Indian Institute of Technology Madras

NPTEL

National Programme on Technology Enhanced Learning

COMBUSTION

Lecture 26
Velocity, Temperature and Entropy
Variation along Hugoniot Curve

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Let us now look at what happens to the gases that are flowing downstream of the combustion wave if the wave happens to be a deflagration wave or a detonation wave, what we have seen so far is if you have a deflagration wave it is an expansion wave and so you have the reactants react into products and the product gas is downstream of the wave, will have the pressure decrease a little bit and density decrease and they would get accelerated and if the acceleration is just only mild then the deflagration wave of course propagates at a subsonic speed relative to still reactants.

And the products will also be accelerating only up to subsonic speeds but if it is a sharpened deflagration it can get accelerated all the way up to a sonic velocity or if it is a strong defloration it can get accelerated all the way up to supersonic velocities, which of course we have been saying is forbidden by the second law. On the on the other hand if you now look at the upper branch of the neo curve we have a detonation wave that propagates at supersonic speeds relative to still reactants and the products go through a compression and that means they are the they are having a pressure rise and the density rice and then they get decelerated.

And for a week detonation they do not get decelerated significantly, so the product velocities still turn out to be supersonic whereas for Chapman joogay detonation it is turning out to be a sonic and for strong detonation gets decelerated all the way down to subsonic speeds. This is what we have noticed, what we want to now look at is what is the direction of this velocity of the downstream gases, what does that mean right. So we have this wave that we wanted to keep and then we have been thinking about away fixed coordinate system in which the wave is like this and then the gases are coming in the reactants are coming in and the products are moving.

So we thought the deductions are all fixed right all right but then keep in mind that if you now allow for a lab fixed coordinate system in which you have still reactants and then you want to have the wave move right, that means you want to now subtract out the incoming velocity from the entire flow field and now start looking at whether the reactants are going to still be going like this or going like this, one of the words sorry products the product.

So the reactants are still and the wave is moving and we now subtract the reactant velocity from the product velocity as well and then we want to find out whether the products are going to be going like this or going like that or still in other words we want to know whether the products are going to actually follow the wave or go away from the wave right. So that is what we want to do now and let us see how to do this.

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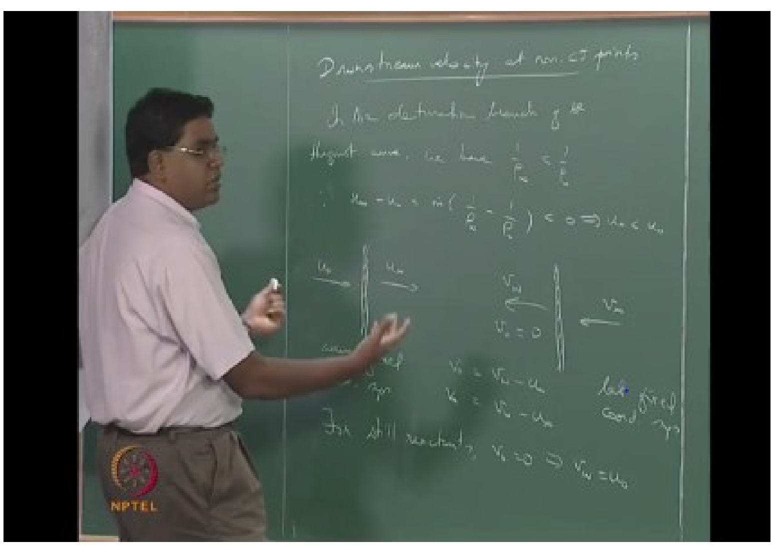

So downstream velocity at non CJ points whatever we do actually also applies to see the CJ points as well it is just that when you say non CJ points its lot more general when compared to what we have done before, which is to look at the Mach number downstream Mach number at the CJ points from where we just generalized saying that weak detonations will have supersonic downstream velocity strong detonations will have subsonic downstream velocities and so forth by just noting that the CJ detonation or deflagration will have sonic downstream Mach numbers.

But here what we are trying to do is to determine the direction of this velocity relative to the wave for any point any point not just the CJ point, so this is applicable to non CJ points as well. So let us now look at the detonation branch, so in the detonation branch so in the detonation branch of the he go do curve right we have 1 over ρ ∞ is less than 1 over ρ not right. Therefore we have u ∞ - u 0 equals m dot times 1 over ρ ∞ - 1over or not you know how to get this, which is less than zero. Which implies that u ∞ is less than you not this is this is no news.

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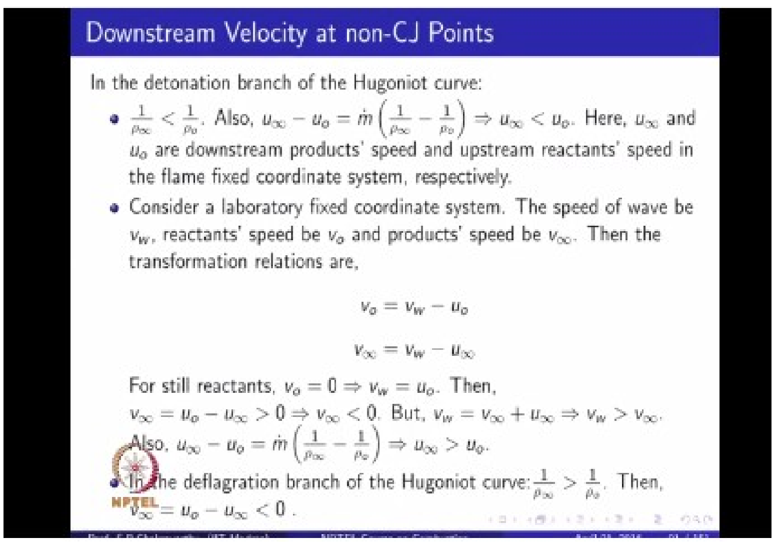

We know that the downstream velocity is going to be less than the extreme velocity because the flow is getting decelerated but that is in a lab fixed sorry a flame fixed coordinate system or a very fixed coordinate system, so if you now have a wave that is fixed in a coordinate system and you had a u0 like this and u ∞ like this is what is the story right but if you now look at it, so this is very fixed right, but if you now have something like a lab fixed coordinate system where you are you are saying.

Let us now have them a move with a velocity V wave okay and we now suppose that your reactant velocity is in this coordinate system designated as V0 and suppose let us suppose let us say it is set to 0 that means we are having still reactants right and in our notation, let us now say that we want to have our V∞ follow the wave right. There is simply saying I want to subtract you from this and if i were to now subtract you not from here it is going to become 0 that is what I am going to get here.

If I now subtract you not from here is if the question is it the arrow going to flip or not okay is it going to continue to be this way or not okay, that means we want to basically find out whether v ∞ - u 0 is going to be positive or negative that is exactly what we are looking for okay. Assuming though that this the ∞ is going to be in this direction so let us do the coordinate transformation, so V0 is = V wave- u0 and v ∞ equals v wave - u ∞ right.

So essentially now the V a wave is now thrown upon this picture, therefore whatever we are actually now beginning to see here for the velocity is going to be V wave subtracted velocities, therefore now if you have still reacted so this is the lab fixed coordinate system for still reactants right V0 = 0 for just in case you want you have been wondering how come we have a V0 yes we will try to subs we will now try to set it to 0or to indicate that we have still reactants which means that our V is = u 0.

Now notice this carefully we can say we wave is = u 0 because of the way the arrows are marked if you now take your arrow for the V wave to be right word that is when it is = u 0 whether you not actually marked this way, alright that is basically say that the V wave exactly opposes you not in the wave fixed coordinate system therefore your wave is becoming stationary right. So this is having the directions taken for these two things embedded in it when you now see be made is = all right.

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If you now say that then be ∞ V ∞ you can now plug V ∞ is taking the direction of V ∞ to be following the wave if you now do that then we wave can be substituted as you not and you can now get u 0 - u ∞ right but what did we what did we notice for u 0 - u ∞ u 0 is > u ∞ which is now >zero right so u 0 - u ∞ is > zero, so if you now have u 0 - u ∞ >zero for V ∞ if V ∞ is >zero with the direction taken this way then that means this arrow sign is correct right.

So you have a positive quantity for arrow sign going towards the wave which simply means that the bone gas is behind a detonation wave will follow the detonation wave right. So this implies that the bone gases bone gases did behind the definition we follow the way right but what but we now try to say the way the bond gases are going to follow the wave will they catch up with the wave will they go past the wave, that does not make sense at least if they were to be able to go past the wave then they will become reactance.

But they supposed to be products, so we better warn them to actually kind of follow the wave rather faithfully right but what is going to happen in reality so the question is then if you now say we then is = so what do we have for the v wave v wave is = u ∞ + V ∞ right. So if you now use this one here you can find that V wave is basically V ∞ + u ∞ and we now find that both you both your u ∞ and V ∞ the way they are defined in these two coordinate systems boot is no more positive right.

So this implies that the they will obviously be >V ∞ and how did we define the V wave and the V ∞ on the same deduction right since V wave is >V ∞ it follows that the bone gases will never be able to catch up with the wave, the wave is going to travel faster than the burned gases right. So this implies that the bone gases although traveling in the same direction as the wave can never catch up in the way.

Right this is true even when you now have a week detonation where the product gases are traveling at supersonic speeds they travel at supersonic speeds that are still less than the supersonic speed at which the wave travels okay. Now when I say that you got to be a little bit careful because when you say supersonic or subsonic it is based on the Mach number and the Mach numbers the way we are actually trying to deal with for the upstream Mach number and the downstream Mach number or relative to their respective temperatures.

And in all these cases the upstream temperature is lower than the downstream temperature okay so the downstream Mach number always would look like it can be lowered it does not mean that the velocities are lower but what we are actually finding out in this is the velocity is lower than the wave velocity, okay therefore it is going to the dog will be able to catch up it follows but it cannot catch up all right. What happens when you now have a defect a shin so in the deflagration branch of the vegan yo of there you go curve we have 1 over ρ ∞ - 1 over ρ not right.

So where is the 1 over 0 ∞ 1 over ρ ∞ is on the right side when you get the solution for the lower branch when compared to 1 over ρ not, so that's actually >0 therefore if you now have 1 over ρ ∞ - 1 over ρ 0 is >0 then u ∞ - u 0 = m. 1 over ρ ∞ - 1 over ρ 0 is > 0 right, so u ∞ is >you not that is no news in the wave fixed coordinate system we know that the flow n the product flow is getting accelerated when compared to the reactants, but now we look at what the what the consequence is when you now have the lab fixed coordinate system.

If you now say u ∞ is > you not and then go back here and look at what happens to be ∞ right, so we ∞ is = u 0 - u ∞ that is coming out of the coordinate transformation regardless of the actual disparity between u ∞ and V you not okay and so although this is this is for a general wave this is for a general wave with still reactants this is for general, we have not said that it said it is a detonation at that point it is only when you say >zero we have invoked this that is for a detonation.

But it turns out to be this for a deflagration if you now plug it in here you find that then we ∞ = u 0 - u ∞ what do you get u ∞ - you are sorry u ∞ is > you not therefore u 0 - u ∞ is now going to be less than zero, that means V ∞ is negative be infinitely being negative the way the arrow is taken this way means that it is going to the arrow is going to get flipped right. So this implies that the bone gases the bone gas is behind it deflagration wave flow away from the way away from the wave in the opposite direction.

So since the guests are going to go away from the wave we do not have to worry about what their speed is relative to the wave speed because they are never going to get there never going to catch up right. So let us not even do the extra thing that we did for the detonation so we do not have to worry about whether they are going to catch up or not, they simply go away so that means in reality what happens is if you now have a deflagration that is propagating this way in still reactants as soon as the reactants react you now have gases flow away in this direction.

If the wave is going like this because you are getting accelerated and you had still reactants and you now have a pressure decrease and a density decrease so it is an expansion that is going on with acceleration, so the velocity that is crude because of this tends to flow away from this region right. That is what you get for a deflagration now we will see a couple of other thermodynamic properties with yes, no this is this is basically based on the way we have actually accounted for these directions for the wave.

And the infact what we should what I should say is you are also assuming a V not like this that is how you can get this coordinate transformation going but of course we set B not = 0 because we want to consider still reactants from where we get v be wave is = u 0 but i wanted to point out previously that v wave is assumed to be like this and you not is assumed to be like this, that is how we got this transformation to be like this and yes true then what happens is, why would you want to do that?

So you would want to do if you want to now factor in the relative velocity of the products relative to the wave, then you are going back to the wave fixed coordinate system right. If you what is meant by relative velocity relative to what relative to what yeah let it to the wave, so if you now want to actually locate your velocities relative to the wave you are going to a fixed coordinate system. Unless you are now trying to do well maybe may be not maybe we will maybe what you are saying is different from what I am saying.

Because when I when I am in a wave fixed coordinate system I am actually counting my reaction velocity relative to the way okay, when I am in a lab fixed coordinate system I am just letting the wave propagating in it primarily still reactants but it does not Harvey still okay but if I am counting for a flow direction I would count it like this if the flow were actually approaching the wave like this in a in a wave in fix coordinate system I would have to reckon we not to be negative in the way I am doing this.

What you are telling me is once I actually find out what my actually ∞ is it possible for me to look at that velocity relative to the wave that means we are we are now trying to look for making this till, if that if that if that is what I understand huh ? Taken is for being 3d its V - the ∞ is me what a question is V - ∞ okay that's because I am digging the direction like this yes but if i take this direction something like this and relatable would become VW + u ∞ so being questioned there is some changes.

So this process okay if you were to take your ∞ deduction to be like this you should get V ∞ be positive that that is what you should expect alright which would which would be basically say the same thing alright, some an you can work that out maybe what you what you do is you assume that V0 is going to be positive in this direction V ∞ is going to be positive in the direction you should be able to show that if you were to actually make V 0 = 0 right.

Then V ∞ becomes negative for detonation wave and we it is positive for refrigeration wave that was that will simply make this different you now right you, now say that V 0 is = u ∞ - V W and V ∞ is = u ∞ - VW all right that is how you will actually get these signs flip you should give the same day right the question is all about being consistent about your about these transformations based on the deduction that you have assumed okay.

So I guess that would be a little bit more straight forward maybe if you would assume the wave to go like this and still assume the reactants to go like this and the products to go like, that it is it is probably a lot straightforward to do the transformation right and all you have to do then is to show that the ∞ is negative in the case of detonations and remains positive in the case of deflagration. So that you are assured opposite ok maybe for the exam right, so yeah but it should it should be the same.

All right let us just go through a couple of quick thermodynamic properties other than what we have discussed, so far before I come back to some realistic depictions of these waves and see what happens. So first thing I would like to point out is a temperature.

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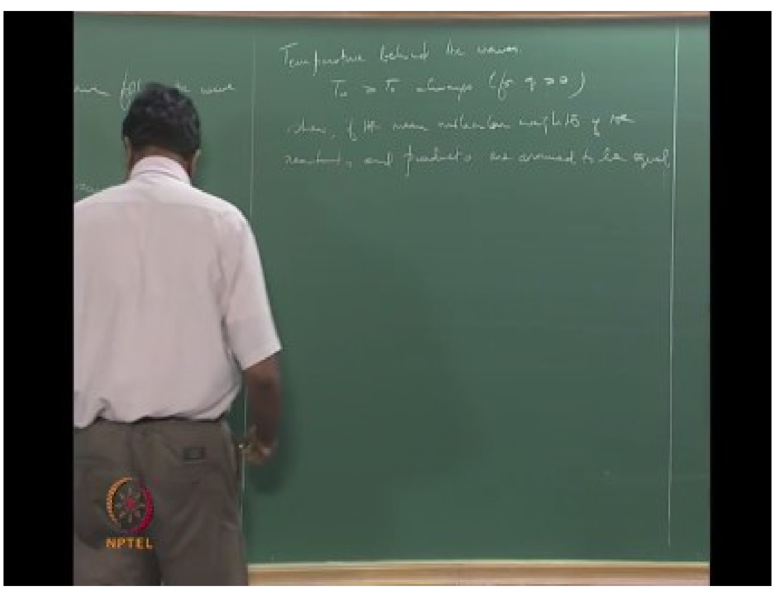

Behind the wave right t ∞ is >T not always for Q >0 what you can show is show if the mean molecular weights that of the reactants and products or assume to be equal that is a 1/∑i=1 to n yI∞/ W i = 1 ∑ i = 1 to n why I not WI=W then the temperature ratio the temperature ratio t ∞/T_0=P ∞/ ϱp/$p_{0/}$ $ϱ_{0/}$t 14 >1hat is to say you can show this at CJ points.

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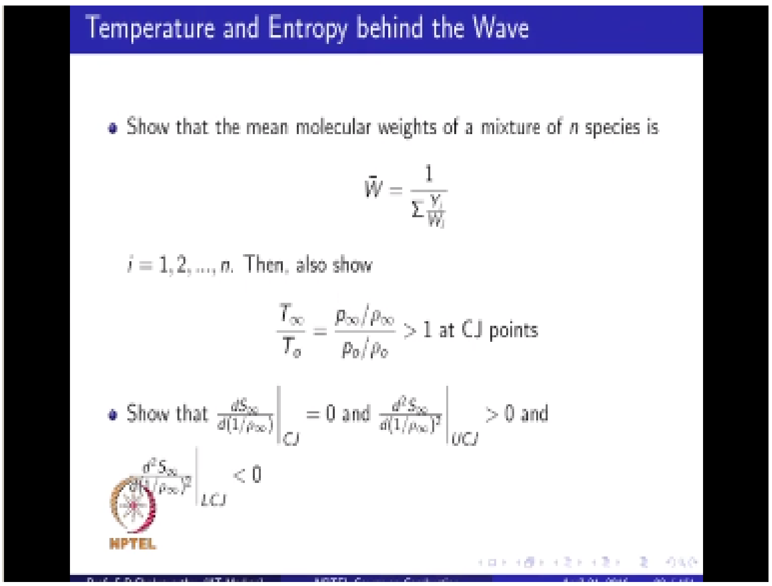

Of considering the simplifying assumption that the mean molecular weight of the reactant and product gases or equal whether that is just a mathematical exercise that you can go through the second thing that I would like to point out is how the entropy varies there is something that we have not talked about at all but it is interesting to talk about entropy variation entropy variation along the Hugo neo right so maybe we have these underlying to distinguish them so it can be shown that and it is on very difficult to show I will show you will tell you how to show this it can be shown that the entropy is a minimum at UCJ and maximum at LCJ.

So that is basically again looking at the CG points because they are more amenable to mathematical manipulation given that you can match the slopes of the agree really and the he go and get coordinates and so on and then how do you show this okay so I am not going to show this but you can show question is how do you show this well it is rather straightforward what you have to do is you see that the gone you curve is having p∞ on the vertical axis and what about ρ∞ on the horizontal axis so it is as if one who ruined ∞ is your independent variable and p ∞ is your dependent variable right.

So what you what is suggested is you now try to express your entropy as a function of 1over rho infinity as a independent variable still and if you do that and then of course the way you do this is you now assume a reversible hypothetical reversible reaction that can prevail between the end states and then use like TD t ∞ des ∞equal to the first law of thermodynamics and so if you now do that then you get a expression for entropy at the end state as a function of 1 over ρ∞.

And use that expression to differentiate this entropy with respect to 1 over ρ∞ at the CJ point note that I am not saying which CJ point because whether it is maximum or minimum you are going to have the derivative equal =0 so you should be able to show this, this is relatively easier when compared to the next step which is you have to now show whether its maximum or minimum right so what you will be able to show is with, with d squared ∞d/d 1 over ρ∞ squared at you CJ > 0 and d square ∞/1 over $\rho\infty^2$ plus a tell CJ as less than 0 right.

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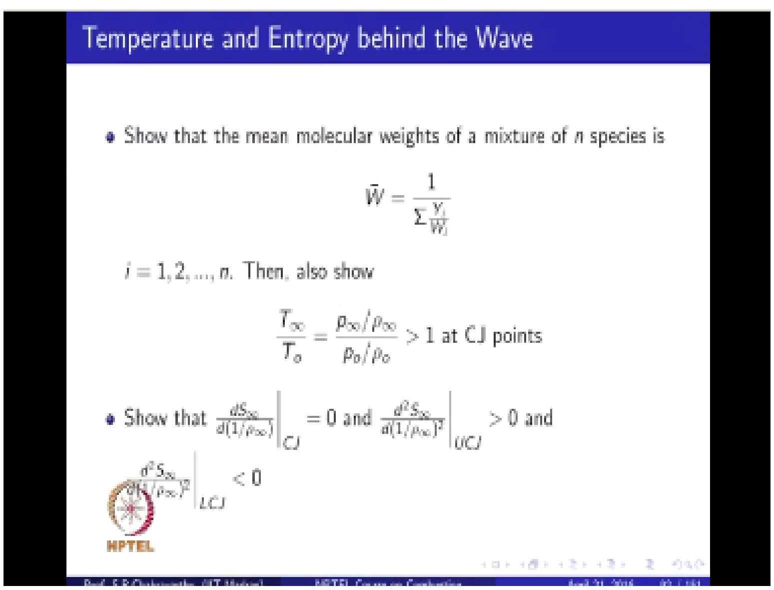

So what is happening what you will find this I am just running out of space there let me use this panel to depict what is going on.

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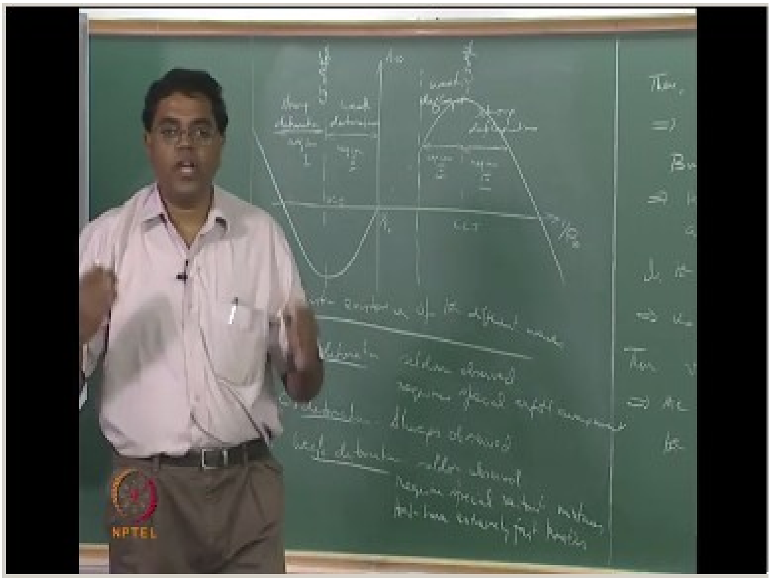

So if you now think about the way I said that is you have your 1 over ρ_∞ as your independent variable and you plot your ∞ as a dependent variable question is how does it look like okay now this is good to do because the 1over ρ_∞ is going to be the same in the Hugo neyo as well as here and we know what happens when you now have the 1 over ρ infinity very about its origin the origin of the Hugo new of course is 1 over ρ not right and then the 1 over ρ_∞ varies on either side 1 over ρ_∞ increases in the deflagration the lower branch.

And 1 over ∞ decreases in the upper branch for the detonation but keep in mind that there is a there is a region here which belongs to the first quadrant in The Hague or which is not covered right the means 1 over ρ_∞ goes from 1 over ρ_0 as the initial condition to a value it jumps to a value that is where the Hugo neo cuts the x axis passing through the origin right because about this you have the first quadrant in there you go plot which is forbidden and therefore you will you will you will you will find that you now have you will now have a curve that goes like that and this is where you are LCJ is and then you have over here a curve that looks like this which is where you now have your you LCJ right.

So what we are basically saying is this is your region1 this is region to this is region 3 this is region 4so that that means this is strong written a detonation you have CJ, CJ detonation this is weak detonation we have a leak deflagration and of course we have CJ deflagration then we have a strong diploma right then they let then let us think about what really happens in actual practice okay what we have seen so far is something kind of trivial we have assumed that we can treat whatever water work happens inside the wave as a blood box and then just do balances across as if they just jump but we need still to conserve mass momentum energy.

And so forth and we have now come upon a lot of facts like we should now be able to say that there are two kinds of waves that are completely apart one goes as deflagration subsonic and another one is detonation and so on and then we further looked at upstream and downstream conditions to point out that this is subsonic that supersonic then you have strong weak and all those things right but did we ever care about whether this really happens in reality okay so realistic existence of these waves of the different waves the first thing is strong detonation what you will find is strong detonations are not very easily observed okay.

So seldom sell observe and why so because it is a strong detonation that means you have to have a large compression and you had to make sure that the gases are detailed rated down to subsonic speeds from a supersonically propagating wave and you have to have large pressures there and maintain okay so invariably the detonations typically happen is if you now have a reactant gas in a confined region and you and they got ignited at the confined end and you know has believed that is beginning to propagate you now have a confined region where the pressure can build up and stay right.

And once you can have this pressure build up then you have a transition to detonation wave for what you work you what you are igniting you now have a detonation wave but the remote detonation wave begins to propagate this, this space is vacated right so you cannot really have the pressure hold on until you are able to actually have this confinement follow the wave right so this is what is called as a low-driven shock tube so that means you have to have like a piston that runs along with the wave and keeps this confinement as it is in order to be able to preserve the very high pressure that has been obtained with the strong detonation.

So it requires a special, special experimental arrangement require arrangement what is called as we were driving the shock now CJ detonation on the other hand is always observed that means whenever you have a detonation wave there is there is a very high chance that it is always a CJ detonation so always observed in fact in the in the experiment that I just discussed if you do not have this were driving you have this detonation wave right and you started out with a strong detonation let us say because we had the confinement and keep in mind what happens with the strong detonation wave you know have a subsonic flow we downstream right and you now have the pressure pulses that go.

And get reflected from this and begin to come back and hit the wave because this is a subsonic flow and the pressure pulses can actually propagate faster than the, the product flow product is actually beginning to follow but at subsonic speeds and it is not going to catch up but it can allow for the waves to go this dude pressure disturbances that are coming from the other side can actually pass through this because this is subsonic typically what then happens is you now have an expansion fan should say fan if you should say expansion wave because we are basically looking one-dimensional.

So you now have this wave that go like this and then there is a pressure buildup and that also propagate so you have an expansion region that is get that is getting created which can propagate through this and then go and try to weaken the wave alright when that happens progressively this wave is getting weakened down to CJ level at which point the products are beginning to actually go at sonic speed right so once the products are going to going at sonic speed the diffraction wave we talked about can never really go past them right they can go only at the speed of the where the products and not really reach the wave at all and therefore you now stop at a CJ.

So any strong detonation that that has been created will always tend towards the CG detonation pretty soon and there is a reason why you will always find a CJ detonation unless you took this arrangement in order to preserve the strong detonation right so if you did not do any such arrangement they are going to be getting a CJ detonation third week detonation now this is all so seldom observed here what happens is you are having the way the product gases travel at supersonic speeds while it is the boiler is trying to follow the wave and if you want to have supersonic speeds at which the products of traveling you have to have chemical reactions sort of happening in the wave happen so fast that they are able to actually produce products that can travel.

So soft so fast so this really means that you have to have chemical reactions that happen very fast so you need to have very special mixtures that have extremely fast kinetics so require special reactant mixer make mixtures that have extremely fast kinetics fast when compared to the flow velocities of the products so that you will get products otherwise you will still have reactions happening well you are still expecting products to happen the products are not happening because the reactions are taking slow but you are taking time to happen so that is about the detonations.

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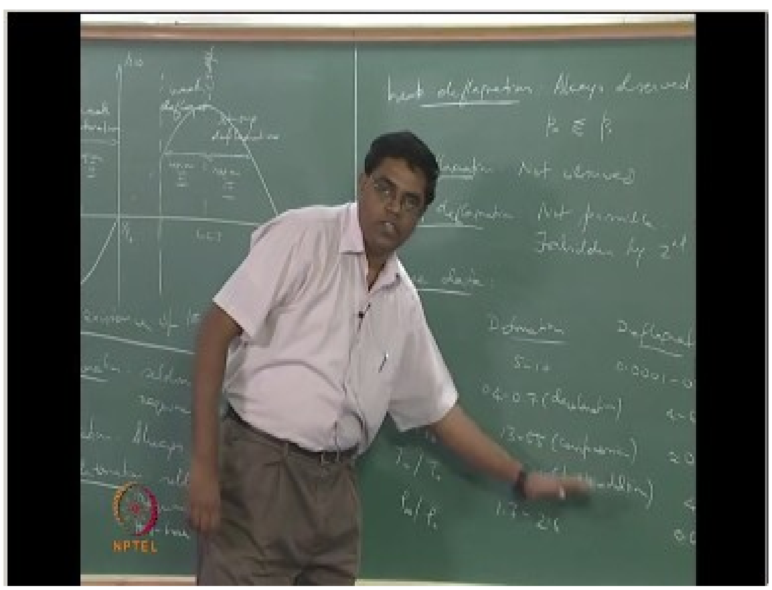

Let us not see what happens to the deflagration should talk about weak deflagration yeah sorry it is actually stopped by anything big what that is only for the reactant that is only for the ∞ condition true that is correct not that is not true entropy is decreasing only for the system because the system is being worked upon with many men you have a compression wave what you really want to be looking for is a the entropy for what is actually causing the work to be done.

As well so it is easy the entropy of the universe that actually and ultimately increases it does not have it does not mean that if you have a particular system entropy count decrease if you do work on a system then entropy can decrease but who is doing the work on the system will have a corresponding entropy increase which will be greater than the entropy decrease that you find in the system because it is a compression you will have a entropy decrease.

Because work is being done on the system all right so that just for another day so according to what you say none of this can happen right well you have to start from here this is your starting point if you were somewhere here you are still low right that is not true so talking about weak deformation always observe right there in fact if you now go back and look at your Hugo neo this is the origin and let us say that is a CJ point what we are talking about is somewhere that is like very close to the, the original value that means if here this is your P_0 and this is your k p ∞ is just about little less than P_0 so most of your week deflagration is happening very close to the original p_0.

And very far away from the lCJ okay the loads you do not even go all the way somewhere here you are very close there that that is mostly what happens you are typically talking about open systems and in open systems you have almost like a constant pressure process it is only very close to the flame it is possible to have this acceleration and this expansion therefore the pressure decreases a little bit not a whole lot right and that is exactly what gives you a week deflagration correspondingly if you are now thinking about a CJD Federation you simply have to say not observe this is primarily coming from the numeric the beans if you just put the numbers in you will find that you cannot get the pressure to decrease significantly at all for the downstream case due to be able to get down to a CJ level.

Right and when you now finally talk about a strong deflagration all you have to say is not possible forbidden by second law this is something that we have been talking about so in reality in the CJ in the Hugo new line we are pretty much confined to a region that is very close to where we started for the peanut and you do not even go all the way to the CJ cannot really go past it at all in reality okay so most of your deliberations are extremely weak deflagration that is why I output it so let us finally give some numbers on what these changes are like so if you now look at detonation on the one hand deflagration on the other hand what are our M_0 it is of the order of about five to ten here at something on report point 0 0 0 1 2 about point O 3 Roberto orders magnitude variation.

But they are very, very small u ∞ over you not how does the deceleration or the acceleration happen this is about point four 2.7 deceleration here it is about four to six you can work this out if you assume constant pressure we can work this out to be about four to six based on the temperature change this is acceleration p ∞ over p_0 this is about look at this number 13 255compression this is about point nine eight there is about 98% pressure recovery there so that slight expansion and this high-pressure jump across the detonation wave is what causes all the damage in India 10asians.

Okay t ∞ over t_0 is about eight to twenty one that is heat addition it is only slightly less over here it is about 4 to 16 also heat addition in both cases we are actually adding heat and finally look at rho infinity over oh not you have about 1.7 to 2.6 and over here it is about point boo 62 about point two five that is about it so get it you get the picture on what do you get for these detonation or deflagration waves in summary you typically are looking at a CTO detonation or a week deflagration when you are looking at these numbers right.

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