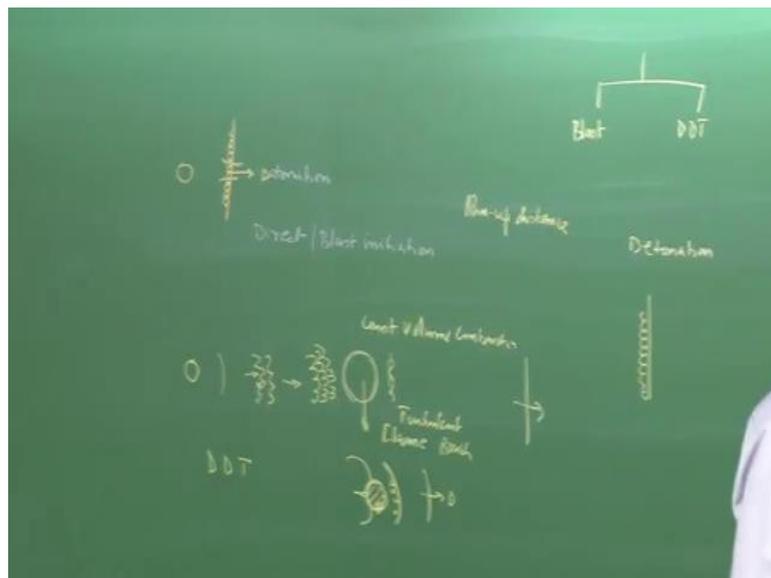


Introduction to Explosions and Explosion Safety
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Lecture - 24
Detonation: Multi-head Shock Front in a Detonation
Triple Point
Transverse Shocks
Characteristic cell of Detonation
Regeneration of Shells
One Dimensional Model
Reaction Shock Hugoniot
Rayleigh Line

Good morning, you know we have seen that there are two ways in which we can create a detonation or let us say form a detonation.

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In the first method, we deposit some energy rapidly at some source, some energy exceeding some threshold value. We form something like a strong shock wave, we ensure that this strong shock wave is formed at some distance away from the source. That time of formation should be such that chemical reactions get completed. If the shock wave is sufficiently strong, the chemical reaction which occur behind the hot zone of the shock wave, there is a temperature increase in the shock wave. If this temperature increase is quite large corresponding to the large mach number this chemical reactions will drive the shock wave and you get a detonation wave.

This we say is a direct method of forming a detonation and this is known as the direct method of initiating a detonation. That means you form a blast wave, the blast wave couples with chemical reactions. The chemical reaction take over and drive the detonation as it is. This is also known since we form a blast wave it is not so known as the blast initiation of a detonation.

In the second method, what did we tell ourselves when we deposited the energy source, when we deposited the energy. The energy release has not been sufficiently rapid and what you form is a flame. A flame moves at a few centimetres per second and as the flame moves what does it do. It is something like a piston which compresses the un burn gases ahead of it. Therefore, the velocity of the gases ahead of it increase.

Therefore, what happens is the flame speed in the moving gas is increases and not only that when the gas velocity is increased maybe the turbulence increases, the intensity of turbulence increases, the length changes. Therefore, you form something like corrugated flame. Compared to a few centimetres per second or a few metres per second, this velocity is much higher because it a turbulent flame.

Ultimately this turbulent flame again drives the gases ahead of it just like an accelerating piston pushing the gases. Therefore, I have a highly turbulent highly wrinkled type of a fame which is formed. We also saw sow pictures saying that, whenever I have blockages or the wall affects, I create since the velocities ahead of the unburn gases are already large. I create shock structures or maybe expansion waves, maybe weak shocks within it, which make the turbulence so high that maybe, when something this there, this is the unburn gases in which the concentrations are high.

Whenever something start burning because of the high turbulent intensity the change which are formed or also terribly fluctuating or terribly mixing. Therefore, what happens is I could have a zone of gases which are formed ahead of the flame, which goes into something like a constant volume combustion. When you say constant value combustion, it is as if the whole thing is just burning as it were.

Therefore, at constant volume I can say well it is something like a sonic combustion which is taking place. This type of a flame brush in which you have intense turbulence that means I have a very intense turbulent frame brush, which is moving at extremely highest velocities of the order of the sonic speed itself, but still it is not a detonation.

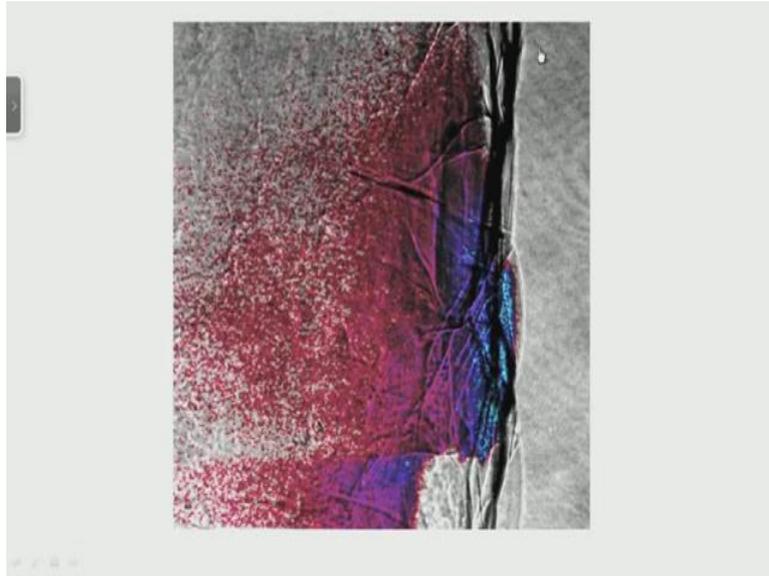
This can, when the chemical reactions time are such that it is able to now form a shock wave, if it is able because now it is able to form a shock wave, it can couple and form a detonation. Alternatively if I have this wrinkled flames, you know the length scale also is somewhat larger in the intensity of turbulence. These wrinkled flame supposing they are hold together some unburn gas mixture.

This unburn gas mixture is now being burn from the outside towards the inside. It collapses at something like a like an implosion takes place and you form a shock wave. Therefore, behind this shock wave chemical reactions occur and you get a detonation. Well this is an indirect way of forming a detonation and this is how in most of the accidental explosions, this is how a detonation gets formed. Therefore, you form a flame which transits ultimately into a detonation and that distance taken, from the source to form a detonation is what we call as the run up distance.

That is this is an indirect way of forming a detonation, which we said deflagration to detonation transition or flame to detonation transition. You know in some cases, the run up distances are quite small, even though you form a flame, the run distance could be small. We must not mistake the mistake these two types of initiation. Therefore, we tell ourselves, well a detonation could be formed either as a blast initiation or directly or as a deflagration to detonation transition.

Having seen the way in which you have something like a compression behind a detonation compared to an expansion behind a flame. We would like to examine a little more about what this detonation looks like. Not to be able to see that I show I few slides and it seen that maybe detonation is not a smooth shock, with chemical reactions occurring behind it, but it is something more than that. Let us take a look at one or 2 slides and try to see what how a detonation one started propagates.

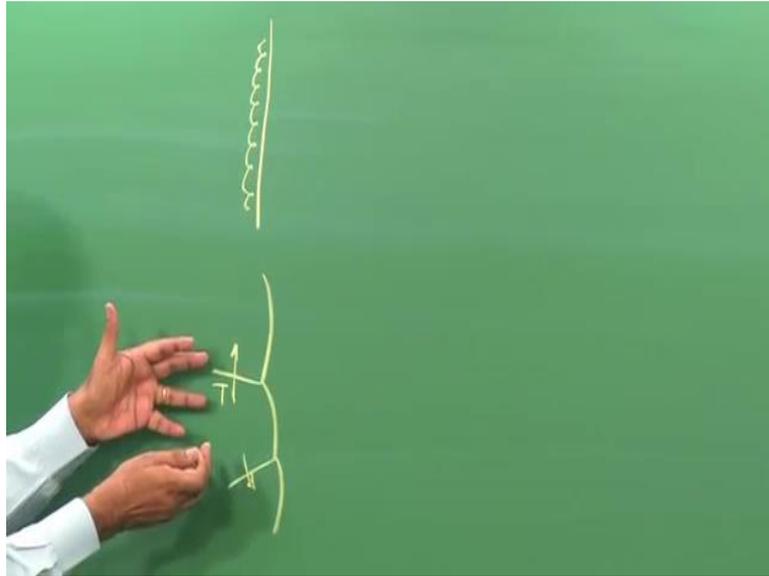
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In this picture, see this is the direction of propagation of a detonation. This is the unburn gas mixture and what is we see, we see some lead shock here. You have one lead shock here another lead shock here, another lead shock here. That means the front of a detonation is not as smooth as we thought it is. It consists of multiple shocks and also behind these shocks you also find I have waves behind the shock as well.

You know I have some wave here, I have some transfer waves here, I have a wave which is normal to the lead shock over here which means that the front of a detonation just like what we presumed here.

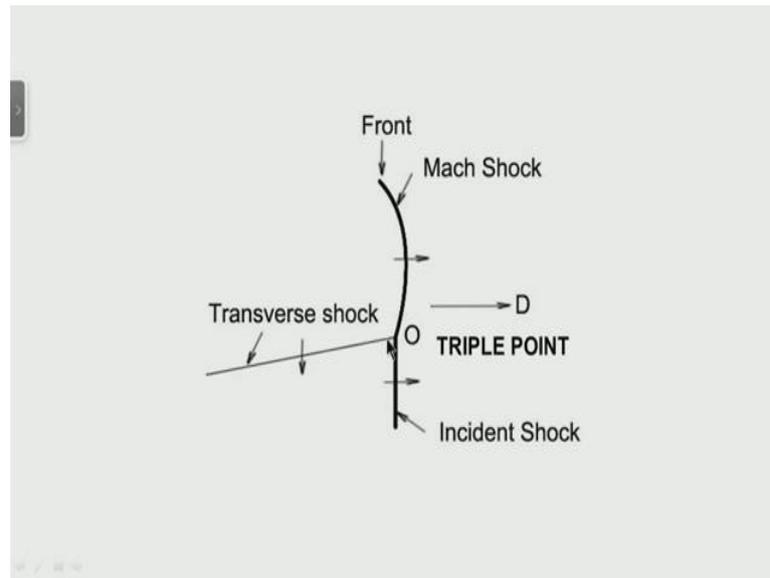
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What did we presume? I have a detonation front a shock front. I have chemical reactions occurring over here and what it is we see. Well there are multiple shocks in the front. There are also waves behind it, that means I have something like a transfers wave. I have lead shock waves or the front detonation waves something a detonation seems to be something like a multiple shocks, which are there in the front, which are there lateral to it.

Maybe these things move in this particular direction. Therefore, if we now say, well a detonation is something like a multi headed shock front or a multithreaded detonation wave. Therefore, maybe we should take a look at this before I start working for the velocities and pressure behind a detonation. Therefore, let us try to simplify this picture and see what it look like. Well the front of a detonation we say consist of shocks well I have a shock over here, I have another shock over here these two shocks at the intersection point.

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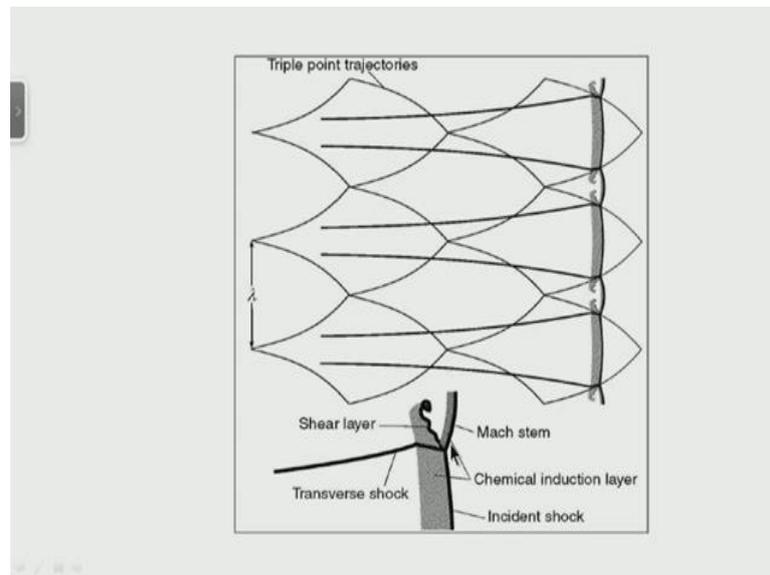
I have a third shock over here and this three shock interactions we have seen earlier when we were looking at blast waves, we talked in terms of mach reflection. When two shocks interact at a very shallow angle. Well it is not a regular interaction that means an incident wave is not reflected as a reflected wave, but you get a third shock, you have a stand of shock which we call as a mach stem shock.

We have something like a mach wave reflection and the front of a detonation consist of a mach stem shock and another shock which is known as an incident shock. You have a lateral shock which is known as a transfer shock. This is how it looks in a two dimensional format. Maybe at the in the intersection of the three shocks over here is what we call as a triple point. Now, if so happens, that the lead shocks maybe the mach stem shock and the incident shocks of these two shocks the mach stem shock is much stronger than the incident shock.

With the result the induction time or time for chemical reactions behind the mach stem shock is somewhat smaller, while behind the incident shock it is much larger. In fact the transfer shock takes the gases which are still reacting and maybe some chemical reactions occur over here. Therefore, the front of a detonation is not a something like a single shock wave behind which chemical reactions are occurring, but you have multitude of shocks.

Therefore, if I were to enlarge this picture for the total detonation what is it I get. Well I had the mach stem shock, I had the incident shock, I have the lateral transfer shock over here and you know what is happening the chemical reactions the mach stem shock is normally much stronger than the incident shock.

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Therefore, the chemical reactions takes smaller time, the induction time is smaller followed by the chemical reactions here. The induction time is much larger and behind the transfer shock again some chemical reactions are taking place. Behind this you also have the slip stream or the zone separating the gases processed here in the gases processed here. You have something like a sheer layer.

Therefore, what is going to happen I have vorticity at this particular intersection point and therefore, when a detonation wave propagates, you know what is happening is, this particular point that is the triple point, is capable of... if I put a sort of a paper coated with some with some material like let us say suit or some substances which can easily be written upon.

Like I have a paper on which I put some carbon deposit and I scratch on it I can easily write on it. So, also this point o which as vorticity can write on a piece of paper if I look at it I find that my shock rejectory that means the triple point, traces a curve something like this, it traces a curve something like this. If I were to start earlier, well the triple

point traces a curve like this comes back over here, the next triple point corresponding to this has traced this curve comes like this traces this curve comes like this.

That means I have something like these cells which are being formed, the cells which are being formed. This the cells are very much characteristics of a detonation. Therefore, let us again review this we say that the front of a detonation consist of a mach stem shock the mach stem shock is strong. The chemical time behind the mach stems hock is smaller, the incident shock is weaker.

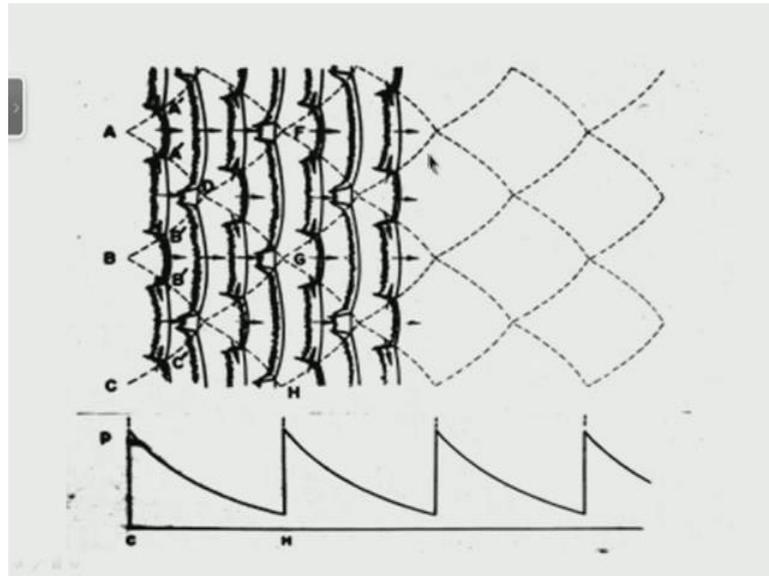
The chemical time behind it is larger, you have a transfer shock behind the transfer shock also chemical reactions take place. How do these things propagate? Maybe let us start with the point here and these triple point comes over here, the triple point comes over here. The triple point meets there is this triple point and this triple point meets over here that means the transfers wave over here and the transfers wave over here hit together over here.

Once it hits, well I have another cell being formed or rejuvenated. Therefore, I have a mach stem shock which is being formed here, this mach stem stock keep progressing as I am showing. Once the centre of the cell is reached what happens is the mach stem shock during this period of movement keeps on decreasing in strength and it becomes something like a weaker, something like an incident shock. But in the neighbouring cell what happens is, well this is the mach stem shock it comes over here becomes weak something link an incident shock.

In the neighbouring cell over here the another interaction takes place, a mach stem shock is form and therefore, I have a mach stem shock followed by incident shock followed by a mach stem stock and this is the way a detonation progresses. Within each cell of detonation, as I just now told, maybe at the intersection point I form a mach stem shock. This mach stem shock is continually decaying. Surrounding this particular the mach stem stock I have an incident shock and this incident shock with transfers wave comes and hits here.

This is also decaying, at this point a new mach stem shock is created and therefore, the picture of a detonation being a regular sort of a one dimensional constant velocity front which moves does not seem to be true. In fact what we have is within each cell of these detonation.

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See we said, we form these cells of detonation and these cells are trajectories of the triple point. Therefore, within each cell of a detonation I have the lead shock which is a mach stem shock with which a cell is being formed. This continually decays and when initially I have a mach stem shock which is very strong behind it chemical reactions occur rapidly because the induction time at high temperature is very small.

As it keeps decaying, well you know what happens the induction time I show the zone of chemical reactions by black line over here over. This the zone of chemical reaction between the shock front and the chemical reaction there is a zone or induction time the time taken for the reactions. As the shock decays this tends to decouple from it and then this shock further decouples it becomes an incident wave. It further reduces in strength.

Therefore, I have totally decoupled reaction, but then the transfer waves come and hit at this point wherein the triple point intersects and a new mach wave is generated. Therefore, the procedure by which a detonation propagates is, well I have the triple point intersection over here. I have a mach stem being formed behind the mach stem rapid chemical reactions are occurring. I am just considering events within a cell of detonation, we will take a look at the neighbouring cells shortly.

You know within the mach stem will chemical reactions occur rapidly it drives it, but during the process of travel the mach stem shock decays in strength. Maybe it starts with a strength which is around 1.2 to 1.3 times the mean value of the mach number at which

it proceeding. It decays down it reaches a value over here and then it further decays chemical reactions get coupled. It further decays and by the time the 2 triple points or the transfer waves intersect, it has decayed in strength to something like 0.6 to 0.8 times.

The mean mach number at which the detonation propagated. Therefore, in their adjacent cell well over here I have incident waves that means I have I have triple point intersecting here. Again a mach stem shock being formed gets into incident shock wave and therefore, the front of a detonation consist of a mach stem shock and incident shock in the neighbouring cell. In the neighbourhood of the other one is the mach stem shock followed by instant shock and this is the front of the detonation.

If I were to consider a single cell, if I were to consider events within a single cell, may be this cell followed by the next cell of detonation, followed by the next cell of detonation what is it I get. I get maybe at the point of intersection of the triple points that is the 2 transfers waves intersect. All of a sudden there is an increase in the mach number to a from a mean value to something like 1.2 to 1.3 times the mean mach number.

Within the cell the mach number keeps decaying, it reaches a value between 0.6 to 0.8 the mean value and again it spikes up, again it drops in the next cell. Therefore, the detonation is not something which is moving at constant speed throughout, but within each cell it is sort of something like a pulse, you know it is sort of galloping. Starts from the high value comes down to a low value goes to a high value comes to a high value.

Therefore, it seems to be propagating in sprats. This is the 2 dimensional sketch and if you were to look at 3 dimensional well its possible, but only thing is that you know this particular diamond pattern gets into something like a fish cell pattern. We have to take a look at that and therefore, if I were to take let us say a pipe in this what I am showing is.

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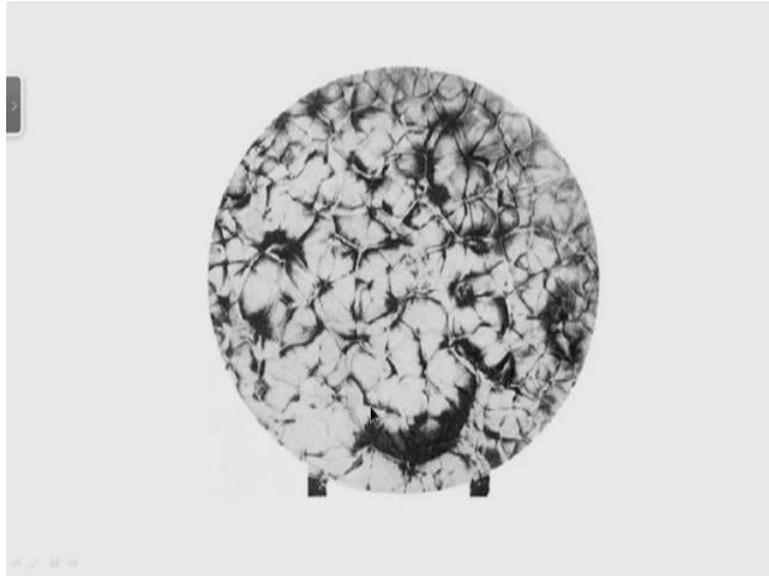


I have a pipe containing some explosive gas mixture. I show this pipe at different instance of time I have a detonation wave propagating that detonation front is over here. Initially and therefore, see behind the detonation front. As I said the triple point can write on the wall if the wall can be made to contain some material on which something can be written like I have a smoke foil of something like sand which is embedded on the wall. I get these particular pattern. As a detonation wave propagates well these scale structure or these cell structure propagates.

You see the front of a detonation is associated with all these structures and you have these structure which is characteristics of a detonation. The front propagates and what is the front the front consist of all these myriad types myriad of the lead shocks. You have the transfers wave behind it and therefore, the front of a detonation is not something which is a beautiful one dimensional or let us say a plainer shock front, but it consist of a series of lead shocks followed by transfer shocks.

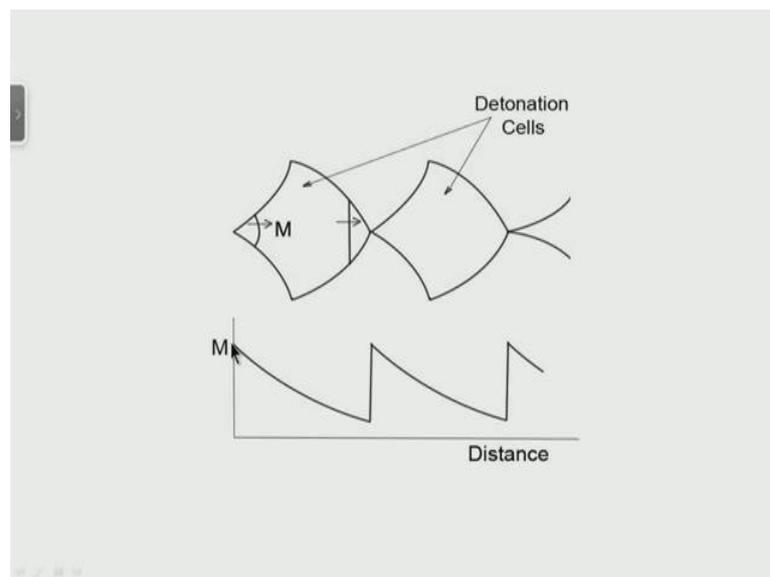
That is it consists each shock interaction consist of 3 shocks, namely the mach stem shock and incident shock and a transfer shock. Having seen that this is the structure by which a detonation propagates just to illustrate the 3 dimensionality. If I were to go to the pervious slide and then I were to put something like.

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On this particular surface I put a paper on which the signature could be written. Well the signature is not only in this plain which I am showing, but it is also normal to it. That means I get the site of pattern corresponds to the diamond structure. Therefore, we say well within the cell of a detonation what happens is I start with a high mach number at the end of the cell the mach number decreases.

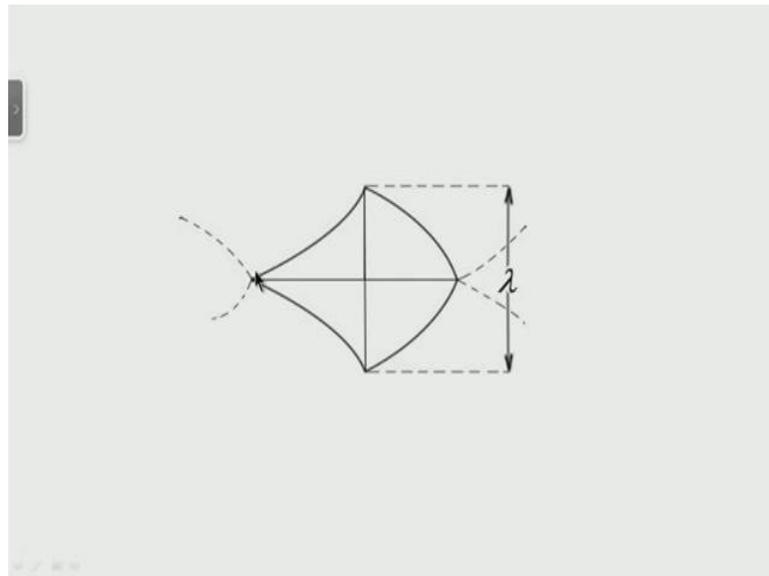
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Again I have sprats starts with around 1.4 to 1.2 times the mean mach number, comes down to around 0.6 to 0.8 times again there is a spike. It seems like in sprats the

detonation propagates and detonation propagates within a cell of a detonation. You have the neighbouring cell over here, you have other cells and these detonation cells are very much a characteristic of a detonation. These cells are also known as cells of detonation. Let us take one more look at this particular one particular cell.

(Refer Slide Time: 20:00)



Well you have the triple point coming along this trajectory, you have triple point coming this trajectory. You have transfers waves over here the transfers wave intersect over here. It starts mach stem shock it comes over here, it decays in strength becomes an incident shock wave and then the writing of the triple point is along this trajectory, along this trajectory. The triple point and the corresponding transfers wave intersect here another cell is born over here and this is the wave from cell to cell the detonation wave propagates.

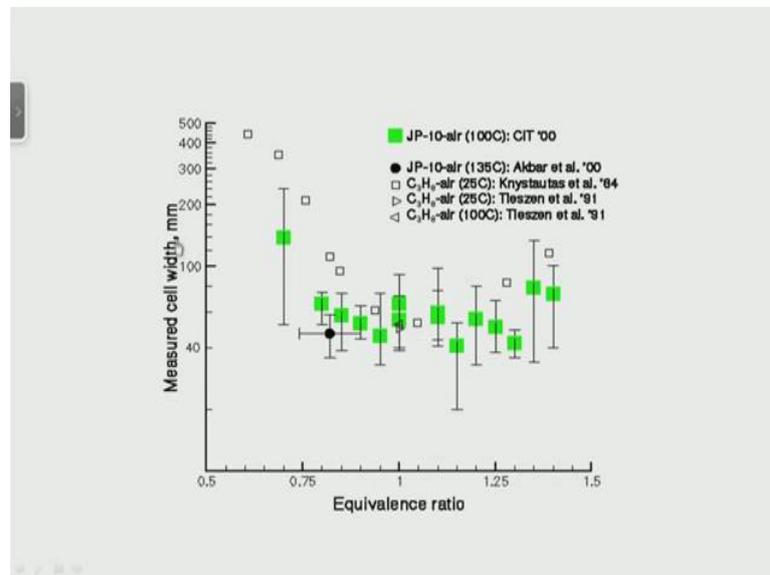
Therefore, a detonation wave is a multi headed structure and this cell of a detonation is something which is very much characteristics and we say, well this the length of a detonation. The width of that detonation cell is called the cell size of a detonation which we characterize by the word lambda by the letter lambda. Therefore, to sum up a detonation wave is not something which is beautiful one dimensional, but it has a structure, it has a particular characteristics structure which is known as a detonation cell.

It is characterised by a particular dimension lambda. This particular cell size is characteristic of the explosive gas used its pressure, temperature it physical properties it

rate of reactions and for gases which are very reactive, lambda is very small, for gases which are not that reactive in which the mean velocity of detonation is slower the value of lambda could be large. There is there are there is sizeable variation in lambda and if I were to just put this this is Sheppard's data.

If I were to say yes measured cell width as a function of the equivalence ratio. Equivalence ratio one corresponds to stoichiometric. You find that if I talk in terms of hydrocarbon mixtures the cell size could be as much as something like 4 to 40 centimetres depending on the conditions.

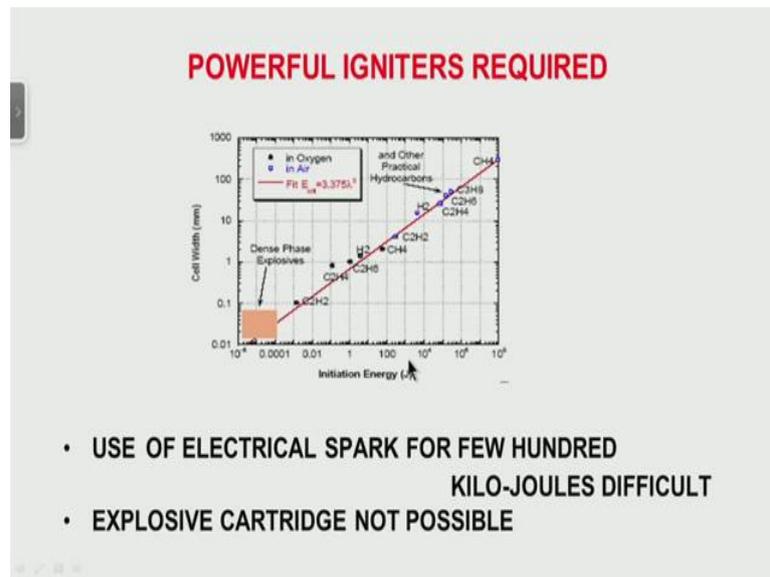
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Depending on the equivalence ratios, but if I were to take hydrogen air mixture you know the cell size could be a few centimetres over here. Acetylene could be a few millimetres over here therefore, depending on the type of the gas mixture, the measured cell width keeps changing. It also depends on this stoichiometric metric because the stoichiometric metric or the equivalence ratio tells us how much energy is liberated in a particular chemical reactions.

The cell structure is not only true for the gaseous explosives, it is true for all detonations whether it is a solid liquid or it could be a gas. Therefore, let us now put together, you know in the last class we said well we formed out how much energy is required for direct initiation of a detonation.

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Namely, the blast initiation which we just saw on the board you know if we were to plot a curve between the initiation energy required versus the cell width required and what was the cell width, it is the width of a characteristic detonation cell. If I were to plot this particular figure I find that the initiation energy that is the energy required for directly forming a detonation is somewhat linearly related to the cell width of a detonation. As the cell width increases well the initiation energy increases and let us take a look.

If I have something like hydrogen oxygen mixture, the initiation energy we said is of the order of some 5 or 6 joules. Well this is the initiation energy, the cell size is around one to 2 millimetres. If I take hydrogen air mixtures well the cell size has grown it has grown to almost like twelve millimetres. The initiation energy has also gone up to something like almost a kilo joule. Similarly, if I take maybe acetylene oxygen mixture, well the cell size is extremely fine around point one mm.

The initiation energy is also small, but if I consider acetylene air mixture and you know inert gas mixture the heat release is lower. The cell size is increased to something like almost 3 millimetres while the initiation energy has gone to something like 2 hundred joules. Therefore, depending on the energetic and the cell size the initiation energy can be related to the width or the characteristics cell size of a detonation. If I consider methane, well methane in air well the energies required are phenomenal something like we are talking of ten to the power 6 joules something like hundred kilojoules.

The cell size is also larger something like almost like twenty centimetres or so. If I consider methane oxygen, if I consider methane oxygen here well the cell size is of the order of something like 3 millimetres and the initiation is low energy is lower at something like 3 hundred joules or so. Therefore, for different substances this particular figure gives the initiation energy plotted on the x axis as a function of cell width which is or the characteristics size of a detonation, which is plotted on the y axis.

This particular curve also tells this what we discussed in the last class namely the initiation energy required is very much greater than what is the energy required to form a flame. In which case it was all in terms of milli joules, now we are talking of kilojoules and mega joules over here. What we need to therefore, notice maybe powerful ignites are required to directly form a detonation, but we must qualify this by saying. Well I can always form a flame and not a detonation by the ignition energy release.

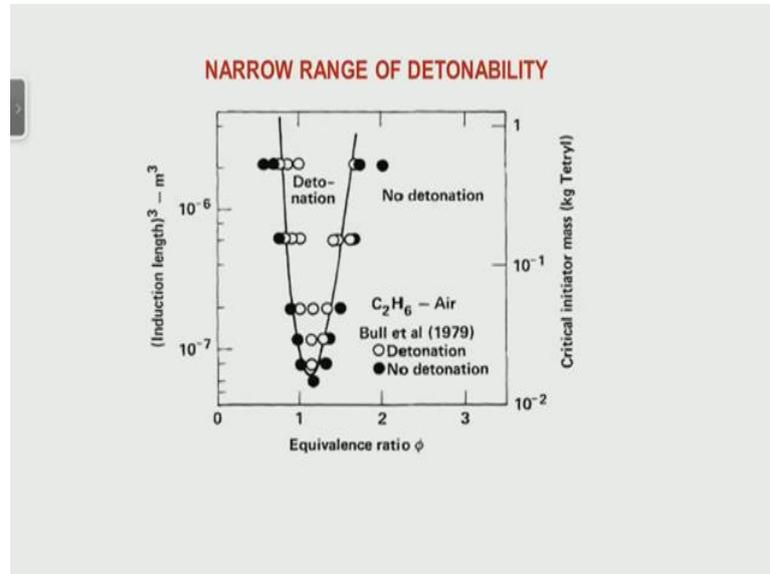
This flame can subsequently transit into a detonation provided adequate turbulence can be generated upstream. I can form a turbulent flame brush and something like a constant volume combustion or a pseudo detonation before forming a detonation. Therefore, we can we can tell well, use of electrical spark for a few hundred kilojoules are difficult because you know in nature, you know whenever we say there is some spill, I can get an accidental. So, I cannot expect to get kilojoules of energy release, I can only get a few milli joules of energy release.

Therefore, directly forming a detonation in accidental spills forming explosive gas mixtures are difficult. In practice I do not have explosive cartridges which really form a shock wave which is going to initiate it. Therefore, in practice the phenomenon of deflagration to detonation transition is more possible than directly forming a detonation wave. We also see from this figure, that when we talking terms of condensed explosives like solid explosives.

The cell sizes are small and the energy required to initiate them are much smaller. We will consider this after a few further classes. Well this tells us the way in which a detonation gets initiated about the 3 dimensional structure of a detonation we namely a characteristic, fish scale or a diamond structure. The characteristics size being, the cell width this characteristics size of a detonation is a very important parameter for a

detonation. Having said that, you know let us go back and see whether something like flammability limits.

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Is there a range of mixtures within which only a detonation can propagate? This data again I took from literature namely bulls data. Here, I find that if I were to consider a particular let us say I have c 2 h 6 with air mixture. You know I have only a narrow region that means I have lean detonation limits this is equivalence ratio equivalence ratio one. I find below an equivalence ratio one it is lean at a detonation wave cannot propagate. If I consider a rich mixture over here, well detonation cannot propagate no detonation in the region to the right of this curve.

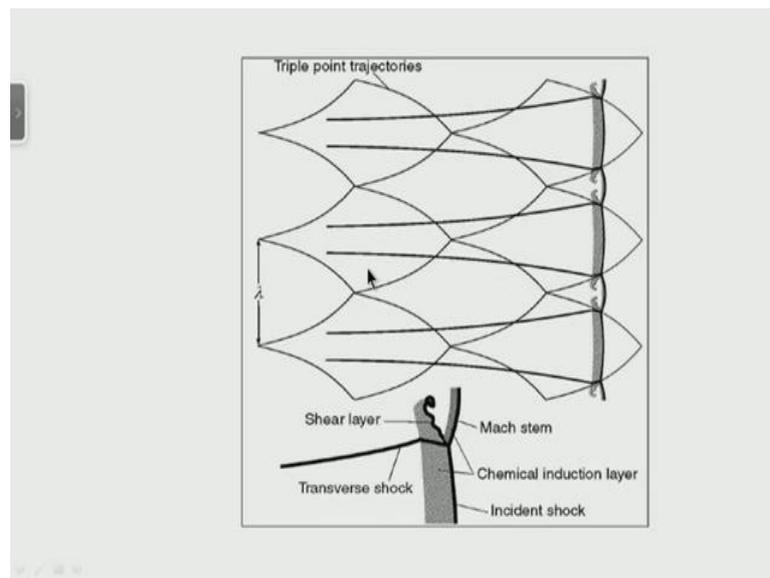
No detonation in the detonation to the left of this curve and only in a narrow region is I am able to get a detonation. If I were to plot on the same curve the flammability limits the lean flammability limit I will be somewhere over here. The reach limit will be somewhere over here therefore, in general the range supports a detonation is very much leaner will very much smaller than the region which supports a flame.

Well you know how do we do this what did we plot in this particular curve for the flammability limits. We plotted the initiation energy versus the percentage volume by volume which we said could also be put in terms of equivalence ratio. Well it is the energy required to initiate a detonation and you have typical shape curves like

flammability limits, but only thing is that the region is much narrower than in the case of flame.

What causes this detonability limit, I think we have to take another look at it and therefore, in the next line I again go back and show you the three dimensional structure of a detonation.

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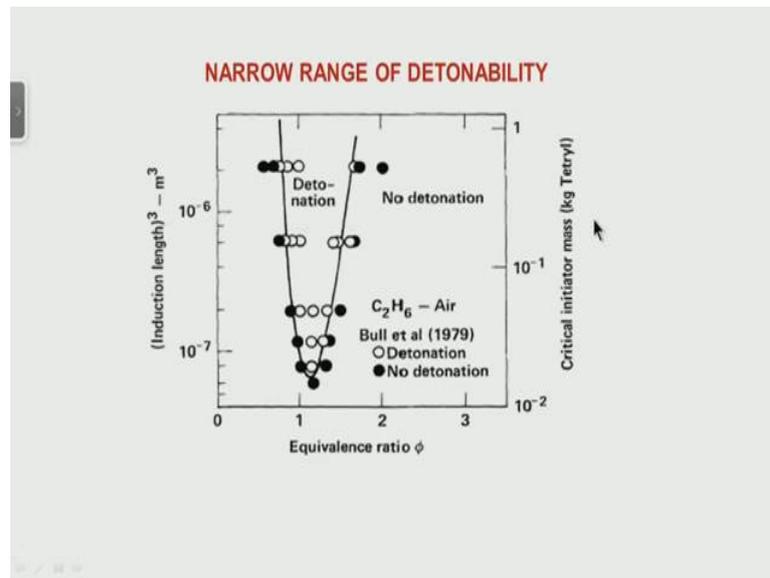


Of the detonation limits if I were to say lean limit of detonability rich limit of detonability. The distance between this that is the detonation then the mixture which you have transfers wave over here. Supposing, within a particular pipe or within a particular region I have just one or two of these cells that means the cells are very large let us say. I do I have no way in which these transfers waves when they come over here can hit each other and create another cell of a detonation. That means the transfers waves if they if it rebounds at the wall and comes back well and good, but you have one transfers wave which hits against the wall.

The second is transfers wave is also hitting against the wall and therefore, if I have something like 3 or 4 transfers waves, which are formed. Then I cannot really maintain the continuity because I cannot energise these transfer waves and come and hit at the triple point intersection. Therefore, when the number of transfers waves are smaller than some limit. You know it is just not possible to propagate a detonation wave.

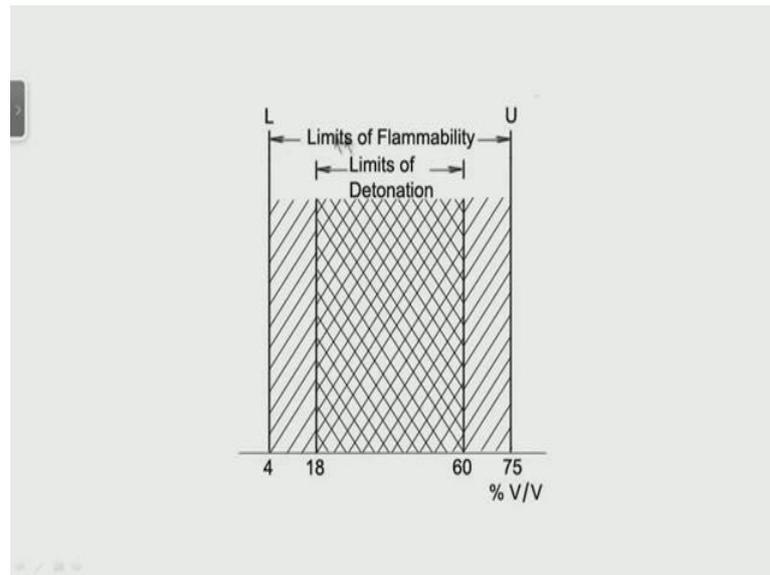
In other words if the number of cells of detonations in a particular region happens to be less than some limit let us say 3 or four. You know the rejuvenation of a detonation is not possible because I am not able to get a multitude of transfer waves which keep on intersecting and keep forming these detonation waves.

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That is one way in which I can say well the limits of detonability are formed. In other words if I were to go back to the previous line all what I am trying to say is maybe in the region of the limit of detonability the cell structure is so large that I do not have number of cells within the region of interest with the result there. The transfer waves or the triple points intersect with each other and keep on rejuvenating the cells and when rejuvenation of the cells is not possible, well a detonation cannot propagate. Well this is the region for the detonation limits and if I were to plot this is what I showed earlier.

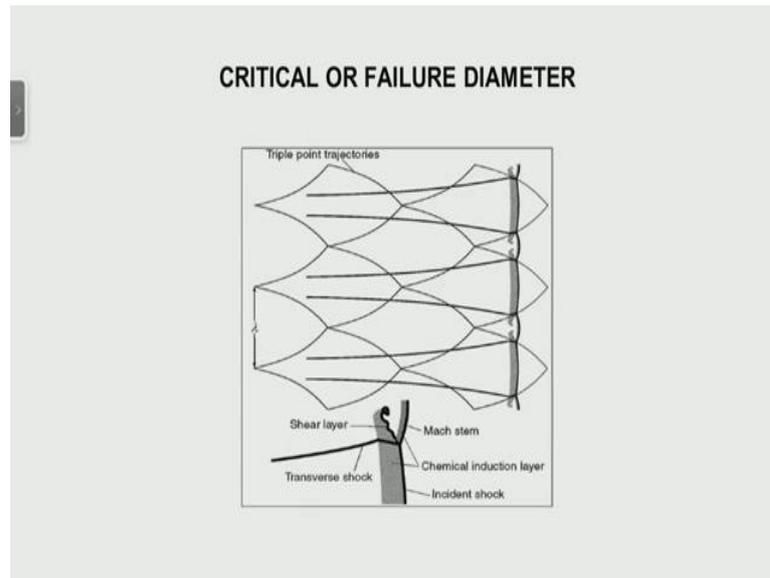
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Earlier I said well the limits of flammability are much wider, this is a lean limit of flammability, this is the upper limit there is a rich limit of flammability. This is for hydrogen oxygen we said that the lean limit is 4 percentage volume in the volume of mixture. Upper limit is around seventy five.

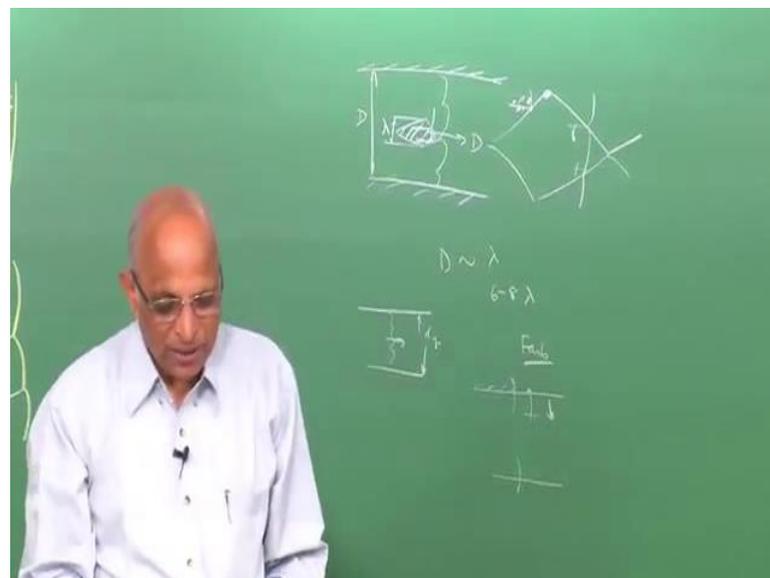
The limits of deniability at a given pressure are between much in a narrower range compared to 4 the lean limit becomes 18, compared to 75 the lean limit becomes 60. The reason why it is required is to support a detonation you need a large exothermicity, I need a shock wave, I need behind the marks mach stem wave which much be sufficiently strong such that chemical reactions can drive it. Therefore, I need more energetic to drive a detonation compared more energetic of chemical reactions to derive a detonation compared to a flame and that is why the limits of detonation are smaller.

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Well this particular point creates one more phenomenon and that is what I would like to go to the board and illustrate. Let us let us take what is this phenomenon I am talking of let me get me on the right side of the board.

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Supposing I have a pipe let us say or a tube in which I am propagating a detonation. This is how we say a detonation propagates. This is the wall of the pipe. Now, a detonation propagates at some steady value, but we said it consist of a series of cells and the detonation propagates through cells let us say I have cell like this I have the cell being

formed this is the diamond cell over here. This is the characteristic width of the cell is the characteristic dimension of the cell. Well I show the cell by like that are a series of cells over here and what is happening.

Well I have within the within each one I have let us say front over here. I have something like this is being formed I have another one, I have this transfers waves. If I have the number of cells within this particular dimension, if I have only let us say single cell over here. You know what is going to happen is, there is no way in which the transfers wave you know the transfers wave behind this.

I have a wave which is coming I have wave which is translating. You know the transfers wave or the lateral wave gets reflected from the wall and if the reflection of the transfers wave is such that it is no longer transport is no longer supported by chemical reaction. Well it is going to weaken and if it weakens out that means if I have number of cells within the pipe, less than some critical threshold. Well a detonation cannot propagate.

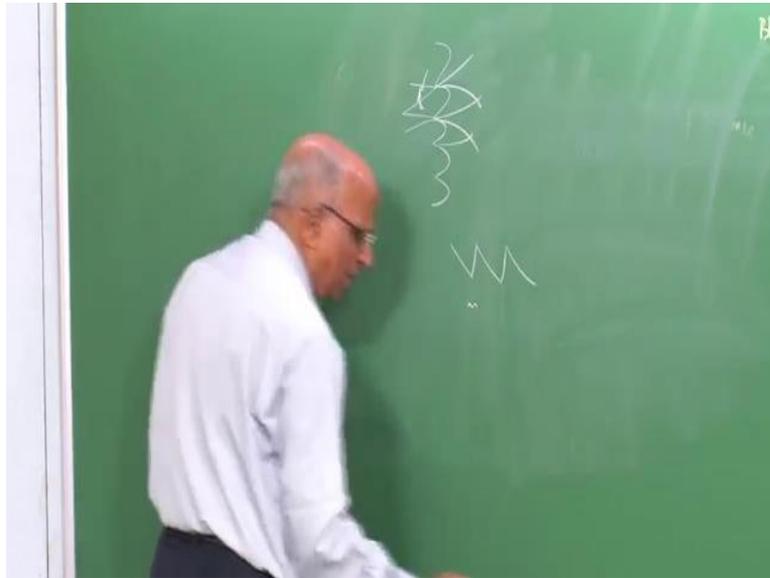
Therefore, if I say that maybe the diameter of the pipe is let us say capital D . If D is of the order of let us say cell size in practice it is something like 6 to 8 times the cell size. Well a detonation wave cannot just propagate. You know another thing which comes in. Therefore, you know, but when we had a flame what did we find well a flame propagates in a pipe and we had something like a quenching distance for a particular pipe. We talk in terms of a critical diameter or the failure or the failure diameter of a pipe for propagation compared to the quenching diameter of a pipe over here. In addition let us say you know some nice experiment have been done with detonation.

If I say along the wall of the pipe I put something like a surface which can observe the lateral waves. See waves are going are going up and down. If at the surface, I put a material like let us say I put a low impedance material which takes the wave. That means a wave which comes here, if it is going to be observed by it is no longer reflected. Therefore, maybe in these cases also that detonation wave fails. Therefore, to be able to support a detonation we need some minimum number of cells within it, such that the transfers waves that is the wave transfers to the front of a detonation or always present.

They can keep on interacting rejuvenate more and more of these cells as it keeps progressing. Therefore, the cell size is basic to a particular detonation. Well this is about propagation of a detonation and we have looked at this you know things are not as

complicated as they seem to be. Having said that let us try to put things together now. You know we like to work with a simple model of a detonation, namely let us say a one dimensional model, but we said...

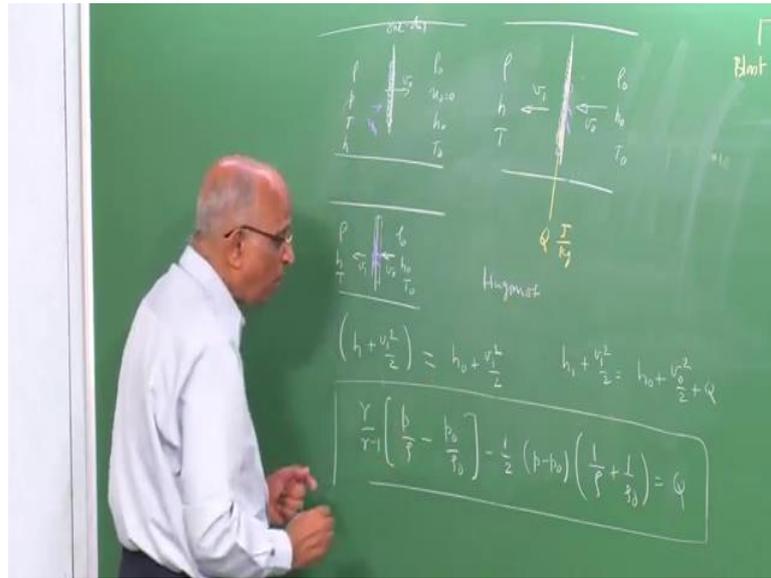
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Well a detonation is not one dimensional, the front consist of corrugations like this. I have transfers wave which are moving. I have transfers waves which are moving maybe one here maybe one here one here and it intersect. Therefore, I form another cell of detonation I form another cell of a detonation within this, it is the velocity keeps changing velocity picks up and changing, but you also said if the cell size is small, well I can I can if the cell sizes are small then the variation in velocity are small.

I can therefore, under certain conditions still use my one dimensional model and within the one dimensional model has a lot of physics in it. To be able to understand a detonation let us go back and still presume that the front is not corrugated with multiple shocks, but it is let us say one dimensional.

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That means I just hope a shock as it were and this shock as it were, let us say is propagating with chemical reaction. This shock is supported by chemical reaction is propagating into a medium whose D is let us say row 0. Let us say it has no the medium has no velocity u_0 is equal to 0 that is a medium is stagnant. Let us say it is enthalpies at 0, let us we just now just said its velocity u_0 is 0. Let this temperature net 0.

Behind the detonation wave that means a shock supported by chemical reaction, the chemical reactions drive the shock let us say it travels with a velocity v_0 into this particular medium which is at rest. What is happening behind the medium, well the density has increased we will work out the density increase in the next class. We will also work out the pressure increase behind the detonation. Well the temperature is also high because chemical reactions are occurring. The temperature behind the shock itself is high pulls you have chemical reactions happening. Let us say that the enthalpy here is h .

I would like to have a model by which I can calculate the velocity of a detonation. Therefore, to be able to do that well the zone of chemical reactions and shock wave is moving as a detonation at a velocity v_0 . I want to write an equation and what did we do when we consider a shock wave. We said writing an equation for something which is moving is difficult because my frame in reference is continually moving. Therefore, what I do is I have a picture of the detonation waves stationary.

That means the wave is stationary well the chemical reactions are occurring behind the wave. What does the wave do well the chemical the shock wave is there, the chemical reactions are occurring. Let us say that the heat release in chemical reaction is equal to q joules per kilogram, is the energy which is released in the chemical reactions over here at the shock itself. That is behind the shock there is chemical reactions are happening. I am still considering a one dimensional picture I have the shock front behind the shock front I have the chemical reactions, which are there.

Now, instead of this moving I sit on the wave that means my frame of reference is with respect to the front over here. Therefore, what is going to happen well the gases approach me because my frame of reference is the detonation with a velocity v_0 . Here the density is ρ_0 , well it is approaching me with a velocity v_0 this being my frame of reference it is with an enthalpy u_0 .

Let us say that temperature is t_0 . Well you know when the detonation wave is propagating it is dragging the fluid. Now, with a velocity because it is moving it is creating some velocity here let us this velocity be u_1 , but in the frame of reference of this what is going to happen the velocity is going to be v_0 minus u_1 over here.

Let us say this velocity is therefore, the velocity with which it is moving is v_1 and the condition is ρ and t . Well I need to be able to solve this equation for v_0 and v_1 . Therefore, I just look at the energy equation, but we have already derived the energy equation for a shock wave. What was the energy equation for a shock wave let us first put the picture together. We had a shock wave, we said that the conditions they are ρ_0 h_0 t_0 , we had the conditions behind the shock wave.

The shock is the equations were written in the frame of reference of the shock wave. That is the observer on the shock that means the conditions here are ρ and t over here. What did we have in this case, we had h . Let us put the same notations down let the velocity be b_0 let the velocity be b_1 here, we had h plus v_1 squared by 2. This is from treating this as a controlled volume is equal to h_0 plus v_1 square divided by 2.

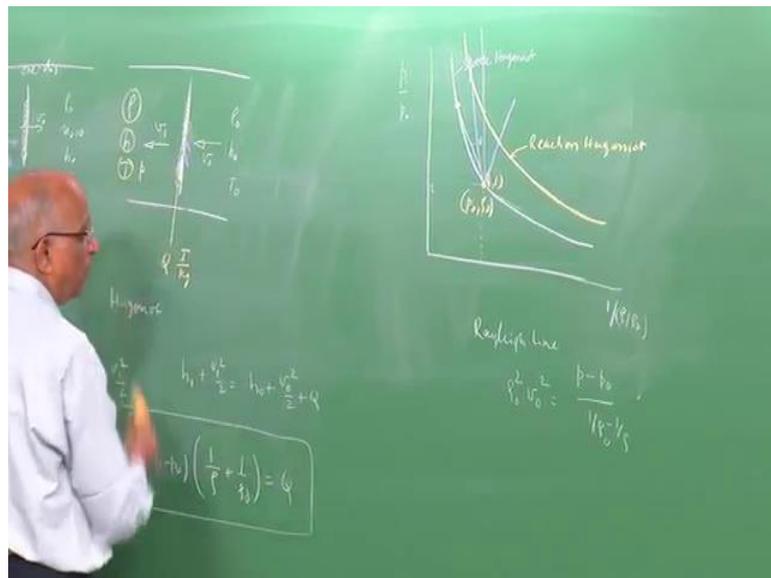
That is the enthalpy and kinetic energies balanced across the particular wave and why did we do this, we defined a controlled volume and in the frame of reference of this we wrote this. In what way this equation is going to change from here. Well in this case you just had shock front no heat was generated therein, but now I have heat being generated

and therefore, my equation now becomes $h_1 + \frac{v_1^2}{2} = h_0 + \frac{v_0^2}{2} + q$ this is per unit mass.

This is per unit mass per unit mass or unit mass over here. Therefore, if I were to solve this equation, if I were to solve this equation what did we get maybe let us put this equation through what did we get from this solution. We got $\frac{p_1}{p_0}$ by $\frac{p_1}{p_0} - 1$ into p_0 by $p_0 - 1$ brought it to the left hand side. I had half into $p_1 - p_0$ into $1 + \frac{1}{\gamma}$ was equal to 0. You will recall this is how we solve this particular equation and now when I solve this particular equation what is it I get well I have a term on the right hand side.

Therefore, this becomes is equal to q well this is the governing equation. Now, what did we call this equation which was equal to 0 we called it as the Hugoniot and what was the plot of a Hugoniot like let us plot it again.

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The plot of the Hugoniot was p by p_0 . As a function we plotted volume ratio that is v by v_0 one over v by v_0 . We said well the initial point is p_0 that is p by p_0 is 1 for the initial point the value of v by v_0 is 1. This is my point one and the equation this when it became equal to 0 we called it as a Hugoniot or rather the shock Hugoniot. This was the equation which I got we will call it as we called it as shock Hugoniot. Now, what has happened to this equation, have added a queue to it that means it now it is our shock instead of having a shock alone.

I have shock in chemical reactions chemical reactions are giving an energy q joules per kilogram. Therefore, this equation get shifted up by q and therefore, I have this is my equation over here. This becomes what we call as the reaction hugoniot. You know let us qualify this a little better, now that we have understood the problem. You know we are looking not only at a shock wave any wave which is travelling. If I have a wave which is travelling and let us say I look at the conditions upstream and downstream of the wave.

I related by the hugoniot equation now when chemical reactions occur behind the wave, some heat is getting released q and therefore, instead of having the hugoniot over here which I called as shock hugoniot I clock in terms of the reaction hugoniot. Now, what does the reaction hugoniot what does it give. It gives states which are behind the wave that means it tells what is the density? What is the enthalpy? What is the temperature? What is the pressure behind the wave as a function of the initial condition?

That is the initial condition is 0 and row 0 which corresponds to the point one by one. That is from the point one my the conditions should be along this because this is the conservation of energy as applied as a control volume is applied at the point of a detonation. Therefore, my final state should invariably be along this curve somewhere over here. Somewhere along this, but I want to know the precise location on what the shock hugoniot gave.

For a shock the final states were over here, but how did we get the state for a particular velocity, well we had the rally line. What was the rally line you recall we had the equation row 0 square onto v_0 square is equal to $p - p_0$ divided by $1 - \text{row}$ minus $1 - \text{row}_0$ minus $1 - \text{row}$. Therefore, we had something like velocity given by the rally kind and we plotted the particular rally line for a given velocity.

That means we said rally line is proportional to velocity we got the end state over here. So, also when I have chemical reactions occurring behind the wave. Well my final state is along this therefore, I should be able to plot a series of rally line. If I were to say my velocity with which my detonation wave is travelling is at this particular velocity. Well it could be here if my detonation wave is travelling at this velocity maybe it is over here.

The slope of the rally line gave the velocity or if it is at this the final state is here and therefore, I should be able to use the reaction hugoniot, to be able to find out what is my final velocity provided I can specify the particular velocity. Therefore, let us go forward

the expansion solution. In other words we find well a reaction hugoniot can give both the compression solution and the compression is associated with a shock.

I have something like an expansion solution. An expansion solution is associated with a flame we said there is a small drop in this. Therefore, this zone corresponds to a flame or a deflagration. This corresponds to a detonation in the zone between the vertical line and the horizontal line. Well you find that the pressure has increased, but the density has decreased. How can pressure increase and density, you know that means in terms of pressure there is compression.

In terms of density there is some expansion, well it is clearly not possible. Therefore, this zone cannot exist because it gives contradictory, the density gives a contradictory picture the pressure gives a contradictory picture. If I were to put it in terms of the rally equation I get the velocity to be an imaginary number. Therefore, we find that in practice only the zones in this zone it is possible, in this zone it is possible.

The zone between this is not possible a region not physically possible. Now, we come back to this particular location. Let us plot the velocity. Well I have the velocity over here tangent over here. Well this gives me the minimum velocity I also have the maximum velocity for a flame over here. Therefore, let us say the point is over here over here upper point over here. I have a lower point which is tangent over here. Mind you we have been plotting tangents earlier also maybe from the initial point, I have the shock hugoniot, I have the reaction hugoniot I plot this tangent.

Therefore, I have a region between this to this. I have a region between this to this. I have a region between this point and this point over here and between the tangent point over here.

That means I get an upper tangent point which is minimum velocity. I get a lower tangent velocity which has maximum velocity. Therefore, is it possible for me to have detonation for different velocities in between these two, is a question I would like to ask. Therefore, in the next class what I would do is, I will take a look at the different regions of the compression solution. Different regions expansion solution, characterise the tangency points which we will call, we will see a steady state detonation is possible under this conditions as chapman jugs points. Then get the properties of a detonation wave.

Well, thank you then.