Combustion in Air Breathing Aero Engines

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Lecture – 01
Introduction

Welcome friends, welcome to this course on combustion in air breathing aero engines. My name is Doctor Swetaprovo Chaudhuri, I am the faculty member at the department of aerospace engineering, Indian institute of science and in this course I will be assisted by 2 teaching assistants who have helped in preparing this power point slides and they are MR. Harsha Vanakar and Mr. Himanshu Davey, they are my PhD students.

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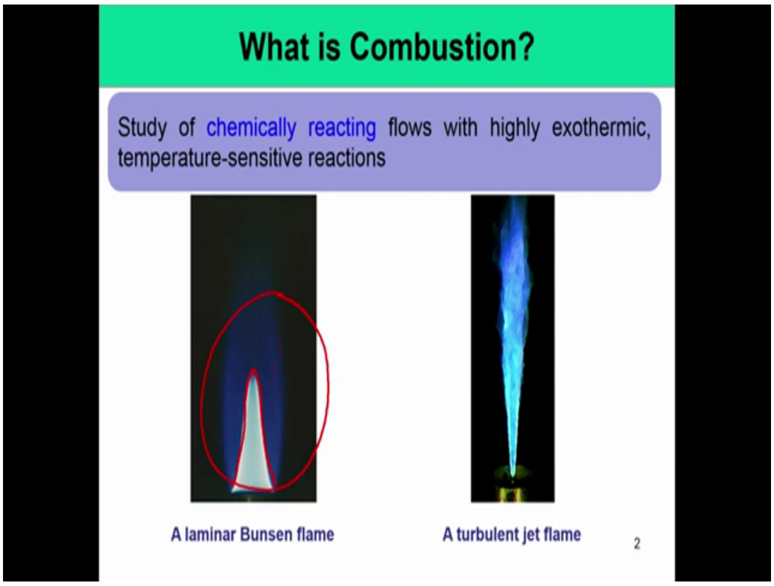

So, in this course, first we will talk about in this thing we will talk about the motivation that first what is combustion, why do we need to study it, why is it indispensable for air breathing aero engines; aerospace engines and those things and then we will provide you about the outline of this course how we are going to study different things the basic approach will be to start with fundamental processes and then go into more complex situations and then go into engines.

But first in this thing as it show this slide will talk about what is combustion. As you see combustion is the study of chemical reacting flows with highly exothermic temperature sensitive reactions. Now combustion can happen in different forms, it can be with something it can be something like an auto ignition it can happen through different kind of flames it can happen through detonations and explosions, but our primary I mean our experience tells that what we encounter in daily life is a we can encounter a laminar Bunsen flames what you might have seen in a your chemistry lab which you can see here, the this is the laminar Bunsen flame that you see this is the essentially the flame structure or you can see sometimes a turbulent jet flame in the laboratory where combustion happens in a turbulent flow and the structure of the flame is highly distorted and the flame structure is wrinkled and so on and so forth So, these are the first 2 kinds of flames that we can encounter commonly.

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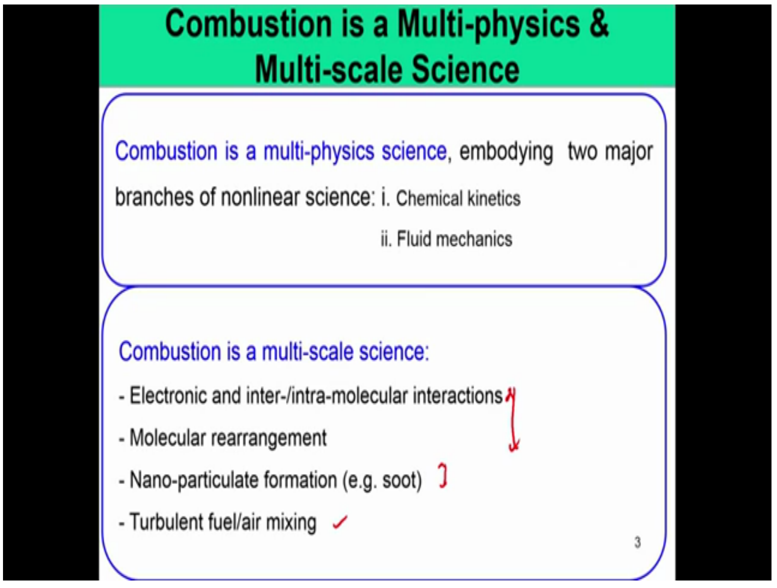

Now, what is most fascinating about combustion is that there are 2 things first of all it is multi physics it involves different kind different branches of science, the 2 pillars of combustion that is involved is essentially chemical kinetics and feed mechanics of course, it also involves thermodynamics it involves heat transfer, but the 2 pillars of combustion is essentially chemical kinetics and fluid mechanics and to develop a great deal of expertise in combustion you need to understand chemical kinetics and fluid mechanics both in equal details. The second important thing is that combustion is a multi scale science, what do you mean by multi scale will be apparent in the next slide, but you see here combustion is essentially it something we have got reactance then you apply some kind of a spark, and the reactants which can be like hydrocarbons etcetera it goes to form products which can be carbon dioxide and water, this our common perception of what combustion is.

Now, this is what we see on a global scale; on a broad scale we see that hydrocarbons like kerosene or like or methane or natural gas etcetera becomes carbon dioxide and water, but essentially what it involves is that it involves electronic orbital rearrangements at the molecular level. So, that is why it is it involves this electronic structure change; you see you can see soot formation now soot formation happens at very very small scales soot formation happens in a candle flame, it can happen in a diesel engine. So, that involves Nano scale processes where as it can also involve turbulent fuel air mixing which are which happens at a larger scale.

So, it is this different physical processes and different which happens at a different scales of length and time that makes a study of combustion fascinating.

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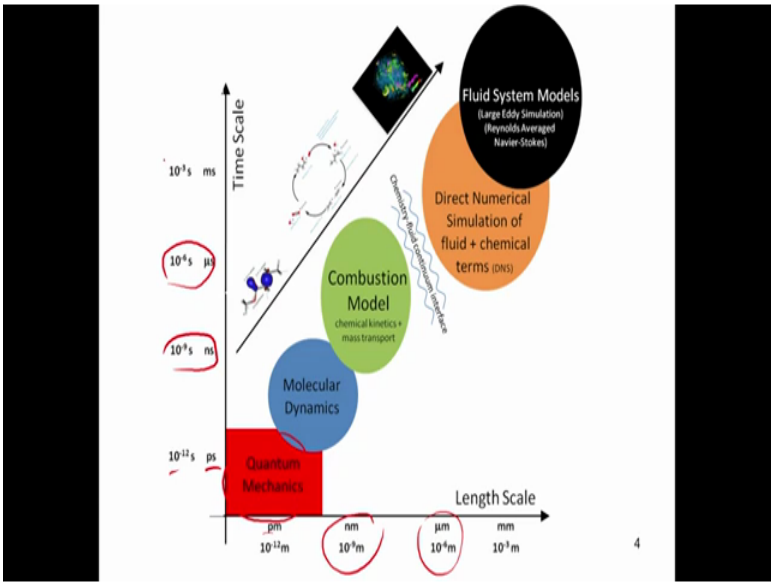

And of course, this is what I was talking about that it involves different kind of time scales and length scales. So, the molecule the electronic rearrangement is governed by the principles of quantum mechanics. So, that happens at the order of picoseconds and at the order of Pico meters. Molecular dynamics which are a study of different how different how large number of atoms and molecules interact among themselves that basically governs is basically when you take from go from singe molecules to multiple molecules and multiple atoms that is that that those scales are of this order.

Then you come to the kinetics models which are of the order of where the time constant of different reactions are of the order of micro seconds and micro meters. Now then you come into fuel air mixing and then the subsequent combustion reactions and those are essentially governed by these kinds of techniques which we might have heard, and like directing numerical simulations etcetera. But those are not involved right those are not will be invoked right now, but I want to give the basic impression that I want to give through a slide is that once again that combustion is a science and of course, that science is used in heavily in engineering and that these things involved processes that happens at different scales of length and time, all the order all the way from Pico meters to millimeters to meters because an engine is of the order of a meter whereas, in time scale it happens from the order of like picoseconds to of the order of milliseconds.

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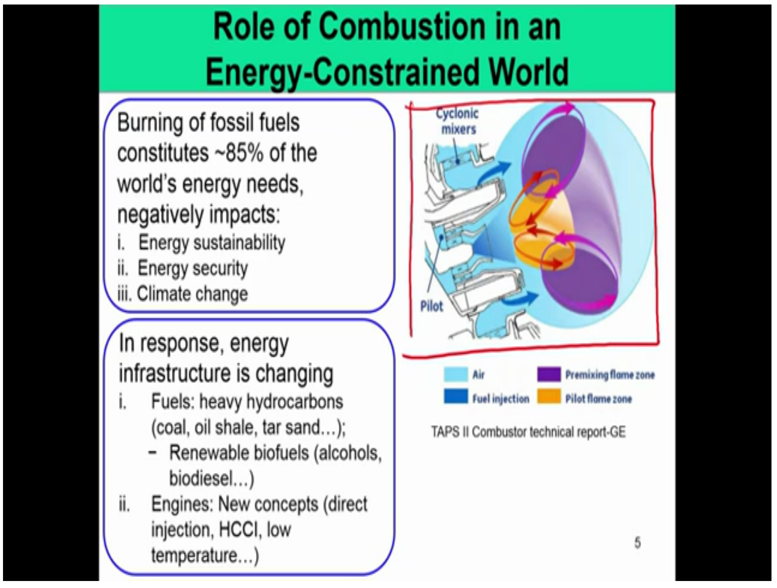

Now, why should we learn combustion? Yes of course, it is a fascinating branch of science and engineering, but more importantly it is role in our in shaping modern civilization is cannot be over emphasized; today if you see 85 percent of the worlds energy needs is supported by combustion of fossil fuels or bio-fuels.

Now, of course, that is huge right 85 percent, and that is even after taking in to account all the development renewables, but then of course, then since 85 percent of the worlds energy need is supported by combustion, it is it has led to many benefits it has made our life smoother we can go from one place to another at a faster in a very short amount of time, but then that also comes with the price. The price is that of energy sustainability that is your this kinds of fuels that we burn this fossil fuels their supply is not infinite energy security we have to get this fossils fuel from some other places in from some other countries and then most importantly which is become paramite which is become a paramount importance nowadays is that climate change because an obvious product of combustion is carbon dioxide, and as you know that carbon dioxide and water vapor both are very strong greenhouse gases.

So, then, but all these things does not mean that combustion itself is bad; combustion is very important it will remain important in the foreseeable future, but as for us that is the present generation and the future generation combustion scientists the onus is on us to make this process more efficient, less emitting and more cleaner and more greener. So, that is the challenge of the combustion scientists how can we optimize this process towards a better future. And also you must understand that the energy infrastructure is also changing.

Now, for example, here we are encountering now modern fuels are becoming more and more heavier in the sense that they are involve very large molecules of hydrocarbons, coal shale oil tars and etcetera and are renewable fuels are becoming very very important biofuels syngas biofuels alcohols etcetera and new engines are being devised. So, so we have to for present and future combustion scientist we have to design, we have to get this kind of new fuels and we have to ensure that there is those bond properly and in new kind of engines which are more efficient which are more clean and which can produce more power in as you might demand for an aero engine.

So, one of this hallmarks of this combustion science is the new this taps combustor this twin annular premix combustor that with the g has got recently these new combustors support the Boeing 787 in most cases, and as you see that this involves lot of understanding of the fundamental understanding of combustion science, this engine has evolved where new understanding of combustion science has played a major role in it is development.

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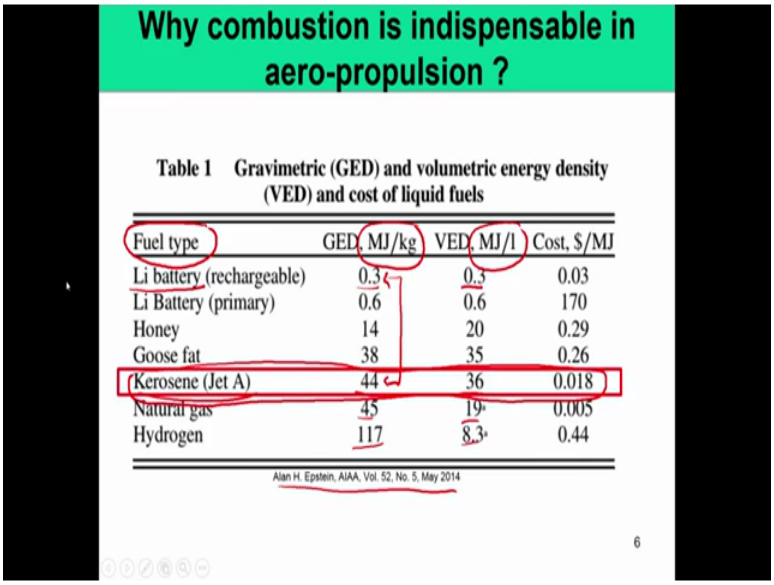

So, the next question is that for aero propulsion which is the main focus of this course that is here the name of the course is combustion in air breathing aero engines. So, why is it so indispensable for aero propulsion and more indispensable in the sense that it is in the sense that it is a even in the next 50 years, we do not see that for long distance flights or for military propulsion we do not see any alternative other than aero propulsion or other than combustion now why is that so? The answer lies in the energy density the gravimetric and the volumetric energy density; basically these numbers what you see here is that mega joules per kg and mega joules per liter and on the left hand side in this table I have fuel type.

So, you see that for a lithium and battery it is about 0.3 mega joules per kg the gravimetric energy density and the volumetric energy density is also 0.3 mega joules per liter. However, and you can see the other numbers where as you see for kerosene which is the fuel of choice in modern engines like modern gas turbine engines runs on essentially different variance of kerosene, you see the same number you see the same parameter that is it is gravimetric energy density is hundred times greater than hundred times larger than that of the lithium and battery. So, why is this why is this number so important? Because in an aero propulsion engine you can only carry some amount of mass as your fuel and you only have some amount of a fixed volume and space which will allow you to carry the fuel.

So, in that given volume you are trying to optimize your trying to carry any things. So, you cannot have infinite amount of space or infinite amount of load carrying capacity which can be filled with a fuel. So, in a given amount of space and for a given amount of mass you get the maximum amount of energy out for kerosene, and that is hundred times more than hundred times larger than that of the modern batteries. So, this is very large cap which needs to be covered if propulsion has to become electric. So, that is why there is we do not see such chance in the foreseeable future and hence aero propulsion as people say even in this very recent paper that you see that aero propulsion is most likely to depend on combustion in the foreseeable future, and that the reason is that to summarize it is basically due to the gravimetric and the volumetric energy densities of the liquid fuels. And also with other things that you see that natural gases 45, but it is volumetric energy density is less. So, for hydrogen it has got very high gravimetric energy density, but it is volumetric energy density is very very less.

So, as an engineer if you are supposed to optimize in this table you are given this kinds of fuel sources if you are supposed to optimize, no wonder we will come up on kerosene and no wonder this has immerged as the fuel of choice in modern aero engines right. So, this is why because of the energy density of a liquid fuels like kerosene, combustion is the main method by which chemical to thermal and then to mechanical energy transfer is implemented in aero propulsion.

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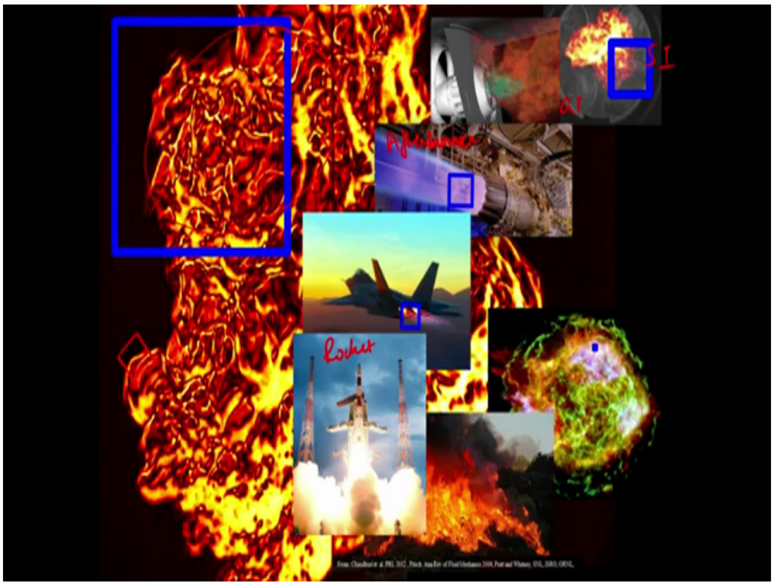

So, where do we see combustion in aero propulsion not only aero propulsion not only aero propulsion in engines, how does how does combustion look like in this engines. So, this is the picture that motivates this is in an si engine this picture, this is in a gas turbine engine, this is in an after burner of a gas turbine engine, this is also after burner this is a rocket engine, and this is a wild fire and this is a super nova. So, in nature you see a nature on engineering you see combustion not happening in a very smooth and quiescent and a very laminar manner that you see in a Bunsen flame rather it happens in a very distorted and convoluted structure because the embedded flow in which combustion happens is invariably turbulent.

So, essentially you can it can be safely said that all these aero propulsion engines that you see these gas turbine engines after burners rockets scramjets etcetera etcetera, all this involve combustion in turbulence flows and the combustion is essentially turbulent in this things the reason is that also. This all these aero engines are work at high pressure that the reason is comes from thermodynamics, that you must extract work only after you have input heat at high pressure. So, at high pressure your density is high your Reynolds number is high, and as a result of which your flow is invariably turbulent and you can get you can only have turbulent combustion in these aero engines; and this is how if you look into the fundamental manner, how turbulent combustion looks like it happens through this kinds of different where the flow disturbs the flame at a different scales and this is how the turbulent combustion looks like. But then as at this movement as you see that this process is complex there is we have a fuel that is undergoing reactions, then you release energy and then that releases heat and this all this happens in a very complex turbulent flow.

So, this means at this movement we are not prepared to right now understand how exactly combustion happens in the aero engines. So, we have to take a step back and understand the very fundamentals of combustion. If you take a small unit of the flame or say for example, this part we have to know or this this this kind of we take this unit flames if you can from this different parts of the of the combustor and the. So, all our the road that will follow is that we will try to understand how does this thing when you remove the complexities of the flow etcetera, how does combustion happen in a very simple environment or in other words in a laminar environment and even preceding that what is the basic thermodynamic mechanisms through which or the kinetic mechanisms through which a reactant goes into a goes from to become products and releasing energy.

So, that is the that is what you will first try to understand, and once we have developed enough understanding of a simple cases that is simple flames, simple processes, simple reactions, then we will be in a position to understand combustion in turbulent flows, and once we have understood combustion in turbulence flows we will be in a position to understand how this a how combustion happens in these kinds of engines.

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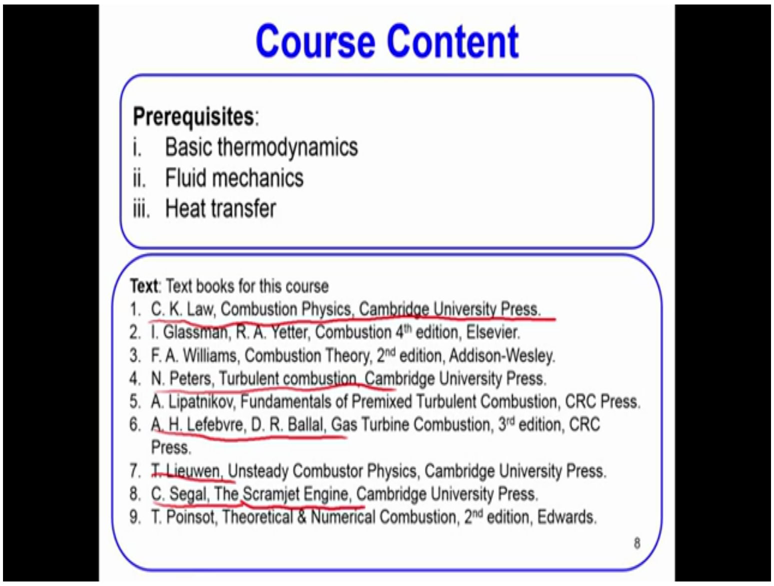

So, with that we have designed course content. So, the prerequisites are pretty basic for this course, the prerequisites are a basic thermodynamics fluid mechanics. And heat transfer and these are the text books we will follow we will heavily depend on this text book in particular for the materials by combustion physics by C. K Law, we will also for turbulent combustion we will go into Norbert Peterss book, for gas turbine combustion we will go into Lefebvres book Lieuwens book scramjets will go into Corin Segal's book.

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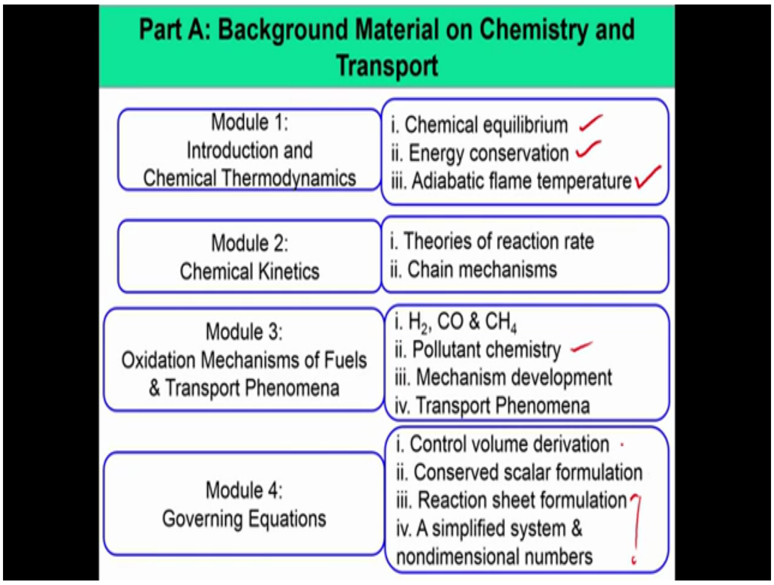

So, here is the outline of the course; the outline of the course is that we will we have divided this course into essentially four parts. The part consists of background materials on thermodynamics chemistry and transport. So, this module one will talk about the introduction which we have just covered, there is why we should learn combustion why is combustion indispensable in endo-propulsion engines, how does a combustion look like in actual engines and how you will proceed from here. So, that is covered in this introduction, and then we will cover in the following will cover chemical thermodynamics and here we will talk about chemical equilibrium, we will talk about energy conservation and then we will using energy conservation we will we will arrive at adiabatic the concept of adiabatic flame temperature. Now this is very very important in terms of combustion engineering these concepts of chemical thermodynamics.

Second this module 2 will go into chemical kinetics, this will tell us how reactants there is a hydrocarbon fuel what are the steps and what are the processes through which the fundamental processes through which it can become a product and for that we will need to understand the theories of the reaction rates in the different mechanisms. How does it happen, that is covered in module three through this oxidation mechanisms of fuels and transport phenomena. So, we will understand how hydrogen is oxidized how CO is carbon monoxide is oxidized, how methane is oxidized because these are the very basic fuels then we will pollutant chemistry works how nox oxides of nitrogen is formed, and how does one develop reaction mechanisms to describe this processes; then we will understand transport phenomena, by transport we mean like processes like diffusion processes like conduction and momentum transfer which happens through viscosity then we will go into governing equations.

Now, we see that combustion happens in fluid mechanics and also there is something called we chemical kinetics is important. So, how can we marry these 2 things how can fluid mechanics and how can conservation equations can be integrated with the chemical kinetics, and which will give us governing equations with which we can study the different kind of flames and combustion processes. And for that we will go into Reynolds transport theorem to do the control volume derivation, then we will do the conserved scalar formulation and this kinds of different formulations for the which is typical for flames for understanding flames.

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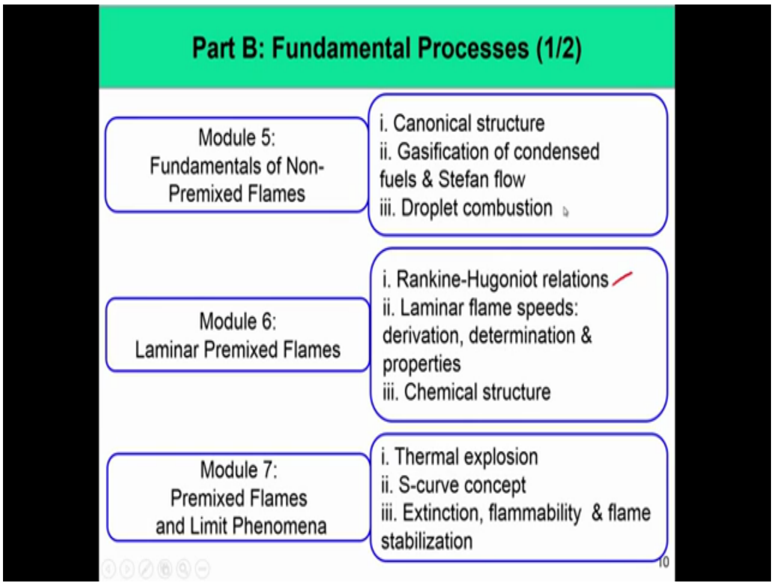

So, in the fundamental processes also we will study about non premixed flame like a chambered flame we will understand droplet gasification and droplet combustion. Then we will talk about laminar premixed flames the thermodynamics of laminar premixed flames which is given by this Rankin Hugoniot relations will cover laminar flame speeds and then will go into the chemical structure of laminar flames, and then we will go into premixed flames and limit phenomena the thermal explosion concepts s curve concepts extinction flammability and flame stabilization.

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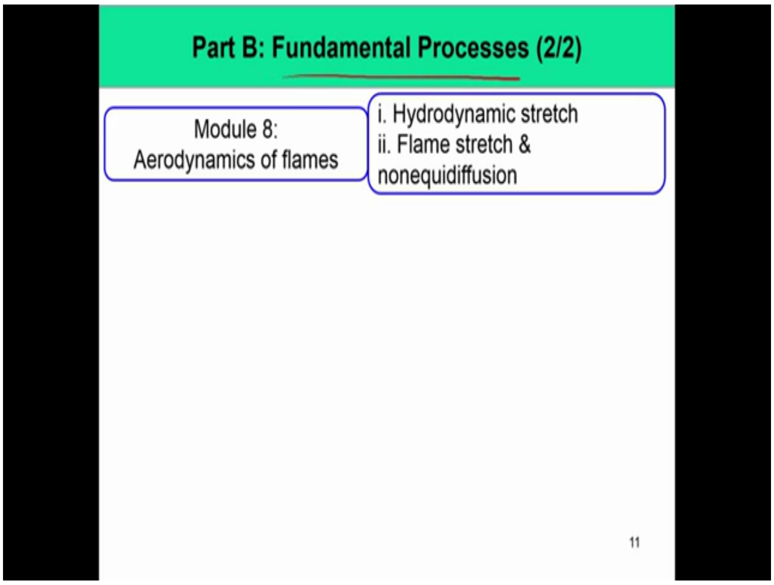

And then we will finish fundamental processes with aerodynamics of flames, hydrodynamic stretch and nonequidiffusion.

Now, these things this fundamental processes as I said that in in an engine combustion happens in a very complex manner, it happens in a very complex turbulent flows. So, to understand them we have to understand how small unit of those of the combustion processes that happens in the engine, how that looks like how we can understand them using this different formulations and what are the different processes that are involved. So, these parts will cover this this fundamental process will cover that.

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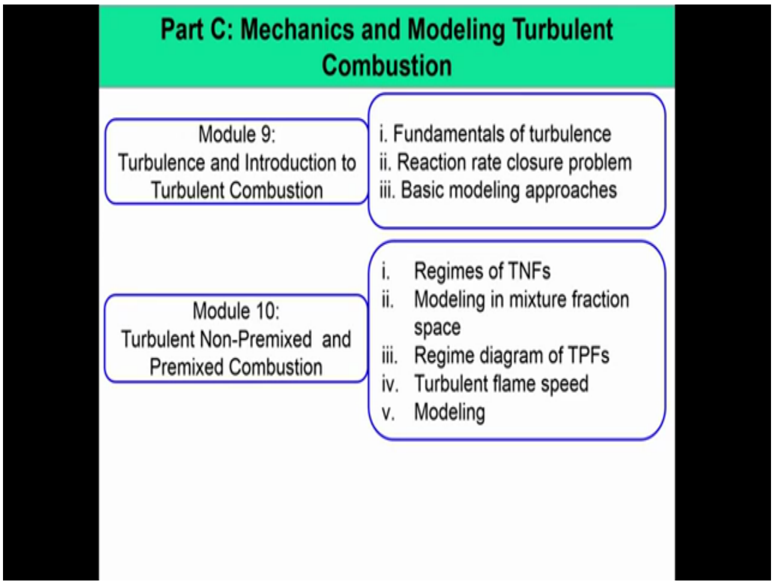

Now, after we have understood these things, we will be in a situation to go to this mechanics and modeling of turbulent combustion, and these parts will be will go into turbulence. So, will look into what is turbulence what are the fundamental processes in turbulence and the reaction rate closure problem and basic modeling approaches.

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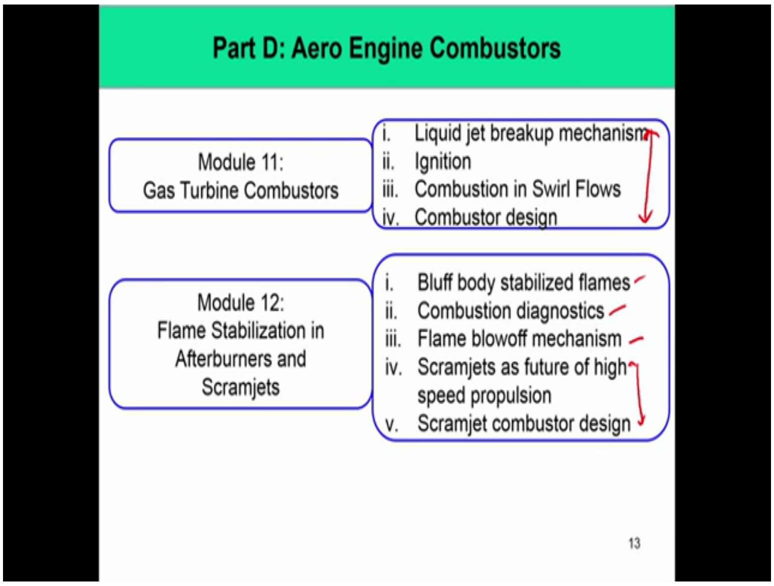

So, these will be I will cover turbulence and turbulent combustion and then will cover turbulent non premixed and premixed combustion, different kinds of flames different turbulent non premixed flame, turbulent premixed flames turbulent flames speed and modeling and then in the final part we will cover gas turbine combustors how does for example, first we will study about atomization, ignition and combustion in the in swirling flows, and then what are the basic principles by which a gas turbine combustor is designed and finally, in module 12 the flame civilizations in afterburners and scramjets.

So, here we will talk about a bluff body stabilized flames some parts of combustion diagnostics, and we will look into flame blow off mechanism and then we will go into scramjets. Now one thing is that these even though I have a formulated in this different modules these modules need not be in equal length for example, in this you can see that in module 11-12 to be talking about lot. So, we can reduce these things, we can reduce the different will be using will be looking into different topics on in preference of their importance. So, some topics can be more important some topics can be less important and will that we will this is the introduction.