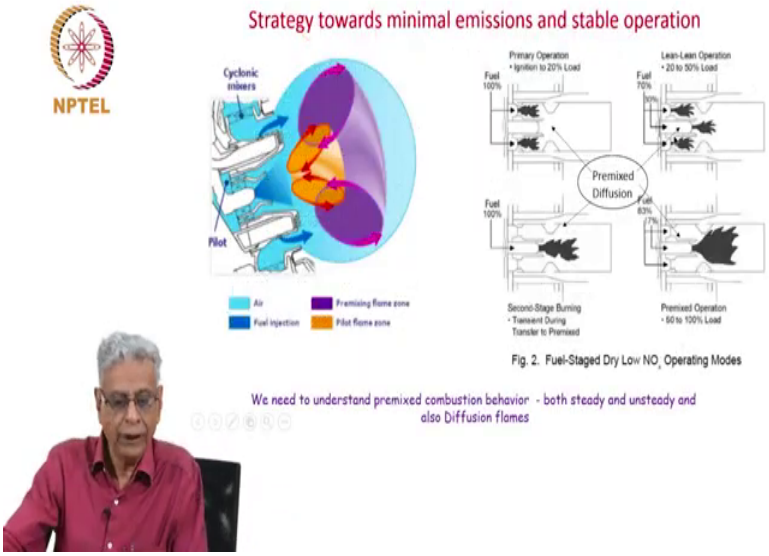

So, let us go to the aspect here. I will explain to you just one of the element rich quench is what is used in one technology which is not shown here. But I will explain to you. In this as I mentioned to you, you have the central zone carries fuel diffusive mode of combustion, but the combustion in this and this are premixed ok.

So, you have central zone which is diffusion and the side two side annular space just premixed. So, the combustion process here is you know pilot flame zone which is essentially diffusion and you have premixing zone which is the premix combustion zone. So, the overlap of this is what gives you the high performance and low emissions.

The well rich quench is used in the following sense. You create first of all a diffusing mode of combustion and when you do diffusive mode of combustion, as I mentioned to you little earlier, the peak temperature will be high. Because, you can go to the mixture ratios which are such, that you can get temperatures of 1700 centigrade. So, what you do is you do not go to that extent, you reduce the temperature to 1300 or something 3 degree centigrade, then introduce air, reaction occurs and NOx gets generated.

Now, this so called quench means you and give little more air do not make sure the temperature rises, but temperature is limited. Now, you allow the residence time in this domain to be small. So, the reaction occurs completion of reaction oxidation reactions occur such that the NOx does not necessarily go. So, it is called rich quench approach to the process of NOx reduction.

So, again we need to understand the premixed combustion behavior here; both steady and unsteady because what happens is that if the inlet temperatures are higher as will happen when the when the compressor pressure ratio is very high, you will discover the flame even though its pre mixed.

We want all of the combustion to occur here, but instead it may actually get flashback because temperatures are higher, we have the burn rate the burning velocity is higher, if they actually flashback because of the processes that occur close to the point of injection and this can be very deleterious to the engine life. So, that is why designing this is a tough call.

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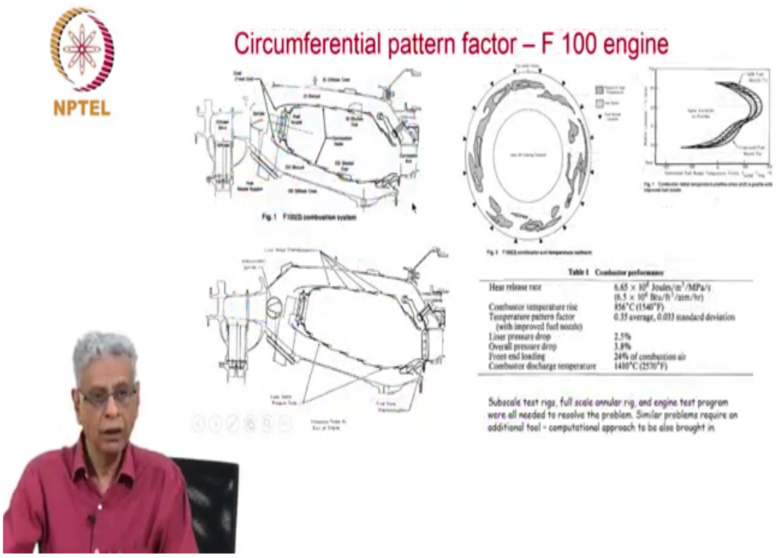

There is something like circumferential pattern factor which is a very serious issue with all engines more particularly with military engines of the client which are developed everywhere. I am just showing you some features of what has been described about F100 engine which is one of the advanced engines developed in US.

You will discover the so called pattern factor which is. What is pattern factor? It is actual the peak temperature of the in the zone divided by a some kind of a mean. We can define it precisely later, but essentially that the variation of temperature across the turbine blade, this is over the cart, it can also occur over the circumference.

You cannot have very uneven temperatures; if there are uneven temperatures, the blades will pass through at one moment high temperature, other moment lower temperature. So, its temperature cycling occurs and we must remember turbine blades are highly stressed because of centrifugal stress as and of thermal stress. And therefore, there are processes which occur which cause the life reduction technique processes occur on the blades and we will make sure that is not very serious ok.

So, you will discover that the so called radial pattern factories like what you see here. It must be not too large at the outer limit as well as the inner limit because at the turbine route as well as a turbine exit for the re-systemly if the temperatures are too high, it will expand and the blade may extend and brush over the outer surface, it should not happen. Therefore, the dead temperatures limited. The temperature in the root is also to be limited because its highly stressed because of centrifugal stresses.

Therefore, you cannot allow temperature variation in the middle portion ok. So, this the how much is the variation is the only question and that should be controlled is the aspect related to reduction in pattern factor. You will find in the circumferential zone, lot of effort was put on the F and G development, you will find some patches of this in this temperature. The various ways of defining and controlling it, which has been extensively studied by those researchers

So, you will discuss some features present here in terms of various aspects of the combustion and just you know that combustion temperatures here are very large, it is about 1700 Kelvin close to and in doing this development, they did subscale test rigs, full scale annular combustion rig and engine test program. They were all needed to resolve the problem. So, you need to apply many tools after understanding the behavior of the combustion processes seen in the engine to get to this stage.

Well, similar problems require an additional tool in these times and that is related to the computational technique which will help you to understand how the behavior actually takes place.

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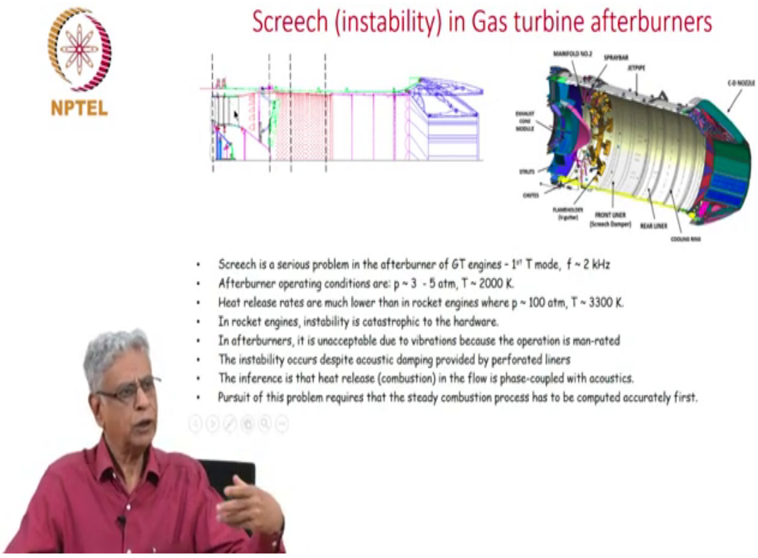

There is a further problem called Screech which is a actually instability in gas turbine afterburner. You see here, you see the afterburner. The gas has come out from the combustion chamber, go through the turbine, at the end of the turbine exit they enter the zone and you have diffusive section here the gases come through here.

And the combustion process with the main combustion chamber actually occurs at few lean conditions; approximately half the fuel is only injected there. Now, you still have ability to use the oxidation potential of the gases coming out here typically around 800 to 1000 Kelvin. They come out here. They have oxygen fraction left in them. So, you can actually burn use that to burn few more fuel inside this that is what the afterburner is all about.

Whenever you need you inject the fuel and then, burn the burn the fuel in this domain, take the temperatures close to adiabatic temperature which is typically around 2000 Kelvin also, then they go to the nozzle. This afterburner is used only when you want extra thrust and used obviously, in only military engines.

The only engine which used civil engine which used the afterburner was a concurred, some part of it is always done like that. but you know concurred does not you know longer they are around ok. I am summarizing the features here. So, serious problem in after burner in gas turbine engines so called 1st tangential mode and you will describe what the modes are and things like that will be discussed later.

Its frequency at which it hitch this is about 2 kilohertz. The afterburner operating conditions are typically 3 to 5 atmospheres temperature of 2000 Kelvin. The heat release rates are much lower than in rocket engines we must remember that, where the pressures are extremely high, temperature is even higher.

In rocket engines instabilities catastrophic nothing that can be done, if it occurs you know you have to write off the hardware. Now, afterburners it is unacceptable due to the vibration caused and let us remember its of man operated operation. So, you can't allow a pilot to get into distressed mode.

So, therefore, both ways is to be avoided. The instability occurs despite acoustic damping provided by perforated liners, many a times in many engines you will discover or most engines will discover military engines you will discover, afterburners will have perforated liners.

Even if this provided you will find instability in some domains of operation. The inference of course, is that the heat release in the flow is phase coupled with the acoustics. Again, this is the matter of detail which will be studied which will be explained.

The pursuit of this problem requires that the steady combustion process is to be accurately computed and the reason is very simple the instability is caused from a given steady state and you must know what the steady state is and the issue is that in the steady state you had a disturbance, this disturbance amplifies; then, you say its unstable. So, we must therefore know the act accurately, the steady state itself; just the key to understand the processes of screech.