Indian Institute of Technology Madras

NPTEL

National Programme on Technology Enhanced Learning

COMBUSTION

Lecture 24
Rankine - Hugoniot Relations 2

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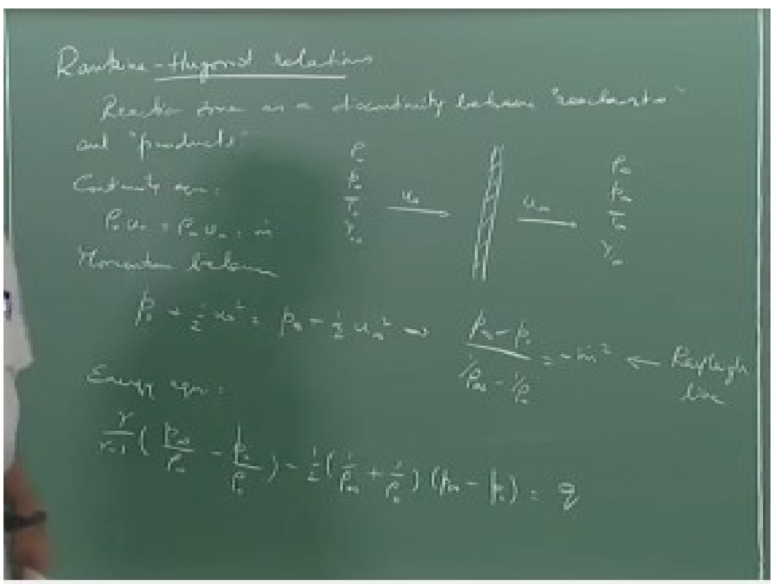

So we stopped here last class where we derive the energy equation across the discontinuity representing the reaction zone and we wanted to see how this looks like in what is now beginning to shape up as what is called has the Hugoniot plot so this is what you would actually call okay to some extent a simplified Rankine Hugoniot equation.

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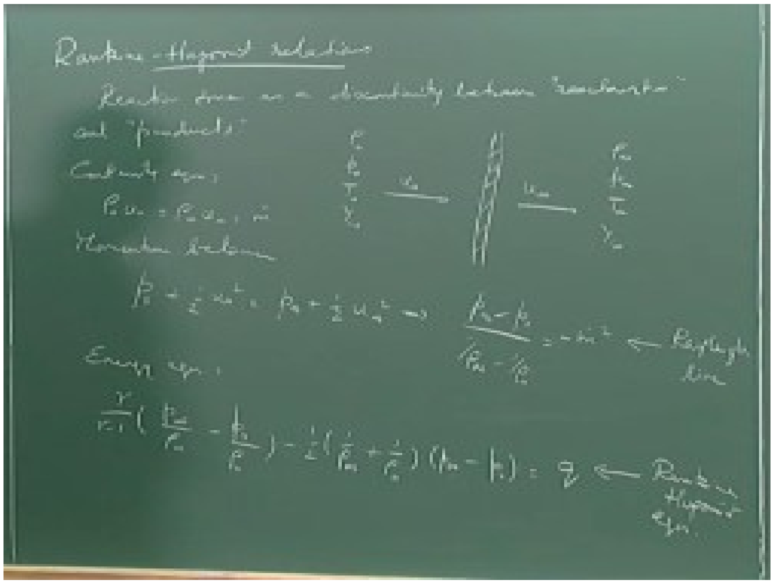

So how does he how do you look at this Hugoniot this curve in the he Hugoniot plot the Hugoniot plot is a domain of P ∞ but 1/ ρ ∞ and then you know begin to look at how this looks like you know have a coefficient γ / γ - 1 times p ∞/ ρ and ρ ∞, so this is itself like a product of P ∞ and 1/ ρ ∞ right and of course we now say P_0 / ρ not as like a parameter that is represents like the initial state and again you can look at a p ∞ times 1 / P∞ coming up over here with a different coefficient of course therefore it is all going to cancel.

Typically you will always look for things like things getting cancelled but that is not going to happen here and of course you now have a mixture of things like p ∞ / ρ_0 and p_0 over times 1 over ρ ∞ times again you have a p_0 / ρ_0 term so this is beginning to look like if you are now looking at like an XY plane you are now beginning to look at a curve that is kind of like some a XY + bX + cY + d = 0 right so if you now have like a leading order term like XY right what would that actually signify if xy if xy = 1 one if that is what you had.

Okay that is like A = 1 and d = 1 then you would simply A and B and C or 0 in whatever format that I just template that I just explained you would be looking at a rectangular hyperbola but since you also have A p ∞ / ρ0 term and I p0 / ρ∞ term we also have some B's and C's that are non zero therefore it is not exactly a rectangular hyperbola but it is going to be modified so it is it is going to be like a hyperbola here.

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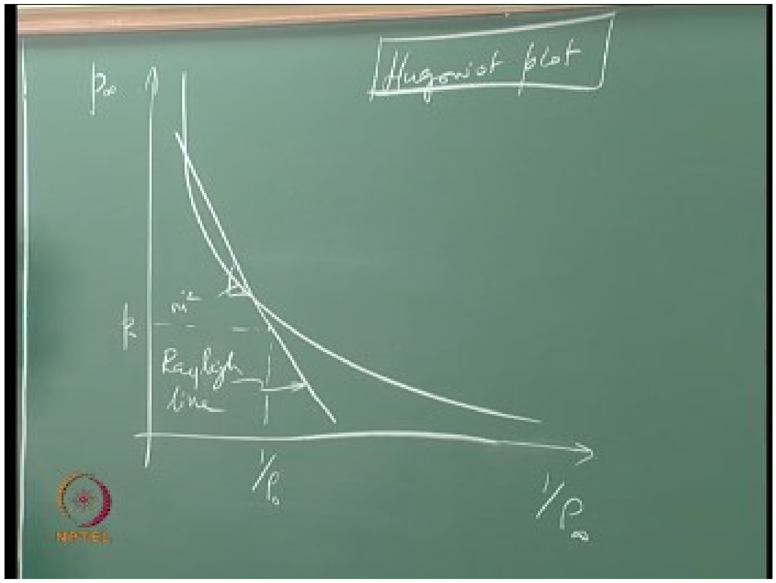

So hyperbola is going to now look like if you know had something like that okay now we do not know exactly if it is going to be a rectangular hyperbola in this P∞1 / ρ ∞ access you domain it is very likely that you could have this cross over to a lower value okay so I am not saying that this exactly is the curve at the moment but what we are trying to do is to sort of construct this curve as we go along okay.

Well why did we want this curve because we wanted to solve these conservation equations across this discontinuity to locate react product properties given the reactant properties including U0 which is something that we are not very sure that we know to begin with and U0 is actually embedded in the slope of the relay line but the hugoniot so this is what is now called these so this is this rectangular hyperbola is what is called as a hugoniot curve right.

And the hugoniot does not involve any m. in other words it is not it is like a purely thermodynamic curve okay so the flow information is actually buried in the Rayleigh line which is a mixture which is a combination of continuity and momentum together so that that carries the flow information whereas this the energy the thermal energy equation effectively is not carrying any flow information there.

And then we are what we are looking for is a intersection of these two these two curves that is a Rayleigh line and the hugoniot curve and sure enough we find that there are a couple of intersection points which will now tell us that if you now started out with the p_0 and $1/\rho_0$ as the reactant conditions and this particular point is typically referred to as what is called as origin of the hugoniot plot.

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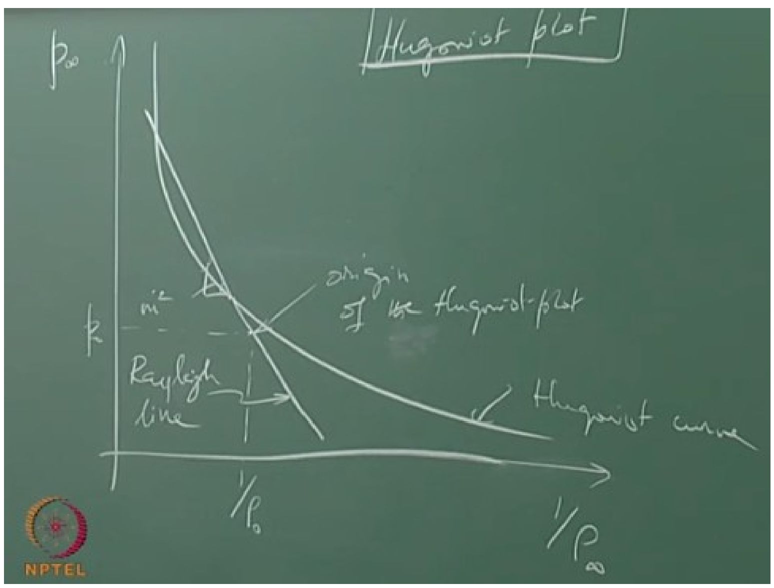

Right and then what we want to see is where is actually the conservation equations where are they satisfied again right so what you will find is that you now get like about two points where they could be satisfied so you have like at least two possible solutions this is a great progress that we have done starting from when we did not do it when we did not have any equations to solve we had like an entire plane to search the solution.

And then when we now had the Rayleigh line we now reduce the possible set of points to a line rather than a plane and since you now also have the energy equation in the form of the you go to your curve we look for point of intersection of course you know beginning to see like about two points of intersection instead of just one right.

So we now have to look at what are the different possibilities for these two points of intersection whether it be only two or whether it be when will it be one and if it is two what are the possible two values and so on right obviously this is a this is a curve which has the same sign for the curvature that means it is always like alike concave facing upwards and side upwards into the right.

Therefore since the curvature does not change sign you do not have any points of inflection in the hugoniot curve when I straight line intersects with this you can have up to two intersection points you are not going to expect more than that right but you could look for one intersection point or none when would you get one section point if the Rayleigh line but tangent to the Hugoniot right or Rayleigh line never really intersects with a Hugoniot.

Then you do not have any solutions right so there is some hope we are now looking at zero solutions one solution or two solutions not more than that good so with this picture we now see how to go about constructing this plot a little bit more carefully right the first thing that we notice is the first thing that we notice is if your $q > 0$ okay so for $q > 0$ there you go into your curve passes to the right and above the origin that is there okay for $q = 0$ you can also check this if you want by plugging in values for p_∞ and ρ_∞ for $q = 0$ the Hugoniot would pass through the origin you see right.

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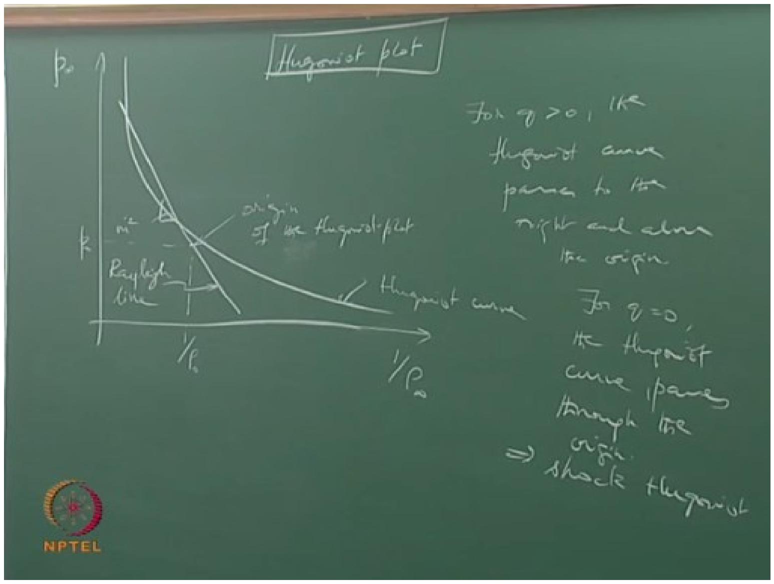

Now what is q is essentially negative of what is called as H∞0 - H00 now H∞0 and H00 or in tern σ i = 1 to n Δ HFI Yi 0 Δ HF I0 and σ = 1 to n Yi ∞ H Δ Hfi0 right so it is only because of the compositions at Yi at the 0 condition and the ∞ condition the Δ HFI0 is the same for both because it is a standard heat of formation right so we are now getting these different HI0 and HI∞ and then the difference between the two is essentially the chemical heat release within it with the negative sign okay.

So that is a chemical heat release if you q = 0 that means you are not having any chemical entities SO the chemical heat release is not there essentially we are talking about a non reacting mixture right if you have a non reacting mixture with the Hugoniot curve that is somewhat similar to what you what you might have gone through gone through in a basic gas dynamics course where you are still looking at the matter of fact if you know think about how we have this equation.

We had like a $H_0 + ½ U_0^2 = H∞ ½ U∞^2$ that is exactly without the U right and that is exactly the same as what you would call as an adiabatic energy equation that you would that he would write for a energy conservation across a shock okay so across a shock you would find that the stagnation temperature remains the same the stagnation enthalpy particularly remains the same right that is true when you do not have any heat release okay or any chemical heat release.

So a curve that actually passes through the origin with $q = 0$ is what is called as the shock hugoniot right now that tells us that if you now have a $q \neq 0$ and we expect typically the q to be > 0 rather than < 0 we not looking at cooling kind of thing right so what is it when you now have a wave that is reacting in addition to being a shock right so you are now beginning to think of it and then of course a shock is actually either phasing a supersonic flow or it is traveling at supersonic flows.

This is supersonic speeds relative to like still reactants what is it I mean this is not something that we thought about we started talking about something like low mach number conditions and all those things but now we are getting into something but of course in what we are doing now we are not really making the Loeb Mach number assumption right we should be now game for any kind of mark numbers that are approaching your wave but the but the language that we are beginning to use.

Is now beginning to doubt admit the possibility of supersonic flows right okay when would that happen so let us just do this a little bit more carefully let me let me diluter this picture of all the terminology that we have that we are now used to and we just want to now redraw this only with things that we want to now take.

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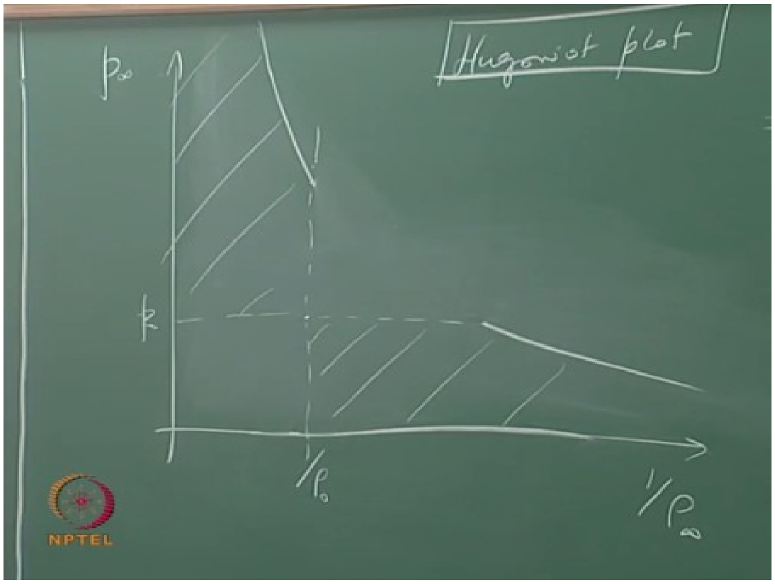

So let us say you now have the origin again I am not going to name it now and let me first draw the he Hugoniot line a little bit farther away and let us now say that you go here and here and let us see what happens here your Rayleigh line can have only a negative slope right so if you know if this is your origin of the hugoniot the Rayleigh line can fill only the third quadrant sorry the second quadrant or the fourth quadrant right.

It cannot go like this so I cannot get into the first quadrant it cannot get into the third quadrant so this part of the Hugoniot is never going to be used right so we now have to erase the spot away from consideration we just do not want to worry about that part of the Hugoniot curve we will worry about a part of the Hugoniot that starts from where whatever $\rho \infty$ is = 1 over ρ_0 okay another part of the Hugoniot where $p \infty = P_0$.

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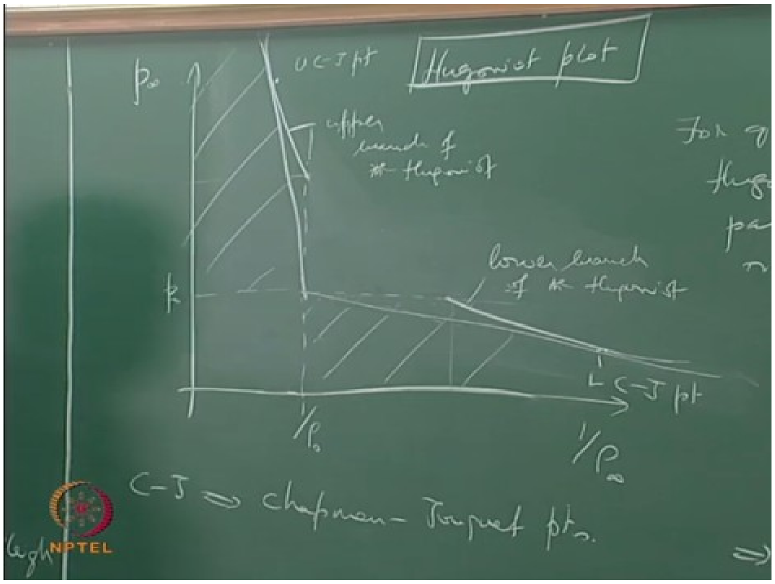

What does that mean if you were to now have a solution that somewhere here that means your Rayleigh line is sort of passing like this it means two things one your final pressure is about the same as the initial pressure the pressure hardly changed when the flow went pass this wave second this Rayleigh has a almost like a 0 slope that means the wave is not moving much so it is possible that if you are talking about nothing.

Yes it is like you do not have a wave so obviously the pressure and increase yeah it cannot be true because the density increase well the density decreased so there was a density decrease that was primarily because if the pressure remains the same and the density decreased that is because the temperature should increase so you had a heat addition all right that is there is a reason why the Hugoniot is shifted away from the origin in the first place so you had a heat addition correspondingly you had a temperature rise but you do not really have a wave that was moving fast enough.

And you did not have a corresponding pressure rise this is now beginning to look like what we were talking about for what is called as Loeb Mach number conditions right the pressure is approximately a constant right so Loeb Mach number simply means that the wave is in moving too fast or relative to the wave the reactants are not moving in too fast right there for the Mach number is very low.

So you now have one branch of the Hugoniot there is now beginning to correspond to waves that are moving kind of very slowly okay and the fastest wave could possibly have a slope that is tangent to this at this point that is the fastest wave that is possible that is the highest m. that this branch of your hugoniot will intersect okay if you for any faster waves the Hugoniot the Rayleigh line is now going to actually go downward and fail to intersect the this branch of the Hugoniot.

Will that intersect the other branch not immediately you now see that you have to actually go to a still steeper Rayleigh that will begin to intersect the other side or if you are thinking about an experiment where you want to conduct a stabilization of a wave by sending in reactants at faster and faster flow rates right between this particular flow rate and that particular flow rate you just cannot stabilize a flame at all and then you again begin to stabilize flames for all draining lines that are now having steeper slopes than this.

You can have points of intersection until you get to this point which has an infinite slope right it is kind of again just like how a zero slope is almost impossible and we are thinking about like very low velocities right infinite slope again is not something that we want to think about but very high very essentially very high slopes that means very high velocities for which the pressure jumps but the volume did not change a lot so this is more like a isochoric process that say what you started out with was the isobaric process right.

So in the one extreme you started out with an isobaric process corresponding to very slow waves right and then you could think about a little bit faster wave is but with a sudden decrease in pressure not a whole lot of decrease okay but from here to here you see that the pressure is decreasing only a little bit okay but the expansion that is the density decrease as you go this way one over density increases.

So density actually decreases there is a significant amount of expansion that is going on right from the beginning for because of the heat addition and then nothing until you get to very fast waves and you can now get these very fast waves to go all the way to the other limit where you are getting close to isochoric process that is like a constant volume situation right and there again because of the heat addition you hardly have any change in volume but essentially the pressure increased right.

So what you then have is this is what is called the lower branch of the hugoniot and this is what is called as the upper branch right and we want to call these points the tangents the tangent relays intersecting at these points as the LC- J point and this is the UC- J point C - J sands for chapman joogay right so the LC- J indicates the highest velocity of what is called as deflagration waves.

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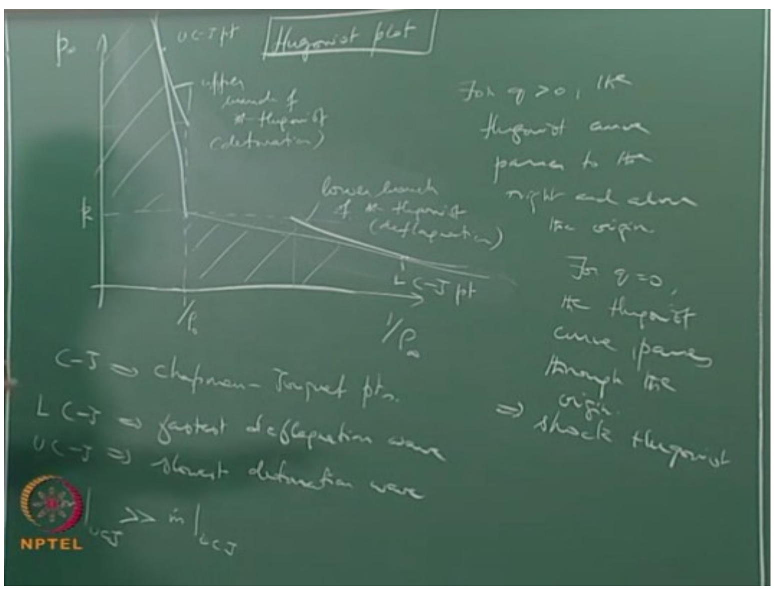

So this is the lower branch corresponds to what is now called deflagration right so LC-J the fastest deflagration wave and the upper branch of the hugoniot corresponds to what is called as detonation and UC - J corresponds to the slowest detonation wave right and the m. UC- J is still significantly greater than m. LC- J that means the slowest detonation wave is still much faster than the fastest deflagration wave that simply means that you now have two classes of two classes of waves that are significantly apart.

There is really no overlap at all in their wave speeds and in fact what I would actually show what I should actually say is this would be much greater than so in terms of wave speeds like instead of writing m. if I were to write U_0 so assuming like they started out with the same ρ_0 right what does now see I told you that I do not even I do not U_0 is right I am still not going to know the U_0 is right.

I am still not going to know the μ^o until the end of this exercise but I am beginning to get some ideas about what the bounds of my unit should be for two different kinds of processes that we are now beginning to think about namely deflagration and detonation right so what we are talking about here is for detonation for, for deflagration waves your μ^o of the order, of the order of a few tens of centimeters per second under laminar conditions.

But your degeneration waves so to a few tens of centimeters per second is still less than a meter per second but your detonation waves are typically of the order of a few kilometers per second so now see that there is like about three orders my three to four orders magnitude difference a factor of three 3, 2, 4 orders magnitude difference between the detonation velocities and deflagration velocities right what we should further notice then is that we want to think about the deflagration is going as subsonic waves whereas the detonations are going at supersonic waves.

But before we do that we want to now quickly go through some mathematical properties because we started out with mathematical equations for these like this one and then we notice that that, that goes like a hyperbola and then we of course had a simpler mathematical expression representing a straight line very, very easy to see this for the railway line and we are now looking at these intersection and so on.

What I would like to first of all before we proceed further is to give you expressions in these are not very difficult for you to derive and these are all like typical exam exercises okay so you can figure out for example depending upon the Q what is this point okay the, the, the, the lowest value of 1over ρ ∞ possible for the detonation branch and where, where is this point for example what are the coordinates of your LCJ point that will also depend on Q and what are the maximum.

So what is the maximum value of 1over ρ ∞ that is possible right and what are the maximum values of P^o that is possible that is of course equal to p ∞ and what C minimum value of P ∞ that is possible what you will find is you will you will notice if you now try to actually look at the mathematics of this, this would ultimately go and intersect the x-axis right.

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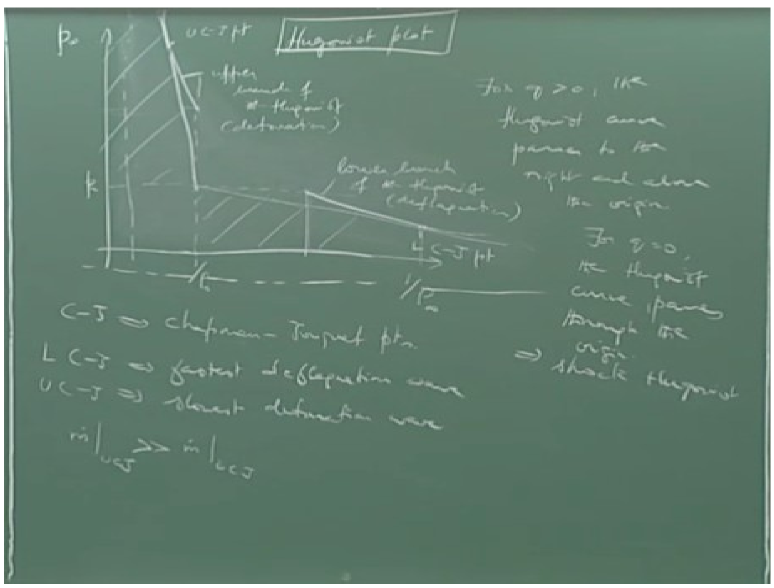

And where it intersects is where you would get the maximum value of 1 over ρ ∞ and the corresponding value of P^o , P ∞ would be 0 okay as a matter of fact what you will find is this, this rectangular hyperbola asymptotes to a value of P ∞ that is negative so what you can actually do is to go ahead and find out the horizontal asymptote for this rectangular hyperbola and you should find that, that is negative and since you cannot admit negative pressures in reality you do not worry about where exactly it has some thoughts.

And you have to stop thinking about it at where it hits the abscissa that is corresponding to your P ∞ equal to 0 and then there is like a corresponding 1 over ρ in that is a maximum value to which the proper the products can expand right similarly you can look at the upper branch and find out that the lowest value of P ∞ can take will depend on Q but the corresponding 1 over ρ ∞ will be equal to 1 over P not right.

Then it can also locate this point the UCJ, UCJ and then where does it go so what you will have to find out there is a vertical asymptote which is having a positive value of 1 over P∞ that is the lowest 1 over P∞ that it can take but it is now going to assume talk to that that means the maximum value of P ∞ that can take is ∞ when it hits asymptotically at ∞ right so these now give you limits for these pressures and densities that it can take in these different branches of the hugoniot curve.

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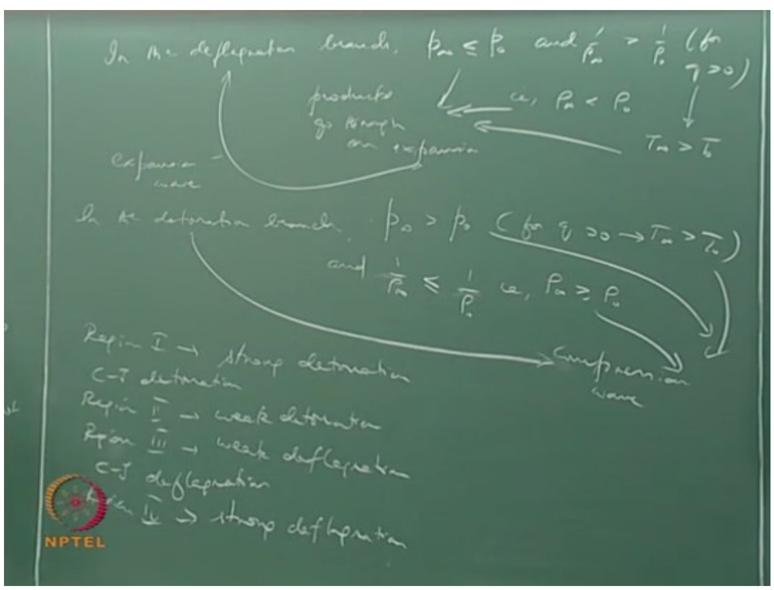

So we can we can go through that but I think I think even before that we can point out that are so in the in the deflagration branch in the deflagration branch p ∞ is less than or less than or equal to p^o right and 1 over ρ ∞ is greater than its suddenly greater its not greater than equal to because it would be greater than or equal it would be equal to 1 over ρ not only for Q equal to 0 for positive values of Q you can never get your 1 over P ∞ to be equal to 1 over P^o.

So it is always greater than 1 over P^o for Q greater than 0 that is that is P∞ is less than ρ^o not the density decreases and the pressure decreases okay for Q greater than 0 you always have T ∞ greater than T^o this is heat addition so the temperature increases right so with the temperature increasing density decreasing is not news but pressure decreasing is indicating these two together then given this means you now have the products go through an expansion right.

So it is when you have an expansion is when your pressure decreases and your density decreases even with the temperature increase right so a deflagration branch corresponds to an expansion wave right on the other hand if you now look at the detonation wave in the detonation branch your p ∞p ∞ can never be equal to p^o for Q greater than zero right only through only, only for cube equal to zero will then he go to your pass through the origin.

And you have only one tangent relay right but for Q greater than zero p as p ∞ is always greater than p^o for q greater than 0 which implies again t ∞ is greater than p^o you always have a heat addition that you are having in mind in both cases right t ∞ is greater than p^o all right so p ∞ is always greater than p^o and what about ∞ can be less than or equal to 1 over P^o right so the highest value of 1 over P ∞that they can hope for is this right.

That is equal to 1 over or not all other 1 over P infinities are going to be less than that and this implies that is P ∞ can be greater than or equal to do not that means you now have a density increase corresponding to a pressure increase accompanying a temperature increase when the temperature increases you would like to think that the density should actually decrease but if the density decreased sorry, if the density increased accompanying the temperature increase that simply means that the pressure increased a lot more right sure, sure enough.

You look at the way the curve goes it is, it is going crazily in the parallel along the pressure axis right so the pressure is obviously increasing a lot so taken, taken together all these things mean that we now have a compression wave right so a detonation basically corresponds to a compression wave so we talked about a shock review we are now beginning to look at one of the branches actually corresponding to compression so it is all kind of going together you can see that there are elements of what we have done, done before in gas dynamics beginning to look like a special case of what we had what we are talking about right.

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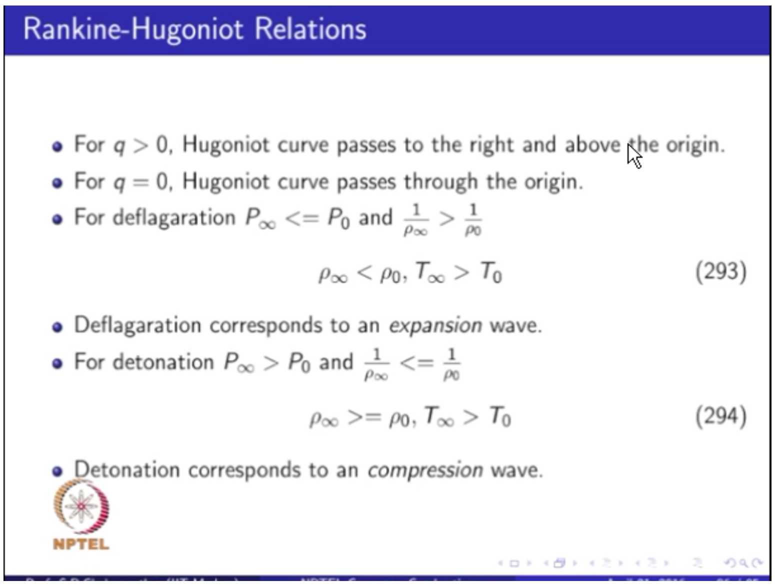

It is a special case in two ways one first of all or it is a nonreactive case okay what we what we went through in gas dynamics is basically a nonreactive case a supposed to a reactive case here and the moment you have reactions then it belongs to only one part which is like the, the supersonic propagation as we will as we will see and show corresponding to detonation whereas the results another part which is corresponding to deflagration that subsonic propagation and where expansion happens rather than compression all right let me also say one more thing so now that we have also come ties to ourselves with some more here we could further actually divide this into five parts.

I should say four parts rather so you now have you can you can now divide your upper branch as something that is above the you CJ and something that is below the CJ again you can divide the lower branch or something that is to the left of LCJ and something to the right of LCJ so let us now call this call this region 1, this is region 2, gives us region 3, and this is region 4 so we essentially are looking at the upper branches a detonation branch the low branch is the deflagration branch.

So what we would like to call this as region one at the moment they are just names we just do not still understand them more completely but let us just give the names first and then start understanding because that will kind of aid as a dozen understanding so region one is essentially what is called as a strong, strong detonation and then of course you now have CJ detonation and then we have region to that corresponds to your week detonation.

And then we have region three this corresponds to a week deflagration and then you have the CJ deflagration and then we have region for that should by now be easier for you to figure that should be called strong deliberation.

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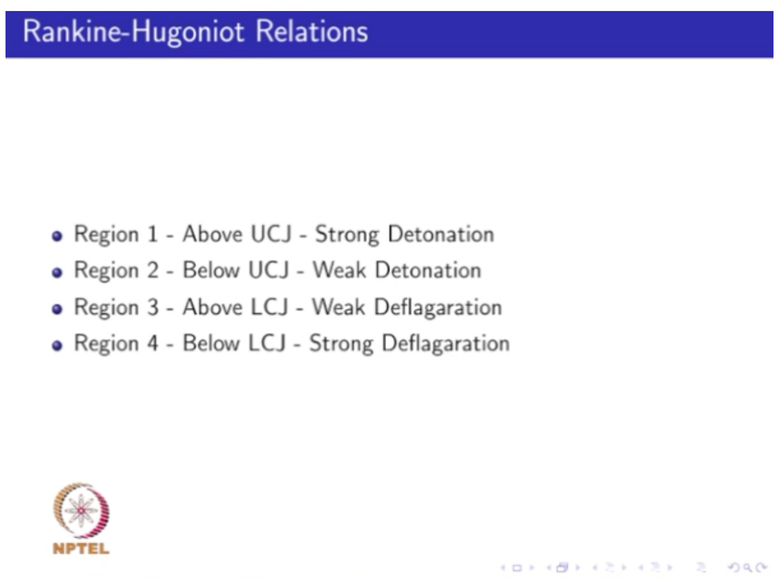

For you to remember this or this stage let us just say that when you are now looking at a region that is about the CJ point here the UCJ point here what that simply means is we are now looking at a solution so that means your, your railway line has to actually pass them out there and then you are looking for a intersection somewhere there right that means the really line is obviously steeper than the tangent really there that means the wave is propagating faster there right.

And it is now leading to a very high pressure and a very, very high density there is a low 1 over $P\infty$ and a high $p \infty$ say a very low 1 over $P \infty$ means a very high $\rho \infty$ so this is actually corresponding to a lot of pressurization and lot of compression so that is why we is basically saying strong but it is going to be a little bit more than that we will, we will, we will all see what is the propagating mach number for the wave.

And what is the downstream mach number for the products it is based on that that actually we now give this normal Fletcher that this is strong detonation but at the moment you can clearly see that you this is pretty strong in the sense it is, it is having a lot of compression whereas a week detonation is just as fast if you were to now look at a solution that is here it is really line is pretty steep as well just a speech test asleep as well.

So it is pretty fast all right but it is not leading to a very high pressure and the departure from the origin is not, not a lot in the 1 over $P \infty$ access so you 1, 1 over $P \infty$ is not lower therefore the $P \infty$ is not a lot higher therefore you are having a smaller amount of compression when compared to the strong detonation so relatively speaking we would like to think of this as a week detonation okay.

What we will actually find is when we now have a flow that is going through a detonation wave just like in a normal shock you should expect that if the flow is approaching the wave at supersonic speeds if the strong if the shock is very strong you should expect the flow to actually become subsonic all the way that is, that is a mark of its, its, its extent of compression so if it has been compressed a lot it also gets decent the flow also gets decelerating right.

So a lot of compression would be in a lot of deceleration all the way down to subsonic levels whereas in a week attenuation you expect that the downstream product flow is still remaining supersonic although not as supersonic as the upstream reactants there is the deceleration all right but not down to subsonic levels correspondingly the CJ detonation should mean that of course you are going through a supersonic reactant flow reaching up to the wave.

But the reality but the products correspond exactly to sonic conditions that is what is the decade that is what is denoting a CJ the detonation similarly if you are now begin to look at this side what, what it means is in a deflagration we are looking for an expansion so any now looking we are now looking for an expansion that means the pressure should decrease and the density should also decrease if you now look at this region the pressure decreases are not a lot.

And the density decrease the density decrease or the or should say 1 over P∞ increased is also modest therefore a P ∞ decrease is also more s right so you are now not having a fairly large decrease in p∞ and ρ ∞ and therefore you are expecting like a week deflagration okay so you are now looking at a railway line that is corresponding to a, a velocity that is still lower than the SI je deflagration right it is slower and so correspondingly you are not really expecting a large decrease in pressure.

And density but for this load deflagration you still can intersect over there so this, this wave is just as low but it is actually causing a large decrease in pressure and a correspondingly large decrease in density right that is a lot of expansion that is going on and that is why we want to term it as a strong deflagration right so you now have a large expansion that is going on proportionately you are now expecting the flow to accelerate.

So when a when a reactant flow is actually going through a deliberation wave it tends to the rate and this is actually common practice so in all these things we always try to relate to what we already have experienced with so what I would like to suggest is when you are dealing with detonation waves you now recall what happens in gas dynamics but what you have learnt in your one-dimensional gas dynamics from your undergraduate.

Let us say if you have gone through a gas dynamics course in your undergraduate level you can recollect what happens across a shock and try to modify your thoughts to accommodate reactions and so on when you are dealing thinking about deflagration waves this is actually more commonplace in terms of daily experience like what happens in like a Bunsen burner for example right.

So if you now have a Bunsen burner and then you have like a cold reactant flow that is approaching the moon is and burner and then it goes through the flame and the flame is like a conical flame and the end and the flow goes through this it now expands and then kind of goes like that okay and then you can also see that occasionally and this is not very difficult for you to think about as a thought experiment or even go back and see if you can do this and see for yourself when you now have like a inclined flame like this in a Bunsen burner.

And if you had like, like a like a little particle that is kind of glowing okay so if you now see how this glow happens as it as it goes along when it passes through the flame it goes much faster than compared to when it try to approach so it is like a little spark of some particle that is just glowing you can clearly see that it this goes faster right so when you now have a deflagration wave the flow accelerates when it goes past it because it is expanding right.

Now well you are here you are not expanding a whole lot and that is because it is a week deflagration and therefore you started out with the flow approaching you at subsonic speeds and you are accelerating to further faster but still subsonic product speeds that is the mark of week deflagration but when you now go to go past the LCJ over here to the strong deflagration what that means is you are now having a very large amount of expansion that is going on correspondingly there must be a very significant amount of acceleration that goes on to the extent.

That we end up finding that the products actually have supersonic speeds by the time they are getting past this wave way although they started out with subsonic conditions for the reactants correspondingly what just like how we found in the case of UCJ what this means for the LCJ is the approach velocities for the reactants is subsonic all right but the flow accelerates through the wave to exactly sonic conditions beyond for the for the LCJ.

Now if you really think about it this is getting a little bit more fascinating it is unbelievable fantastic okay how can I have a wave that started out to be subsonic go through a flame and accelerate so much as to become supersonic is it possible for me to do so the answer is we do not come across that at all right so in Boones and burners and stuff you do not really get supersonic flows so what is going on the answer there is outside the picture of what we are talking about we started out with the mass conservation equation we started out and then we went through the momentum conservation and then we went through the energy conservation.

We also talked about the species conservation but the energy conservation keep in mind is essentially coming out of the first law of thermodynamics but we never really considered the second law okay and, and we will never do that actually, actually except to state that the this part of the wave that is the strong deflagration is not possible if you now start taking second law into account.

And there is a reason why you will never really find a way of starting from subsonic flows going through a strong deflagration to accelerate all the way to supersonic speeds that typically doesn't happen because it violates second law right and I think I may be able to show that briefly later on but let me also point out that I will try to show first of all the detonation waves all degeneration waves in or in fact I should say all detonation waves travel at supersonic speeds and I should also show that all deflagration waves travel at subsonic speeds.

The way I would like to show this is to consider the CJ detonation and the CJ deflagration I would like to show that the CJ deflagration is supersonic which means the slowest detonation is supersonic that means all of the detonations are going to be supersonic and I am going to show you that the fastest deliberation they see their the lower CJ deflagration is going to be subsonic.

There for all other editions of subsonic right and then we would also consider the downstream Mach numbers for the you see you CJ in LCJ and show that they are actually won thereby we can clearly see how these things are demarcated right but before we do that let us go back and just write out the properties of the Hugoniot curve on where they intersect what the awesome totes are and all those things the next class thank you.

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