Indian Institute of Technology Madras

NPTEL

National Programme on Technology Enhanced Learning

COMBUSTION

Lecture 1
Introduction

Prof. S R Chakravarthy
Dept. of Aerospace Engineering IIT Madras

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Hi today is the first class on this course that we have under the NPTEL program combustion. So we will just start with the course outline the first thing that we will do is a little bit of thermodynamics, but what are we going to get out of here is essentially the adiabatic flame temperature. Number two is we do some chemical kinetics this is going to tell us how fast okay, how fast will explain these things as we go along.

Number three is some mass transfer definitions, so this will lead to the Fick's law, number four conservation equations. So here the most important thing that we will bother about is species mass conservation, and then we will also worry about a mixture momentum, mixture energy and what is called as multi-component diffusion alright. Then we will go through what is called as Schvab-Zeldovich formulation.

Number six we now do what is called as Rankine Hugoniot relations, seven Premix flames, and diffusion flames. So here we do two things one is what is called as the Burke-Schumann problem, and then we will do droplet burning.

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And then we do a few more things, which is first of all we do partially premix flames, and then we do turbulent flames. So that means if you now go back we can now realize that these are laminar, so here we will do a overview and this would be both pre-mixed and diffusion flames, and let us say we do a little bit of solid propellant combustion, spray combustion, detonations, in this essentially we restrict ourselves to what is called as the ZND model. And lastly we do some combustion instabilities all right.

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So this is like what is planned for about a 40 hour lecture and there is a little bit ambitious for a 40 hour lecture, we will try to squeeze as much as we can, but if we cannot we will let it overflow all right. So we may not really finish everything by about 40 hours that is the first thing, the second thing is this is a course that is pitched at the level of a senior undergraduate to a first introductory graduate level course in combustion all right.

So that is kind of like, we are not talking about very advanced level combustion, at the same time we are not talking about something that is too introductory all right. So we have to get reasonably mathematical here to get the equations in shape. Therefore, somebody wants to actually get into some kind of a computational approach, or a theoretical approach you should be in a position to do this from this course onwards.

So that is essentially how this is shaped up all right, with this we should now start thinking about what we are getting into. Combustion what does that mean? Right, so what is does it ring in your minds when you say, when you think about combustion? Obviously it is something like a fancy technical sounding term for something that we are very familiar with in our daily lives, essentially the process of burning if you can say that you would not be too far off the mark okay, you would have covered most of what we come across.

Then the question is what is burning all about all right, so we are first of all understand these things in simple English right. So combustion is like let us say approximately the process of burning, then we have to think about what is burning all about. So we now start thinking about what we are familiar with when it comes to burning okay, what are the most familiar situations when you come across burning.

Anybody? No, no like practically when you come across burning match box okay, anybody else? In stoves, flash fire, furnace fire, okay. So furnace fire okay, jet engines okay, so he wants to go, jet engines okay. So let us know this start listing these things, so combustion is like process of burning. So example matchstick okay, what else we see answer the stoves, forest fire and jet engines okay, anybody else wants to say anything more?

IC engines, rocket engines, jet engines okay, fine so IC engines okay, anybody else wants to say anything more that you come across? Candle, so somebody is very romantic guys okay. So candle flames. So now you see we are we are now getting into some Jordan, so on the one hand we have something called a flame, the other hand there is something called a fire okay, these are things that we come across.

What do they mean? In plain English flame and fire are they different or the same, can we say that? My flame remain steady fire, steady fire yeah fire which is really not increasing you okay. So well in technical combustion literature even unsteady flames or flames okay, and fire is typically something that spreads more and more or less in an uncontrolled fashion, but you could have essentially something like turbulent flames that are there in furnaces, for example, like very large furnaces or oil fired furnaces again okay. So coal furnaces many of these things actually have very large fires right.

So if we think of them as fires, but they are also typically classified as flames, but the steady flame that you call this flame is something that you can for example associated with like a candle, so you light up a candle and it just stays steady unless you now see how big that candle is or how long that is been burning right. So for example, let us say you are burning the midnight oil for an exam the next day and then you had a power cut and you have to light up the candle to keep going on all right.

Somewhere through the hours you are going to now have the candle begin to flicker what is going on there, the flame become fire? What is going on is you now have a buoyancy driven flow that is like the candle vapor mixes with air and burns and produces products that are hot, and because they are hot they move upwards, and they begin to actually oscillate because you are now beginning to have some sort of a instability in that flow of hot gases that percolates back to the flame.

Again the flame begins to start shaking all right, so it is an unsteady flame there at that time, it is not necessarily fire yet at all okay. So what are we, then if you want to now analyze this kind of situation, so that we now just talk briefly about how candle works right, but what happens in a jet engine for example. Let us say consider the other situation okay, so if you now look at a candle let us suppose you now can draw a wick over there, you now have a flame, and this could be moving back and forth okay in an unsteady fashion.

But essentially you are having a wick in which you now have feel coming out in vapor form ultimately, and then mixes with the oxidizer that is around, and then you now have a flame there okay. But if you now look at a jet engine let us get a little bit more specific maybe we talk about what is a favorite get engine for you or anybody turbo jet okay. So say turbo jet now of course I am interested only the combustor the turbojet I am not interested in the compressor and the turbine and so on.

So therefore, I am going to draw some sort of a schematic of how this looks like oops let us see how this notice comes about. So I will have a fuel injection and then a spoiler over there and then you have a flow that is coming out I made a mistake let me just redo this. So let us say, and then I had a spoiler box into which in it they have an atomizer, and then yeah right, so I have had a airflow come over here this is fuel, and you had the air come out some of the sides.

So this is like what is called as primary air, this is like secondary air, that is like dilution air and so on. So you now have a flame that is sitting there okay, highly turbulent flame right. So what are we been talking about for the basic elementary processes that constitute combustion. So to give you an example of where the kind of answer I am looking for one thing you have a flow, we have a flow of air through this okay.

And then you have a fuel injection that means the fuel has to flow through the fuel nozzle and get out there all right. And then what do the fuel and air do, not yet they mix right. So one of the things that we are talking about is flow, the other thing that we are talking about is mixing, and the third one is there is a chemical reaction that goes on all right. So effectively we are talking about three major things that we should be keeping in our minds when we are looking at combustion.

S combustion basically means flow mixing and chemical reaction all right. So in a little bit more technically sounding jargon we could say this is like convection, diffusion right, and reaction. Well we are talking about the three basic things okay, so you could argue, well I could have convection and diffusion would that be combustion probably not okay I will come to the next, then can we have diffusion and reaction would that be combustion maybe yes, can I have convection and reaction would that be combustion maybe yes.

So we are looking always at chemical reactions being present when you are talking about combustion right. So from the question that he asked I kind of take what I want okay. So what kind of chemical reactions are we talking about when you were talking about combustion, any chemical reaction, exothermic what did you say oxidation, oxidation what else, fast oxidation. So there is a person back there who is not just sufficient for him to be slow it should be fast why, that would be an explosion, otherwise what happens cannot you have slow reactions that continuously happens.

Why would a slow reaction cause an extinction, you, the heat would be convected out if it before it gets preheated. So how does the heating happen in the first place right, so you have exothermic reaction that is happening and the heat could be getting convected out that means it gets washed away okay, before it can preheat what the reactants to get up to this temperature at which they can react.

So how is this happening, why we use a binary yeah, but how is it actually getting heated up. Let us say I had a flame right in front of me okay how do I know that without seeing, because if you look eyes to see right, how do they know that it is there they are getting into a flame zone radiation and conduction. So essentially what you are talking about is some kind of a heat transfer that happens to the reactants in order that they actually get heated up to the flame temperature where they get in and start participating in reactions and constitute the flame right.

So if you now have a reactant flow that is coming in it has to get heated up and get into the flame, and then the flame itself happens and when the flame has happened its job is to actually heat up the reactants that are further coming in. So that they will come and participate in the flame, and the flame is there it now produces products that will go away right.

So what is the flame now, that is like twisting yourself right then I have asked you what is a combustion zone it could say something like. Can we speak English like we do not know anything about flames or combustion, the flames or reactions are taking place all right. So a flame or a combustion zone is nothing, but a flames where the reactions are taking place nothing more you see.

Now what has happened is so let us just record this, so this could now the diffusion here could also mean heat transfer okay, predominantly conduction that the reason why I am writing this under diffusion okay, conduction heat transfer plus radiation all right, plus some radiation. So for example, what is meant by radiation for example you can see the flame if it is like a diffusion flame it gives out light or more than a pre-mixed flame like an orange flame that gives you a lot more light back in those days they used to use combustion for lighting okay, at night.

So that is essentially coming out by radiation, but most of the energy that is being consumed is released in heat rather than by light. So it is not significant unless you are looking at some specific situations which we will talk about as we go along. But you look at the factor that is refraction of energy that is involved in the radiation heat transfer works as the conduction heat transfer.

The thermal double, fine, fine let us not worry about how that idea okay. So we have this going on and so we have the convection going on and the reactions going on, we also notice that these should be fast exothermic okay. And typically you want to have fast exothermic chemical reactions mainly when you deal with gases, gaseous reactants, because when you now want to have reactions happen molecules have to collide okay.

So if you now have two solids where you do not have a mobility between the molecules of the solids it is very difficult for them to collide in the first place okay, it to a lesser degree similarly with liquids, but with gases and as you pressurize small more okay, the molecules can actually interact, bombard against each other much more. So you are able to actually get fast chemical reactions mainly with gases.

Therefore, most of combustion not all okay, most of combustion is essentially happening in gas phase. Now does it make sense, I would like to counter that by saying no, no, no most of the combustion actually happens not in the gas phase, because I use petrol in my car, I use diesel in my bus okay, these are all liquids. I could be burning wood or coal which are all solids yeah.

So these are typically what we would use for getting energy for transportation or otherwise what are we talking about gaseous, they have to vaporize, because they just simply do not withstand the temperature in the first place of the burning. So they vaporize actual combustion reactions that are happening or happening in the gas phase most of the time, from in most applications all right.

So those are the ones that are significant, so what has happened in the last, let us say half an hour is we have made tremendous progress okay. We were just barely beginning to spell the word and here we are talking significantly about convection, diffusion, chemical reactions. So what this means is you need to know fluid mechanics okay, you need to know transport phenomena, and at least a bit of chemistry right.

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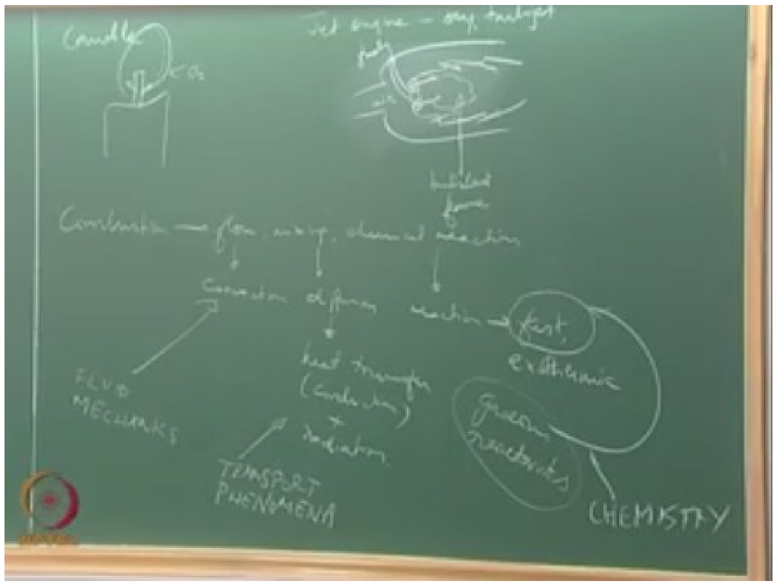

So at least a bit of chemistry so you need to know a minimum of three basic subjects before you can actually get to doing combustion.

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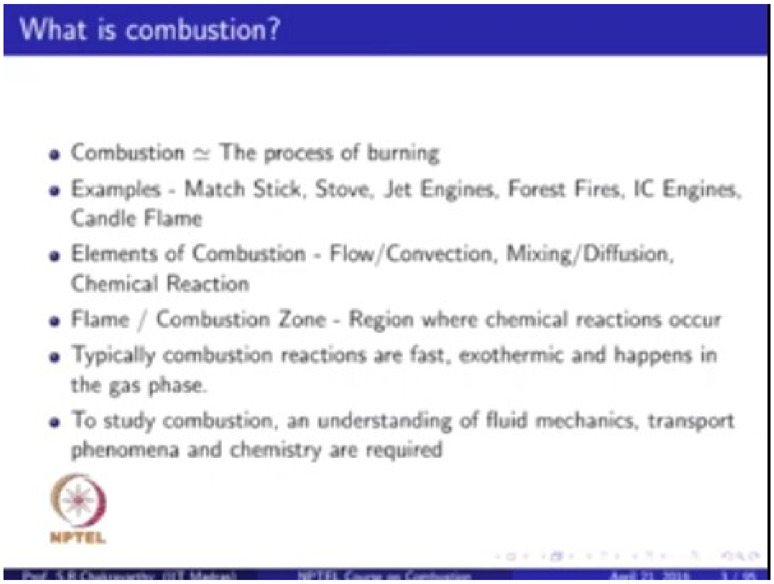

Okay so no wonder you cannot do this too quickly in your career, so you have to wait until you are like a senior undergraduate or a that is a starting graduate student before you can master some of these things to some extent before you can actually do good then let us look at what we are supposed to do right.

So the first topic is actually speaking thermodynamics apply to combustion okay so we are not going to really do combustion itself you are going to be basically be doing thermodynamics but applied to combustion the goal being we will now get what is called as the aerobatic flame temperature that means the best estimate for the temperature without any heat losses is essentially what you what you are looking for all right and when you now look at the cap and this is not going to tell you how fast things are happening thermodynamics always talks about changes.

Okay from like an initial state to a final state or state 1 to state 2 in fact initial and final or even misnomers to be used because they have a connotation of time before and after thermodynamics just does not care about time at all it is only talking about a change from state 1 to state 2 all right and of course the direction of increase in entropy is what is deciding what the direction of change from path one to take state 1 to state 2 is okay that is all thermodynamics can do for you but if you want to now start worrying about how fast these exothermic chemical reactions are supposed to happen then you have to do chemical kinetics it is there is also something that you are familiar with okay.

But we will go through this and we will bring in some notation that sort of like algebraic or trying to algebra science chemistry if you will yeah, so we will try to do that and plus also talked quite a bit about the details of chemical kinetics where they play a rule and so on then we have to worry about mass transfer definitions this is picking up a little bit on transport phenomena ultimately leading to what is called as Fick's law that is involved in mixing to two species so when we talk about species that is like a new term okay.

We are not talking about biological species but we are now looking at chemical species, okay so chemical species simply means a particular compound or an element okay, so we want to now cause we treat them in an algebraic sense call them like X or Y and then we want to call them a species as opposed to compounds in mixtures or something so then we will be in a position to actually look at conservation equations what we will now find is the there is a need for something called a multi-component diffusion equation.

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Which is the multi-component counterpart of Fick's law because what we will note is Fick's law holds good only for a what is called as a binary mixture okay. That means you can have only two species in the mixture and if you want chemical reactions to happen between them that means one of them should be a reactant the other one should be a product, okay it is not like two of them react with each other now because anytime you have a bunch of reactants you also have to reckon with reckoned with products right therefore that that is a very restrictive situation for you.

So we will have to look at how the multi-component diffusion equation works out for a truly multi common mixture multi-component simply means more than binary more than two kind of two species. Schvab-Zeldovich is a new term for you except I want to point out at Schvab-Zeldovich is like a father of combustion I should I should point out at this stage a little bit of historical background okay.

Combustion how old is it. 1.5 millions here 1.5 million years ago okay was human pay very human beings are at the time yeah they were okay so did so they discovered fire that is what you are talking about you get you get in you quickly get into this confusion like do we do we have the considered combustion that happened before human beings discovered it or after so it is been around for a longtime so right back from the Big Bang maybe if you want if you want to call that combustion.

Now I want to also point out that we are restricting our cells to chemical reactions here that means you are looking at exchange of electrons from atoms and molecules okay whereas we are not necessarily looking at nuclear reactions where you will have the nuclei participate in the reactions as well, now these days for example you look at the hotel preliminary lecture at the 2006 combustion symposium at Heidelberg by ED law he would now say all reacting flows including biological reactions should be combustion okay but that is not the conventional sense in which we know combustion.

So typically we will be dealing with chemical reactions alright so I do not know if Big Bang included only chemical reactions are also other things but fundamentally we can imagine that burning happened even before human beings were around but one of the first things that human beings discovered is fire, okay maybe before even inventing the wheel alright so it is been around for a long, long time what do we know about the science of combustion.

So this is technology so this is the classic case where technology precedes science you do something figure out how it works right but do not know why that is the difference between how and why yeah, so what about the science what is been the state of combustion science over a period of time. That is like the progression of science alright but specifically the combustion science what have we known about combustion science over the period of time.

For example when you now look at how mechanics progress you know that with the advent of decor’s there was some progress vividly with the advent of Newton there was some progress and so forth alright so what do we know about let us say combustion science made good progress in three weeks laminar three weeks plain diffusion is well historical, right okay so what has happened is bulk of the science of combustion had to wait until significant progress had been made in any of these three fronts right there is fluid mechanics transport phenomena and chemistry it turns out for example if you look at transport phenomena all right.

So you look at a mass transport, momentum transport, energy transport right so you look at momentum transport this is due to a flow being viscous okay Newton figured this even the latter half of the 17th century or earlier part of the 18th century but Fourier was the one who figured out in the earlier part of the 19th century the heat transfer, heat conduction okay that is the energy transport it took further out for Fick to figure out the mass transport, so mass transport actually happened quite late in the game okay.

And then we have to worry about multi component diffusion and so on so it took quite a bit of time for this to happen and we are now already looking at later part of the nineteenth century okay chemistry so for a long time it is been alchemy okay so chemistry also started making strides only in about the 19th century later Potter there about is.

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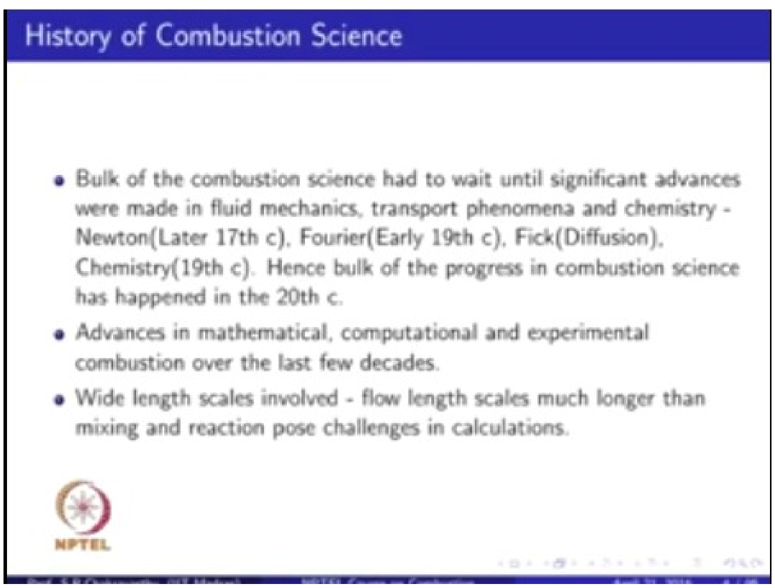

Putting all these things together it is only in the late 19th century that any combustion science ever pretty much happened of course you can you can argue about this significantly but it is very late in the game when compared to lots of other classical mechanics related sciences, okay bulk of the progress in combustion science has pretty much happened in the 20th century maybe we are still very early in the 21^{st} century so we cannot compare the bulk now with what happened in 20^{th} century where bulk of the progress happened.

And interestingly towards the second half of the 20^{th} century you now made strides in all three fronts in terms of approaches one of them is mathematical analytical okay there are some progress was being made in the early part as well but you needed significant mathematical tools like asymptotic expansions perturbation methods and so on which matured through application to boundary layers and all those things earlier on and then they were big being applied later on in combustion.

And computational combustion has seen a huge investment of time and effort in the later part of the 20^{th} century and similarly in experimentation there is like a big emphasis on laser Diagnostics that has happened because we are essentially looking at things that are happening at the molecular level all right the other thing that happens with combustion is the multi scales okay so the fluid mechanics part of it there is a flow part of it happens over a fairly large length scale.

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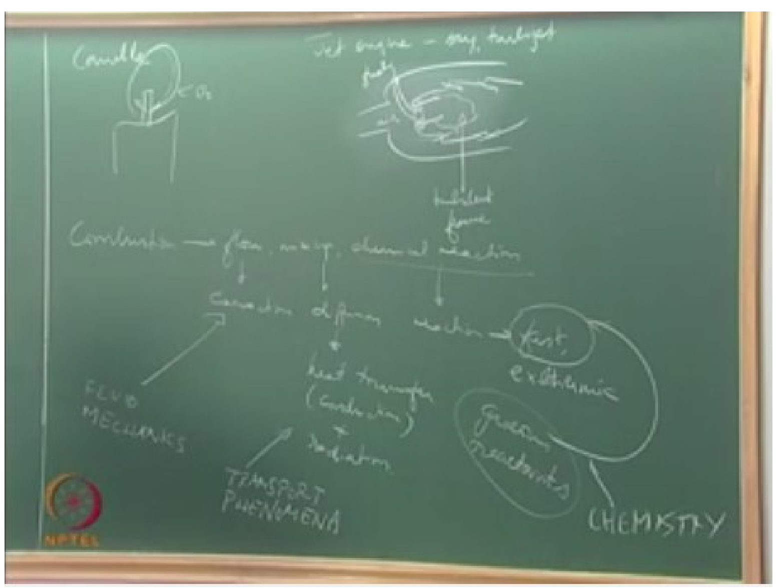

Okay it has to now go from this end of the combustor to that end of the combustor where as the mixing and the reactions happen in much smaller regions and even in these smaller regions the mixing happens in a smaller region in a macroscopic sense okay but the reactions are happening in that region in a microscopic sense okay you are still you have to get molecules to mix with each other.

That means we are now trying to transcend between here and here we are to transcend from a continuum framework okay to a molecular level frame work that is a little bit a little bit hazy right so we have to figure out how to handle these things together yeah so fundamentally you are now having a multi scale problem here and therefore doing combustion calculations or Diagnostics is difficult you have to keep the big picture of the flow at the same time as looking at the molecular level processes okay that is very difficult.

And therefore combustion problems have eluded solution very well for a long time it takes a lot of effort to get into combustion this is not to discourage you this is to actually encourage you because it is this challenging stuff plus also on to point out that looking at the future okay combustion is becoming very significant it is becoming significant from two counts one we have a energy demand that is growing in the human civilization and most of the energy in the foreseeable future of let us say the next several decades like in our lifetimes is going to still come from combustion energy.

Okay the fossil fuels or coal or some other things and of course when we are when we are done with burning everything that can burn we will still find something more that will burn okay good I cannot believe that combustion will come to an end in about70 years or something like that when it actually started when we do not know right, so it would happen right and it is going to happen more and more in the next few decades next several decades in fact okay so we need to be solving combustion problems for tapping energy from different sources I said fossil fuels coal as well as now biomass.

Okay so for example that is like a new renewable energy that you can think about second thing is the pollution and environmental problems that is like global warming and so on this is also caused by combustion so on the one hand combustion is required and other hand combustion is bad so it requires combustion engineers for you to engineer your combustion in such a way that you get what you want and you do not you try to avoid what you do not want.

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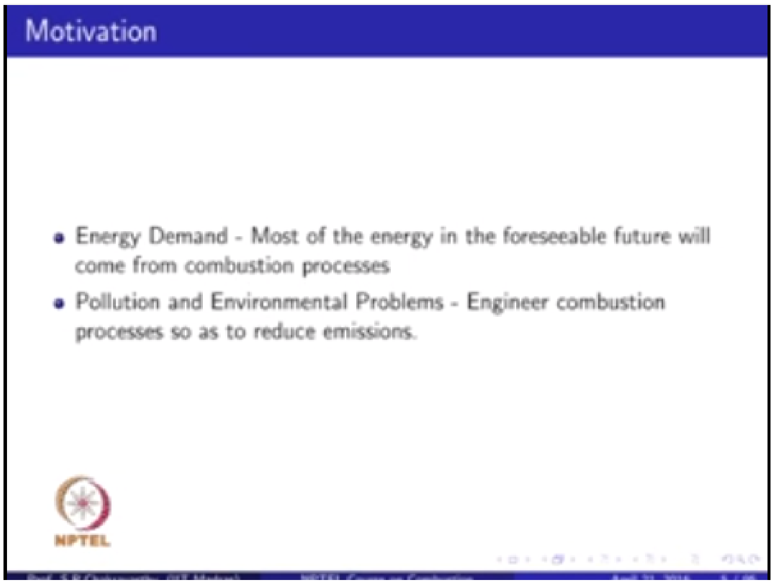

Okay so that is engineering that we have to do which means the combustion research and the engineering that we do now should be lot better than what has been done before okay that means we need smarter people working in this area so because it is highly challenging and the practical challenge is a lot more therefore let us continue with where we were okay summer somewhere in there the in the first half of the 20^{th} century we now have Zeldovich show up okay and he is like a leading figure in combustion in fact the every combustion symposium do they give the Zeldovich medal for life time achievement for a combustion researcher.

That means like they give the best metal after Zeldovichh okay we do the drank kind Hugo knew your relations those of you who have done gas dynamics we would have come across at least Hugo part when it when you are dealing with shocks alright so what we want to try to do is something similar which means we now to try we now try to deal with flames as if like their shocks.

Okay what does that mean it is like we want to look at them as like surface of discontinuity so you have reactants on one side products on this side do not worry about what is happening inside okay you just have a discontinuity between the two separated by the flame can we analyze the situation like this without getting into the flame and we was find there is not at the end of it we will find that it is not possible to avoid getting into the flame.

And therefore we will we will get into the premix flames we will spend quite a bit of time doing this we will try to find the laminar flame speed and then we will look at flame stabilization issues flammability limits ignition and quenching all these kinds of things over there how to treat flames globally when given a flame speed and how the how the flame speech should be computed in the first place flame shapes versus flame structure and so on.

So I would to distinguish these things as you go along then we get into diffusion flames so the name suggests obviously that when you now have pre-mixed flames the reactants are mixed by the time they get to the flame whereas in the case of diffusion flames the reactants are just mixing right as they are burning so they are kind of busy mixing as a burning okay so that is what this is then of course there is like a standard problem that was published in the first symposium or the combustion first combustion symposium 1928 the celebrated Burk Schumann paper we will go through that.

And then and we will look at further advances to this that has happened through years even as leaders like the 80’s or 90’s and of course droplet burning is pretty important from a practical point of view and it is also covered in the diffusion flames these are extra topics okay so once you are able to do this much then you have to get into realities like these are like a little bit advanced so we will talk a little bit about these as we go along maybe one lecture each or two lectures each and soon. Some of these are picked because I do research in this area okay so we can only talk about what we know right.

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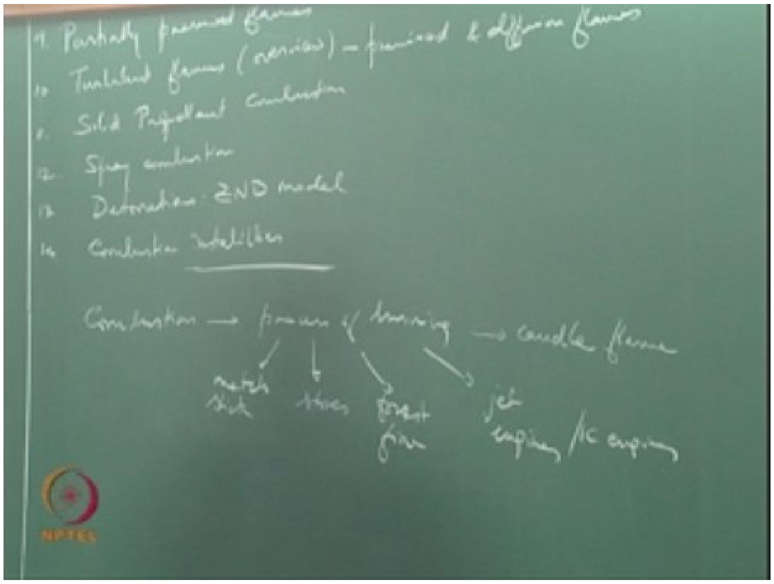

So okay what little we know so that that is what this is all about so that is how this is the structure I also want to talk a little bit about the books that we want to go through.

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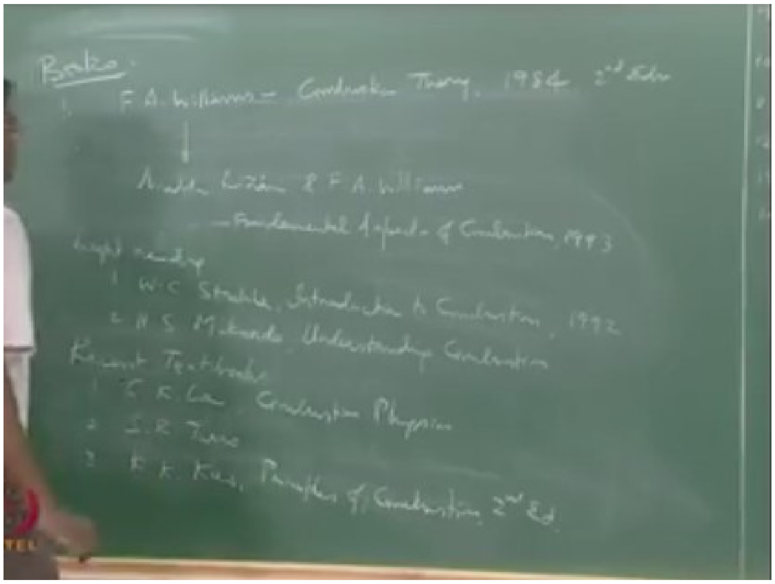

So let us talk a little bit about books the first book that I would obviously look at is Williams, so this is a combustion theory this is a thing that second edition came out in1984 I will give you the publisher details and so on the website that goes along with this these videos but effectively I want to talk a little bit about these books now Williams is now the living father of combustion in some sense because most of the advanced level graduate students could not have escaped his textbook.

It is it is a little bit dense it is difficult to understand but you have to work on it indeed and you will reap rich rewards once you do that a derivative a smaller book was also written by
so this is a Spanish name so you have two plants that I guess is lenient with all this tilde LA and this accent here and F.A Williams this is a fundamental aspects of combustion this is around 1993 or thereabouts I will give you the specifics in the website if you want to have light reading I can suggest two books to start with one is W. C Strahle which is introduction to introduction to combustion.

And this was around 1992 as well and then there is an Indian author H.S Mukunda this is understanding combustion this is actually in IIT Madras publication as a matter of fact then there are more much more recent books that there are comic deserve that have come up so recent textbooks I would like to just about a couple of two or three about three or two or three one of the most recent ones is C.K Law this is combustion physics the second is maybe you can say Stephen Turns S.R. Turns forget the name of the book again I can get back to you on that. Then there is a K.K Kuo which is principles of combustion second edition so these are more recent in the last five to ten years.

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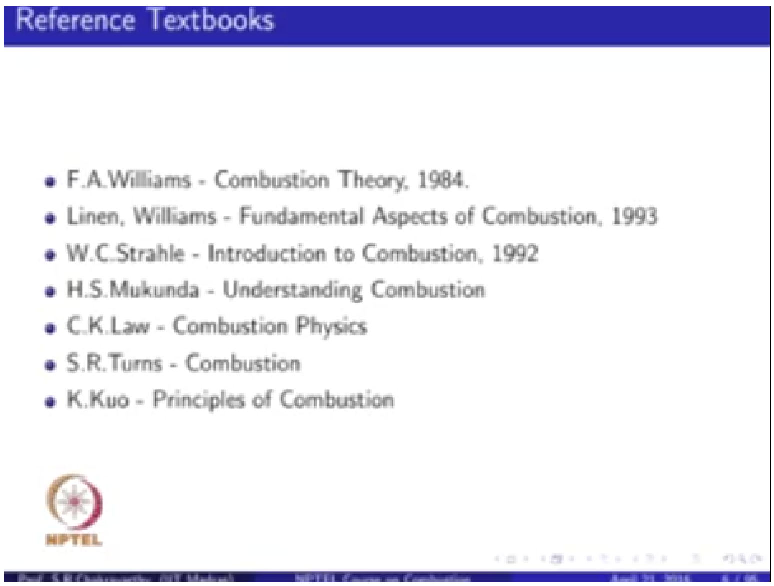

And these things are improving there are a lot more books that are coming up and but they typically many of them focus on specific aspects of the science because it is simply difficult for anyone to do all of combustion and therefore they typically focus on one particular aspect like maybe one book would be more on chemical kinetics the other work would be more on computations and so on.

Okay so there is a lot of books that are have that are there but I would like to start with maybe you can you can look into can look at some of these I will follow one or two of these books and I will try to point out which book I am following at a particular point okay so that you can go back and refer to it as you go along with this let us stop the introductory lecture and we will pick up from the first topic the next class there is combustion thermodynamics and look at how to calculate the aerobatic flame temperature from there on Thanks.

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