Indian Institute of Technology Madras

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COMBUSTION

Lecture 51
Detonation Wave-ZND Structure

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So what we have done so far as far as definition is concerned is to come up with a way by which we can get the detonation wave velocity for which we realize that we do not necessarily have to get into the wave structure and like what we did for the deflagration in any case it is also important for us to actually think a little bit about the detonation wave structure if you want to get into applications with detonation waves as we pointed out for example in pulse detonation engines which is coming up as a good alternative to engines that are commonly used now.

So today we will just look at detonation wave structure now in reality a duration wave is highly three-dimensional the structure is very, very complicated but just for the sake of simplicity we could still adopt a one dimensional approach by which we now try to see what happens within the detonation wave just like how we did for the deflagration wave where we said we look at a plane or deflagration and you have upstream heat conduction and reaction rates towards see later to downstream part of the flame thickness and.

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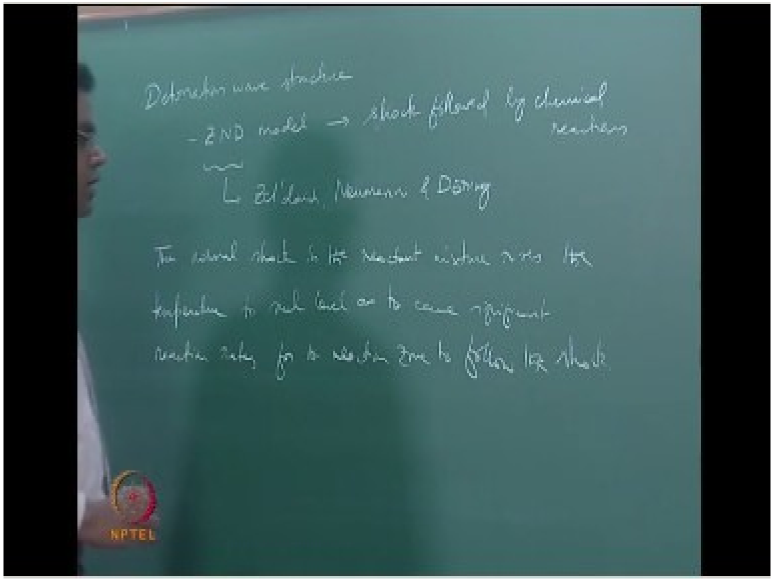

So on similarly we can have a similar approach and the first kind of a advancement that was done in this is what is typically called as the ZND model which stands for Zeldovich as usual as with most things in combustion it also it always has to have Zeldovich there so this actually stands for Zeldovich Norman and during who independently all three of them independently evolved this idea in the time frame of about 1940 to 1942 that is that is around the timeframe of course let us say he restores to historical perspective about this detonations or something that is that there is some more destructive most of the time and this time frame that we are talking about was also the time of the Second World War.

So there was good reason to expect why people should be working on this at the time so the basic idea of the Z dandy model is one of shock followed by chemical reactions that is to say a detonation wave is nothing but starting with the shock followed by chemical reaction so keep in mind detonation waves propagate at supersonic speeds so do normal shocks so we are talking about a normal shock propagation and the job of the normal shock is as far as the detonation wave is concerned with respect to this model is to increase the temperature downstream of the shock to a high enough level that will now get the reactions going at as fast rates as is required for the reaction zone to follow the DD shock right.

So previously in the case of deflagration if you now let the reaction rates happen by themselves then the propagation rate is limited by how fast the heat release in from the chemical reactions can get conducted upstream to the reactants whereas here we do not have that problem in fact that the problem here is can we have the chemical reactions happen fast enough to be able or the for that layer of chemical reactions to closely follow the shock so effectively then the entire detonation wave is all about the shock rising the temperature of the of the downstream gas still reactants as if as a matter of fact because you do not expect too much reaction to happen within the shock.

Because the normal shock is only a few mean free paths thick that kind of thickness is not sufficient for significant amount of collisions to happen between the reactants for appreciable reactions to happen therefore you are essentially rising the temperature of the reactants to a high enough level such that the reaction rates are appreciable and then this reaction layer will faithfully follow the shock this is essentially the approximation we will see how this approximation can be relaxed as we discuss this a little bit further but within the framework of the sudden.

The model the essential approximation is the first thing that you have is a shock and then you have chemical reactions so the normal shock in the reactant mixture Rises the temperature to such level as to cause significant reaction rates for reaction zone to follow the shock so in fact what typically happens this so if you now think about how, how to look at what happens within a detonation wave.

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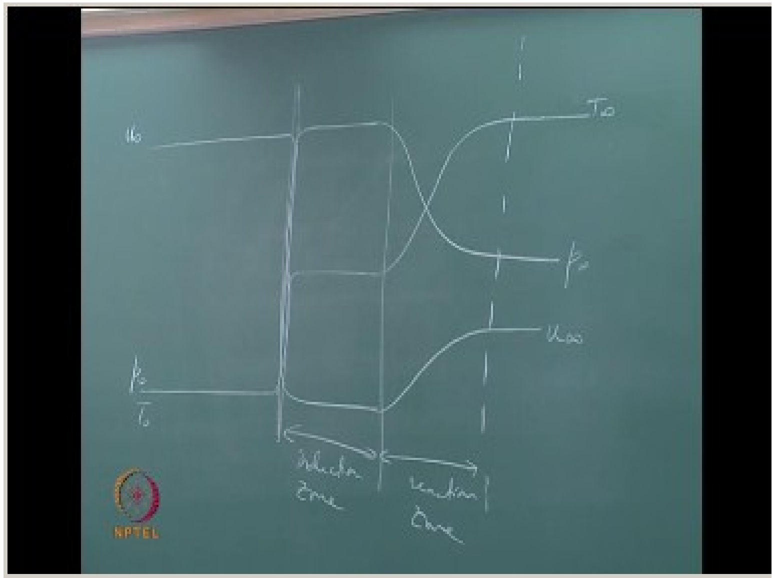

let us say that is suppose now you consider the thickness of a detonation wave the first thing that we that we are looking at is like a shock that happens right here which is very thin and then see if you now look at how the temperature varies so you now start with a T^0 then across the shock the temperature actually increases to a jumps to a value.

But that is not the end of the story right because in reality now if you have chemical reactions you have to reach something like the flame temperature and the shock itself is not going to raise the temperature up to the flame temperature it is going to rise it up to some point and then subsequently you now have a region where the temperature remains constant for, for some distance and then it begins to increase very similar to the way it increases in the in the deflagration wave pattern and then and then levels off so this is for example your t α they are starting from T0.

And this temperature that they did this value that the temperature rises to just downstream of the shock is sufficiently high enough for chemical reactions to happen in this in this region so of course in this picture we can try to alter so in this picture we now have a region that is where the temperature levels off just after the shock which we will now call the induction zoom and this is the reaction zone so the induction zone is where you have a the reactants or now elevated to a temperature and then go through a induction period keep in mind this is not a very, very long period.

Because the entire flow is happening very fast right so you have a short induction period when the reactants begin to sense the temperature and then cause reactions that will cause additional further increase in temperature so this is the this is the time when the reaction rates are just barely beginning to build up because you have the exponential dependence on temperature right and the nit shoots up so you have this induction zone where you have nearly more or less a constant temperature.

And then you have this sudden rise this Roy's unlike in deflagration is having a significant convective effect along in the case of deliberations we had a preheat zone which is primarily containing a conductive diffusive balance with no reactive component and then the reaction zone where you called a reactive diffusive balance with hardly a convective effect but here you have significant convection happening in this reaction zone as well because you have very high very fast flow rates there so if you now have if you not think about this kind of a situation for the de temperature correspondingly if you now look at the pressure right.

So if you think about the pressure and then let us suppose that you start with the same line for P_0 as well the peanut of course we are normalizing things right so the P_0 actually goes up to a significantly high value and then think about what happens when you have chemical reactions you have a pressure that decreases right so you actually go through a decrease in the pressure through the through the reactions so you reach a pressure that is higher than what you actually see outside of the detonation wave so you that you think that you got a very high pressure behind the detonation wave and this is the jump that you are beginning to talk about alright.

But in reality you went through a fairly further increase in pressure we will begin to talk about that pretty soon okay that is because in the shock you have a pressure rice and then you have a chemical reaction similar to the deflagration where you have a pressure decrease all right now you can give you can say okay this rise is lot more when compared to this decrease all that surface correct so getting in you can quantify this to find out that you do not have a big difference between these two in any case you have a pressure Raise.

And followed by a DK that is the important thing that you have to think about similarly can we now think about the velocity right so across a normal shock the velocity decreases right and then we are talking about a sharpened you get a nation wave for most part in any case all the in all these detonations we found that the reactants follow the wave so the products follow the wave at a velocity that is or a Mach number that is lower than the incoming Mach number right so you have to end up with a lower-velocity than we start out with that means you start with a high-velocity that is your you not and then this decreases significantly across the across the shock.

And what happens when you have when you have a flow going through a diff regression situation where you have a temperature rise that then the density Falls and therefore the velocity increases right so you now have a velocity increase that that happens over here so you get a u infinity so the velocity drop that you sense across the detonation wave in a ranking Hugo nay framework is actually this but in reality if you go into the wave you find that the velocity drop is even further down before it actually restores to a level that is higher than here but lower than there so these are the kinds of things that are going on similar but then of course if you now think about a reactant concentration right.

So if you now liquid reactant concentration you started out with a high reactant level so let us say yr but no change across the shock right so the reactant concentrations are pretty much remaining the same and Meg into DK only a maybe you can you can look at the deficient reactant go all the way down to zero over here or fairly low value so you say you can say why are not and then why are infinity right so this variation happens only in the reaction zone it does not happen before that so begin to understand these kinds of things so can we now think about how the state of the gases move through the reaction so the detonation wave thickness within a run can you go to your framework right.

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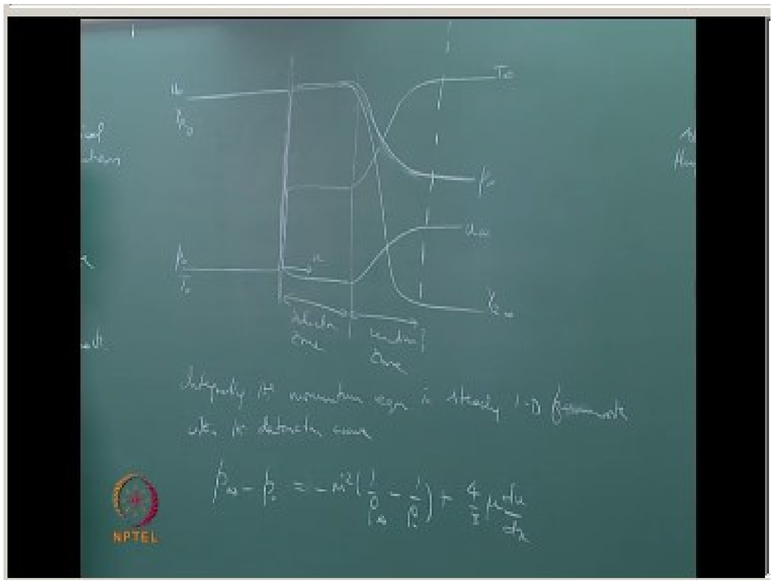

So if I want to now do that I let me just then plot where you have p ∞ and then 1 over ρ∞ is what is classically plotted but I am going to actually track the state of the system before it reaches p ∞ that means my pain-filled my asthma as I go along X whatever is my π I am going to try to track so from the origin which is your $P_0$1 over P_0 right and the to your curve is goes like that and what does the sudden model say it is a shock followed by chemical reactions this offset for the hug on your curve is essentially coming from the fact that you have a heat release okay the heat release is going to push the new more and more heat release in the K in the wave is going to push the you go new to the top.

And to the right so when you are now looking at how a shock is going to be represented that is a diabetic process that means you do not have any heat release across the shock itself right the heat release comes behind therefore you have to follow the shock you go neon so the shock you gone you is now going to be passing through the origin so that is a shocker go ne you and we are looking at the chap and yogi wave so that is a you CJ point and that means you are looking at a tangent railway line to the to the actual her gone you with a very full heat release but then we are looking for how you are trying to locate your point between successive really lines intersecting successive you go ne you curves for different q that means as we go along from here to there you are having heat release happening.

And then the velocity gradient also keeps changing so what we want to do is look at a real a line with viscous effects alright so the viscous effects will now bring in the velocity gradient into it so integrating the momentum equation momentum equation in four in steady 1d framework we have done this twice so for Witten so here what we are talking about is within the detonation wave we can now get p ∞-p 0=-n.21/∞-1/ρ 0+4/3 by dx sock she can now fix your ex going this way right when did we get this before when we wanted to show that when you have very low Mach number this will actually be of the order of listen number times Mach number.

And then the convective term will actually be of the order of gamma times Mach number squared and so on a rail of very low mach number conditions for continuum flows with low notes and numbers you got a pressure equal to constant approximately that is when we try to integrate it once the next time we integrated it was in the wrong kind Hugo in your framework but that is like saying all the gradients or within the wave that means we are looking at outside the wave to get jump conditions so you do not have the du/dx term at all right so now we have a d you by dx a term kept in nor to see how what happens when you now traverse through this rave like.

So if you do this then what we find is you now have a decrease in you with increase in X so you start with negative du/dx and then you to have a pie and then you go to 00 du/dx and then you have a positive du/dx and then again you go back to 0 d/dx so if you have a 0 du/dx then you get back to the railway line that you familiar with all right and that is the rail line that we have plotted here so you start from here right that is 40 du/dx you go through a 0 d/dy/dx again and you go through a 0/0du/dx again so you go through this three times once at the start once at the end.

And one somewhere in between all right that means our system should actually the yeah the system should actually lie on the original railway line three times starting at this point anything at this point alright but also somewhere in between okay so how do I represent this curve this is basically again a straight line with the same slope a minus m dot square right but now having an intercept so if I have negative do you by dx maybe I can use it different color chalk piece I can now think about several really lines that are parallel to this like this.

And these are with negative du/dx and if I want to go positive I have to draw lines that are like that and these are lines with positive by dx so the original railway line now begins to look like that corresponding to 0 du/dx right okay so if you if you strictly follow the idea of having a shock followed by reaction reactions and the heat release is happening only in the reactions what it basically means is you will rapidly go from the origin through a negative set of du/dx loins k-through a set of negative du/dx really lines along the shock you gone you right as rapidly as you can go up to the peak pressure and I told you I will talk about this right so you go up to the peak pressure all the way.

And then stopped turning around when you have when you now get this du/dx to flatten out 20 back again right so the positive du/dx begins to decrease back to 0 that means you are your path would now go along the shock Hogue not as much as possible you see the moment the shock you go neo is deviating from the railway line like in tangent relay with a positive so with a negative du/dx your du/dx is now beginning to grow right back to zero and then that means it now begins to go away from there and reaches your 0 d/ dx and then you have to go through the positives du/dx region right when the pressure begins to fall again therefore you now reach this situation where you got this peak.

And then you go through positive du/dx lines and then come back to this come back to the 0 dy /dx rail a line right so this base we means that you are now going to have a peak that is called the one normal's pike slower and slower the chemical reactions you have the delay in the chemical reactions so you have a shock that first happens to increase the pressure right then you get to follow more and more of this path if your chemical reactions are bit faster if you can try to actually get the chemical reactions to be faster you could hope for other thoughts maybe use a couple of other colored chalk pieces here you could use other parts our destination is from here to there right.

So you could you could either go like this or like this but usually this one the D blue line requires ultra fast reactions that means you are very much farther away from the shock you go but you are beginning to think about reactions happening even within the initial layer itself as the increase in pressures are happening so you do not really go all the way to the 11 normal spike at all right whereas if you had modestly reacting mixtures you could still go through a pressure that is higher than the sharpened boogey downstream pressure right.

And that that would lead to something like a one moment spike but the worst case one moment spike that you can get a venue when you are thinking about the ZMD model where you are saying all you have is a shock to begin with and then you have chemical reactions following that alright so this is this is a way by which you can compute the four moment spike and get the worst-case pressure or worse case the best case depending upon what your goal is you want to have your detonation wave inside the chamber.

And you want the chamber to withstand the pressure this is the worst case pressure but if you want to cause destruction by pressure by having a very high pressure region then this is the best case pressure for you right so this is the extreme pressure that you can think about but the framework of the certainty model think we should stop saying anything more within the one dimensional framework and I am not going to cover the three dimensional details because it is too complicated for this course you.

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