Gas Dynamics

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Module - 15
Lecture - 32
Supersonic Jet

Hello everyone, welcome back. Till last class we were discussing flow inside the nozzle, and as we looked at the discussion, we did not complete the full range of P b by P 0 values we could go to, and we said that we will deal with the remaining later.

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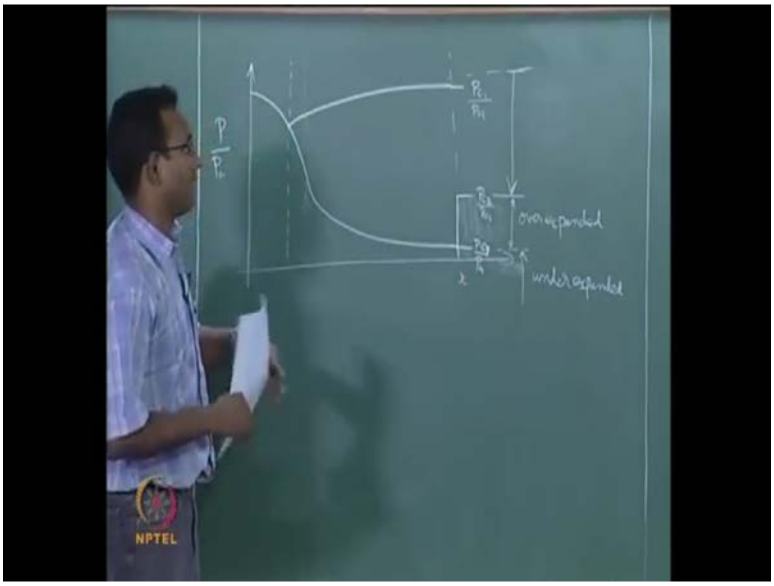

If we looked at that particular plot of P by P 0 1, plotted with x and we say this is my exist plane, this is my throat line, we did this and it went up, I am not drawing it really nice to scale. May be, I will make it a little better, it looks more like this. And we said that if there is a shock at the exit it will be here, this is the throat condition. So, this is my P critical 1, P critical 2 and if it comes out straight here P critical 3, we did all this and then we said that, if I decrease my pressure below this value, this particular region is called under expanded region. If it is in this region, it is over expanded region and since, previously we were interested only in pressure profile inside the nozzle, we said that anything below P critical 2, my pressure inside the nozzle distribution will never change. It will always be this particular curve, we said this and we were seeing plots of it also and we discussed what it will be if P 0 is changing and keeping P b constant etcetera, those are all just variants. Maybe I can change both, maybe I will increase both or I will decrease 1 increase the other whatever I can do so many variants of it any of them, I can do. If I think about those variants everything can be normalized to P by P 0 1 and it will fall on this particular curve.

Now, we said up to here we have solved a problem from P b equal to P naught, all they are down to here. We have solved and I also gave you very special case that if P b equal to P C 3, then also I can solve it critical 3 that is the flow is fully supersonic and it comes out also as supersonic jet that also we discussed. We were left out a huge range of pressures here just below P C 2 all the way down to 0 pressure value which may be very low and expect for this one point P C 3. We have missed a whole range of regions and we called this region over expanded and below this region under expanded, over expanded and under expanded Jets, I called the nozzle is such that when it comes out, this region is over expanded and this region is under expanded and we said that only change will be outside the exit plane of the nozzle.

So, up to from P b equal to P equal to P naught 1, till P b equal to P critical 2 everywhere this is what is happening. I am confusing, here it should be P critical 1 divided by P 0 1 here, because I am plotting P by P naught 1 as my axis, it should be non-dimensional Zed everywhere anyways. So, if P b equal to P critical P equal to P naught 1, all the way to P b equal to P critical 2 everywhere, I have already solved this and we know that up to P critical 1, there will be no shock inside completely isentropic after that there will be a shock inside and after that it will become subsonic and It will raise up to that pressure. And there will be a point where the shock comes to the exit, after that we said there is no change inside the nozzle.

Now, we are outside we want to solve for this region, this extra region here. Over expanded cases, I already told you the change is only outside. So, we are going to talk about the jet coming out from the nozzle. From now on, we would not consider whatever is happening inside. It is all done all old history for us. We know how to solve it. We already solved 1 example numerical problem also, we will say that is easy to solve. Now, we will look at the remaining portion.

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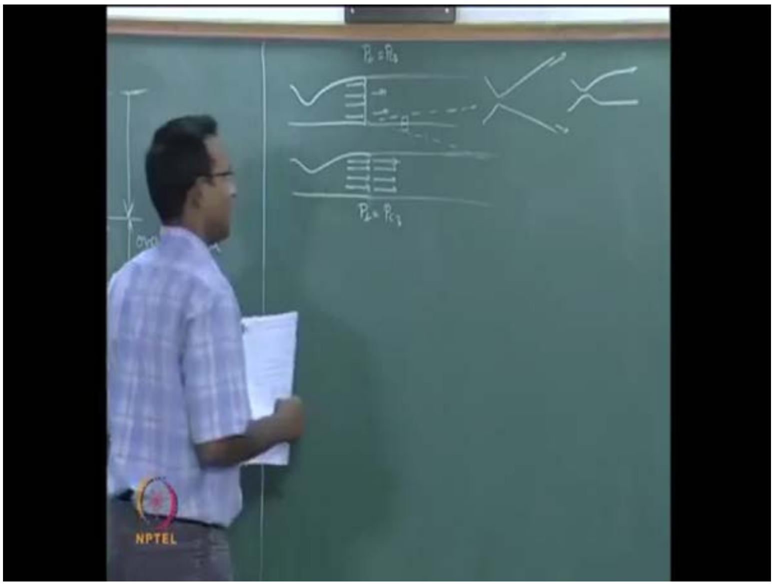

I want to look at some nozzle. We know we are solving it 1 d. So, I do not need to worry about shapes being symmetric or anything, it is just 1 d problem. This is my exit plane and if my P b equal to P critical 2 P c 2. Then what will I have? I will exactly have a shock at the exit and the flow will be just going straight. I have also done one more thing in my drawing this nozzle very carefully.

I have drawn it such that the flow is going to be 1 angle only. I have made both the edges parallel to each other. Otherwise, if I have a nozzle that is more like this. Now, the flow here will go this way, flow here will go this way. I do not want to be thinking about 2 d problem. So, I will not be worrying about all this, I will just assume my nozzles will look more like this. Exit will be always parallel. If I think about this, I do not need to worry about that particular aspect of naught 1 d kind of thing. It is always 1 d in my opinion we are solving only 1 d gas dynamics as of now.

So, my jet is going to be just parallel to whatever is incoming expect for before the shock it is supersonic. And after the shock it is subsonic, exactly same mass flow rate that you know. So, it just goes out as a straight jet and we assumed one more special thing we are inviscid gas dynamics. So, there is outside air and it is stationery and this gas is going with some reasonably high velocity. I have to draw arrow such that these are longer and these are shorter. We know high speed flow becomes low speed flow here and the pressures are matching exactly.

So, no fluid element is going to push the next fluid element, pressures are equal across these 2 across this line. So, this fluid element is happy that this pressure is the same as this. So, no force exerted or both are equally applying force one against the other, nothing goes wrong, nobody is able to push against anybody both are equal force. But, we are neglecting this aspect of, this fluid element is moving fast and the other fluid element is not moving because of that there will be this abrasion, the shear which we are neglecting here, currently we are going to say there is 0 shear stress. We are going to assume inviscid flow, because of which this jet will just be a straight jet without any question, no trouble, life is very simple for the jet. It just has to keep going straight forever.

Why is it just going straight? There was some region where there is high mass flow rate injected into some region where there is no flow, that region where ever there is higher mass flow will just keep moving like that. In reality, there will be some viscous shear stresses developed in this region. So, this region will become slower, this region will move faster. So, you are going to develop this whole dotted line region is called the shear layer region where there is shear force is important, I said important, I am using careful words even other places there will be shear stresses. We can neglect it compared to other forces like inertial forces that is the only way for this, anyways that is too much of fluid mechanics for today. We would not want to go there, we will still assume inviscid.

The other special cases, I have this nozzle and I am having P b equal to P critical 3, if this is the case again, there will just be a straight jet going all the way straight, no troubles, same area as the exit area everywhere and we said inviscid flow is just going to go straight, the only difference now will be whatever is the velocity here at the exit it will be the same value here. Why is it the same value? I go back to this curve and I see there is no change between P C 2 and P C 3 up to exit, it will be the same here. So, I am going to say and there is no shock at the exit, this time it will be same on the other side.

Ideally, I am supposed to draw all arrows exactly equal length, it will be the same velocity here also and it just keeps going forever like this. While in this case, that velocity vector has decreased in length when it goes across the shaft, it should decrease much more than that, if you think about it but it decreased at least for a moment.

So, what happens in between this case and this case. Let me erase all these disturbing things. The shear we will assume is not here for now. We will get back to this after finishing jet flows. We will add shear to the problem after that, I will remove these 2 fluid elements also.

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So, if I look at this, I have this at P critical 2, I have this when I decrease the P b to P critical 3, in between what happens is our discussion for now. What should happen here? The pressure is low across the shock, pressure becomes high we said this flow is over expanded, we will go back here. Why did you call it over expanded? Because, the fluid at the exit of the nozzle is at a lower pressure, it has expanded too much inside the nozzle compared to whatever we expect, say I want this line here, I expect this pressure though it has expanded too much to much lower pressure, that is why it is called over expanded. It will be very confusing when we go to propulsions and you talk about a rocket is going up, pressure is decreasing outside but I call it going under expanded operations, it will be opposite if you think about it but actual explanation is coming from the point of view of fluid sitting inside at the exit of the nozzle, that is the only way we define this over expanded or under expanded. I am going to say this fluid is much more expanded than what is needed for the outside world.

So, currently it is over expanded condition that is what I am going to look at. When I look at it this way, what should I need to make the pressure to go up? It should be a set of compression waves and typically, we will say that compression waves bunch together and form a shock. We will keep it that way for now. I have not given you complete proof yet. We will go to the shock tubes and deal with that wave, that is towards last part of the course probably.

So, we need some kind of a shock, if I think about simplest thing say I am very close to this P critical 3 and I am increasing my pressure here slightly. What kind of shock should I have at the exit? Only thing possible is oblique shock, there is no other choice for you. Why? If it is a normal shock that is the other possibility you have, if it is a normal shock then it is too strong and it will make it to go to P critical 2, that kind of exit pressure. But, we want much lower than that, we want pressure lower than this but more than this, that kind of intermediate value. So, I cannot have a strong shock like a normal shock, I can have some other shock. We can have so many other combinations, we will just think about simple situation right now, so an oblique shock.

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So, I will draw a case where my exit will have an oblique shock. Can it be an oblique shock like this in my jet? This oblique shock will meet the pressure that side by the way, if there is a oblique shock like this. What will be my flow direction? Which way? Will it go down or up? Fluid will go down, if there is a shock like this then my jet will be doing this. If my shock is like this, how do I know this, go back to the fundamental problem we had. If I have a wedge like this, my shock will be like this, it goes like this and it turns this way, that is the same region, this region is what talking about here, that region if I think about it that way.

If I have an oblique shock like this, then the pressure here will be same as the pressure in the back pressure. Is this the correct flow situation? Direction is what, direction has changed as in it should be other way you are saying. Direction of the jet should be straight you are saying, that it is not the most important way. I want to look at it. But, yes final correct thing will be direction of jet should be straight but not right now there is some other mistake here. What is the mistake? At the bottom line, the pressure here is same as the pressure here, there is no shock here, which means the pressure here is same as exit pressure.

But, outside world we told is P b greater than exit pressure, that is why it is under over expanded jet, it is expanded too much compared to this which means this pressure is lower, which means currently I have a layer where pressure here is higher. I will draw with h pressure, here that is lower pressure, this is higher pressure. What will happen naturally, this fluid element will push that fluid element up, along that border there is unequal balance, one guy is pushing less, other guy is pushing hard then the boundary will move. What does that mean? This last fluid stream line is going to turn inward. We said this fluid element turns this way, why for the same reason that side? So, it formed the shock now, I am going to say for the same reason here, this fluid element will turn inward and for this to happen there should be a shock setting. I will draw it much more clearly.

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Now, I am going to say this fluid element wants to turn this way, to make it happen there will be a shock like this that is supposed to happen. Now, that it is getting too much confusing. I will draw this nozzle with red only near this portion. So, this white thing is my shock and both the fluid elements have turned inward which means now my final streamline, the jet boundary that stream line is going to be turning inward. What does that mean? My jet say I think of that jet has 1 slab of fluid here, that slab of fluid as it goes in is getting shrunk, is that logical? Is that suppose to happen? The slab of fluid when it is coming out, it is now getting shrunk concise. Is that logical? What is the reason for it? No reason. What is the reason? Why should it be shrunk? Because of exit is not very clear, because of increase in pressure, because of increase in density. Yes because it is getting compressed. That is the idea of the shock anyway, to make the pressure go higher, because to make the pressure go higher, it has to be compressed.

The size of the slab also should be lesser as, I go there right. I am thinking about 1 slab of fluid going like this. It is increasing in size as it goes here. Why does it increase here? It is expanding, it is increasing in mock number and when it goes here, it suddenly having change in size here, all this time we talked about one mock number at each location axially, after exit I cannot talk about that, why because the 2 different problem problem. I have introduced a 2 d component here oblique shock cannot be a 1 d problem, it is a 2 d problem. Now, I am going to talk about inside here, 1 mock number above the shock there is another mock number, that is the best I can do now, it is already 2 components at every section.

So, the idea of this is this. Now, I say I increase my back pressure a little more. What happens? The shocks have to be a little more strong, the shocks have to be strong. I will draw the picture again here separately. This is my nozzle looks like my chalk writes very thin. May be, I will draw this with white only, just I can manage. It will become lot more strong and the jet boundary will be shrinking faster. That is what you have, if you think about the case before this must have been this, where the normal shock is there, jet is going very straight.

Immediately, after that if I decrease pressure some more, it jumps to this case where it is shrinking a lot and then when I decrease further, it goes to this case where it is slightly expanding and eventually it will reach this case. How does it reach this case from here? I keep on decreasing my pressure, back pressure it is going to tend to P b 3, P c 3 eventually. Back pressure is somewhere here, I decrease back pressure, what should happen? Here my oblique shock should be less angle beta will decrease. When will it become this case do not talk about P b.

Now, tell me something about the beta. Beta will not become 90 degrees, beta will not become 0 that is why I asked this question. Beta will go mu, the mock angle that is the weakest shock you can ever have. Beta will become mu that is the specific reason why I ask this question, in fact if I draw that particular beta here, it will just become that mock wave which will just tell the fluid not to change anything. We always talked about mock wave as a wave that says stay as it is, do not change, do not increase pressure or decrease pressure. It is a wave that says do not change anything.

So, all this time it is telling compress, compress, compress, if I increase my back pressure, it tells compress more or compress faster, then I go decrease it goes to a point where it says that do not change. There is the point where it will say do not change, this whole sequence happens in here. Of course I have not drawn it the correct way, this picture should have been in here, that is the full normal shock. It becomes high angle oblique shock to a lower angle oblique shock to eventually becoming mock angle. This is the whole thing that is going to happen. As I decrease my back pressure, it is going to tend to this finally. We will talk a little more about this between this last picture and this picture after sometime. We will look at what happens in this region? We will draw much bigger picture now.

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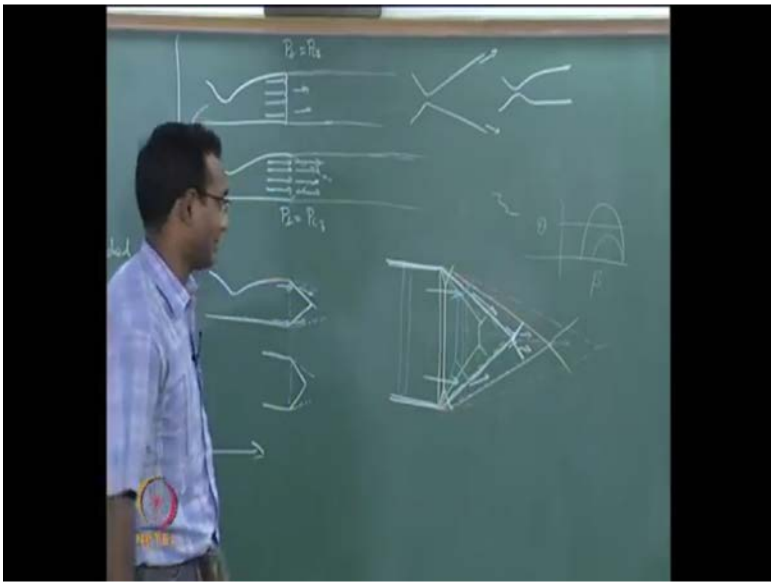

This is my full nozzle now. This is my full nozzle and I am having an oblique shock from both sides. I just wanted to draw it slightly wavy so that, you remember this is a shock ideally you should just draw straight lines because in real life it is a straight line. When you see pictures from experiments, it will be a straight line really. Now, fluid element here is coming at this angle and because of oblique shock it is turning like this, same thing here and it is turning like this.

So, my jet boundary is going to be parallel to these vectors post shock vectors, something like this and you can say that the jet that full slab of fluid which I think about somewhere here has now shrunk to this size here. Of course, I am assuming that the slab does not get distorted. Actually it will get distorted, we will ignore that thing, it just looks like it shrunk. Of course, here it will be more like this, it will be dragging slowly the slightly behind, we will ignore that part right now. What happens after this point, they are both going to crash into each other if we look at the velocity vectors here and here they are going to be crashing into each other, that is not allowed.

We already talked about this problem. We said when there is 1 shock that is right running, 1 shock that is left running. Now we have talk about what happens when they interact, what should I satisfy downstream of the point? Pressure and velocity direction, 2 conditions, always those 2 conditions in supersonic flow typically, these are the only boundary conditions, pressure and velocity direction condition.

Now I have to think about drawing some line, I would say on this side of the below the line all the fluid from below will go this side, above will be all the fluid from above. Typically, if it is a symmetric problem that will be the line of symmetry anyway since, fluid mechanics has lot of line of symmetries, we will just keep it line of symmetry as the horizontal axis for us. So, the fluid that is coming at this angle has to now turn back to become parallel to this axis, to do that there will be another oblique shock, then the flow here will go straight similarly exact symmetric problem.

So, I will just go this side of course, it looks like I have not drawn the jet boundaries symmetrically, I will adjust that and then this side also, it will go straight like this, this is for a simple system. Now what if I increase my back pressure a little more, what will happen if I increase my back pressure? This angle will go increase higher. Let us say I will use, I have one more color here I will use green, I think it will work, I will draw another sharper shock, if this is the case then it is a stronger shock which means the jet will shrink much faster. I am drawing everything on green on top of the other one, something like this and these shocks now we will send the flow more strong against each other.

But, remember longer oblique shocks will have much lower mock number downstream of it. So, the mock number downstream is lower compared to the previous downstream mock number and the angle that it has to turn by is now higher. A weaker mock number flow has to turn high amounts, sometimes there will be a point where it will not be possible for it to turn by a attached shock. What happens at that point? We will go cross that theta beta M curve, if this is a weaker mock number and I want this strong thing to happen, it has crossed. So, what happens in that situation? It becomes a mock reflection, that is what I want you to think about now, since I have introduced you to the other simple thing now you can think about the mock reflection along this dotted line, there is going to be this mock reflection happening out there.

So, if I go even higher pressure, I have 1 more color, I have so many colors here today. I will just use all colors. So, I take blue and draw 1 more, now I do not need to draw the angles, vectors everything you know. I will just draw the new shock point, new shock will look more like this and if I have 1 more color, if I draw 1 more slightly higher P b then I may have this, if I increase any more, let us say I reach my back pressure original P c 2, then if I will just have 1 straight shock out here.

So, if you look at it shock is doing a continuous change. If I think about P c 2, my shock is sitting on the exit like this. If I decrease it slightly, normal shock is almost normal shock most of the places, only some portions it is oblique shock which means only those regions the pressure is lesser, other regions it is roughly the same as this original whatever exit pressure. So, on an average this fluid element has shrunk, this slab of fluid has shrunk on an average. When I decrease pressure more, it needs lot more change. So, it goes to a point where the more of oblique shock is happening, less of normal shock is happening and it just continues like this.

Eventually, there will be a point where there is no more normal shock, the whole thing is oblique shock and beyond this point I keep on going, let us say. I will again start using colors, I go again and I will start using orange. I will go in the same order, if I decrease pressure further then my oblique shock may become this, this will be a point where if I decrease further, my oblique shock will become so weak that it will be just a very weak wave, my mock wave. This whole thing happens as I go from P c 2 to P c 3. The whole sequence goes through this whole sequence, someday I will show you a video of this whole shock moving slowly out and forming this X like shade. It is a nice thing to see, it is fun to explain. It is better than just watching it anyways.

So, this whole sequence happens, during this whole time what happens to my jet boundary, more difficult question to ask. At the exit, if there is a shock then we know it is like P c 2 here, it is just going to go straight, no change. When it is just a small shock in that small region alone what should happen? I will take that small region and draw it better so that, you can see what is happening there.

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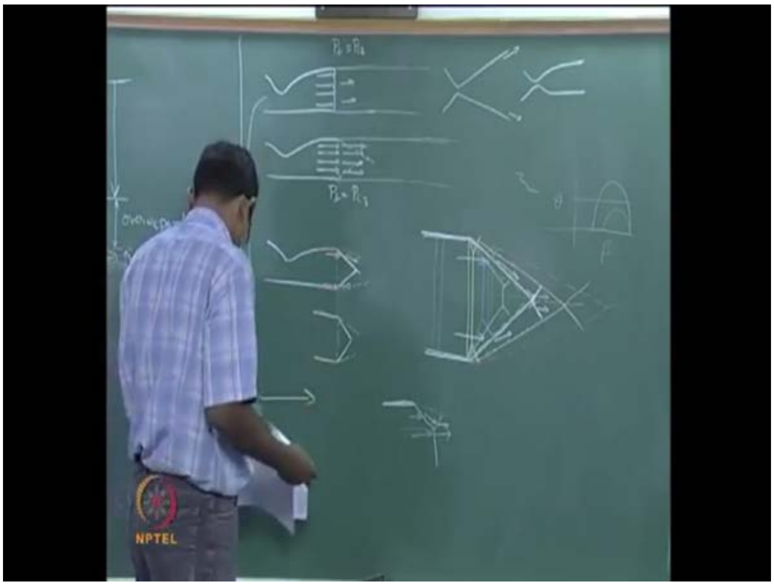

This is my nozzle exit edge, 1 edge only. I am showing there is a shock and that is reflecting like this with a normal shock. Here if this is happening there locally the fluid boundary is this. I will erase the extra things and below this line, fluid is just seeing a normal shock. It just jumps like a normal shock. The remaining region is going to come straight turn like this and go like this.

If you see this beauty of nature being symmetric or very continuous, all that is same here. When we discussed before we said that when looking at all these pictures, we said that it was going straight, suddenly it went to shrinking too much, it shrinks lesser and lesser becoming parallel again, that never happens in nature. Nature is never discontinuous you think about it. What is really happening is between this picture where there is a shock at the exit, to an oblique shock, there are so many of this sequence orange, blue, green like that, where it goes slowly from being straight to a little bit of curved, a little curve and then when this goes more to a blue, It will be a lot more and when it goes to green, it will be a lot more.

Eventually, there will be a point where it will become something like this then it will go along with whatever we already thought about. So, it is very continuous. Nature does not like discontinuities there is always some mechanism in nature which gets rid of any discontinuity in life. Similar to it does not like any singularities, anyways, that is 1 part of the thing.

How do I think about this in another form. Why do I? I have drawn all these shocks but I said that specifically I have drawn this particular shock it bounces off this way as a mark reflection and I stopped drawing the shock just outside the final stream line. Why did I do that? That is the next question. I am slowly getting involved in every detail of the problem.

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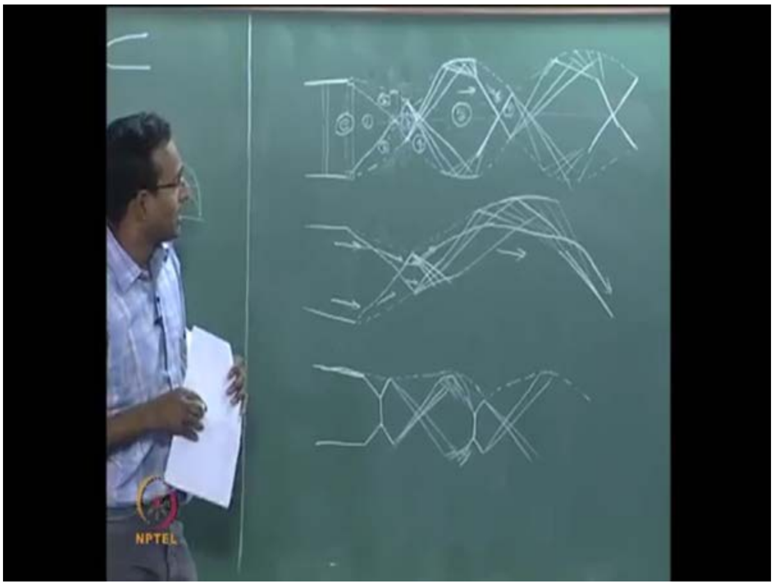

So, when I look at that, the way I want to look at it is I will take a simpler case where this is my exit plane and there is an oblique shock. There is another oblique shock and I want to think about it as each of these shocks are some wave which is carrying a message, this is how we did it in 1 d shock moment, moving shock problems. We said if I suddenly close the door at the end of the pipe, the shock travels telling the pipe closed that kind of thing. Currently, what is going to happen is there is a slab of fluid, it is coming with some reasonable velocity and suddenly you are seeing when the slab comes to the exit, this corner is seeing higher pressure. Why higher pressure? It is over expanded jet, this is over expanded compared to the outside world.

So, this pressure is higher than this inside. So, it is seeing a higher pressure, what is it? It is suddenly pushing, it is like a piston suddenly pushing against the fluid slab way. So, there will be a shock that is forming and what is the job of each of these shocks formed? They have to go and tell all the fluid that there is a pressure jump there, any wave created has to be telling information to all the fluid element as much as possible till it loses its energy. It will go and tell it is not lazy, life is very nice for those people because our messengers may take break and all they do not. They just go continuously, no stop till they lose all their energy they just keep running.

In this slab, it just has to run straight from that corner to this corner because that is all the fluid that is having this action. So, what will it do? From that point, it has to go all the way through, it cannot stop half way. Why cannot it stop half way? This fluid came to know that the pressure has to be increased, this fluid also came to know that the pressure has to be increased, because this guy went up all the way by the time I reach here. The same fluid slab when it is here, both the shocks are at this location, 1 is running this way other is running that way.

Should I stop there? They do not know, messengers are supposed to be purely messengers, think about it. They cannot think for the kings, they are supposed to carry the information and tell everybody in the whole world. They are not supposed to be thinking half way, they just do their job, they are just going go cross and just keep telling increase pressure by so much, increase pressure by so much. Because of this what happens is the shock continues pass that point and here also the shocks continuous pass this point. So, you go to a point where that fluid slab of course, it has shrunk in size. I did not draw the jet boundary line. So, ideally the fluid element has already shrunk in size to something smaller. Because they all obeyed the messenger, remember their life is very ideal in nature world, everybody obeys the kings orders.

Everybody just does their duty without taking rest, in the middle all that these messenger do not take coffee in the middle, some where they just keeping running across all that very nice job and finally, there will be a point where this shock has gone all the way to the end of that fluid and just stays there and tells the pressure has to be increased. All this point after that also the fluid element that shock sees that there is a fluid outside. Ideally, it wants to go and tell them also, all it is supposed to do is, if you see a fluid tell it to increase pressure. It is doing very well till here, when it goes outside that guy sitting outside the boundary condition, is very adamant. Boundary condition guy is the atmosphere, it is going to say whatever you tell me I am not going to change my pressure.

So, what happens suddenly is that messenger is going to be pulled out, somebody else is put in that place who is going to say decrease pressure so that, the pressure will be the same at that point, only for that 1 point the boundary point, there is a exchange of messenger suddenly. Now, what will that messenger do? He has to run, he will again start running, he is going to say decrease pressure by so much and typically it is done by a whole bunch of expansion waves and they do not go all together, they are now like a shock, they each individually.

So, there will be a whole set of fan of expansion waves running out, they are going to go run this way and similarly, the same thing is happening on the other end and they will also send out an expansion wave fan like this. It will be a whole bunch of expansion fans created, 1 from this end, other from that end. They are created and they are going to run across. Why? All because I will label the regions here, this is 1, 2 this is also 2, this is region 3 and E is same as region 1, there is no change here and from 1 to 2, the pressure has become equal to back pressure, that is the idea of the shock, same thing this side same equivalent shock here and then because the shock is continuously going pass that point, their pressure increased from 2 to 3. 3 is above the back pressure because atmospheric pressure gas is processed by a shock. So, it is going to be higher than that pressure.

Now, this higher pressure is not liked by atmosphere. So, it is sending out an expansion fan to decrease that pressure. What is going to happen? I already told you the flow vector direction. I will draw 1 more picture parallel. I do not want to disturb that picture. I am drawing velocity vector here and I am showing you region plot and pressures I am describing, here flow velocities are parallel, It is as if this jet has been shrunk to a smaller size jet here. I will come up to that point, jet has become smaller size jet and they are going parallel out like this and when the jet comes out of this point, the very first point when the jet like thing comes out immediately. It is seeing pressure outside is lower than the pressure inside, that is another way of looking at the same place. 1 way of looking at it is the compression wave comes here and sees an adamant atmosphere boundary condition, it says pressure cannot be changed.

So, the boundary is going to replace the compression wave, with an expansion wave at that point so that, the compression and expansion gets cancelled at that point alone they will be cancelling, everywhere else it is going to continuously expanding that is one way of looking at it other way of looking at it, it has got compressed and now, I have a new jet going out like this, as if it is a shrunk jet coming out and that jet, when it comes out immediately is it seeing the pressure here is higher than the outside pressure. What should it do, it has to expand?

So, there will be expansion fans here and the fluid element goes out. Of course, you know expansion also adds to it some velocity vector component. So, it is going to turn out so because of that my jet boundary is going to increase like this. I am not drawing both the pictures exactly the same but you understand the idea. I am not drawn the same expansion angles now because of this the region for here, it is also going to be atmospheric pressure region for here is also going to the atmospheric pressure and how far will these expansion waves run. They will run till it goes and hits the other boundary till that time no conditions so it will just keep on going till it reaches the other boundary. What happens when an expansion wave goes and hits the boundary which is again adamant?

It is going to say the pressure has to be fixed, expansion tells I have to decrease pressure. So, it will be replaced by a compression wave which will tell increase pressure. Why is it a compression wave versus previously It was a shock, this is just 1 wave, 1 expansion wave going, it needs to be replaced with 1 compression wave, while here there was a whole bunch of compression waves together coming as a shock. So, they all have to be replaced by a whole bunch of expansion waves together at that point and they are all running at different speeds.

So, they are separating, it is a way of thinking about it. So, at every point there will be a compression wave forming, there will be so many compression waves like this forming over all. What happens when a whole bunch of compression waves come together? They will eventually form a shock, they all come together and form a shock and this picture seems to be a little nicer to draw. So, I will draw this 1 here, this is smaller and I will draw my initial axis and It will form a shock lines, same thing will happen on the other side, they will all form a shock together. I think this picture is nicer than this picture. Let us just look at this one and again now I will mark my region 5.

Now what happens? All these compression waves came together formed a shock and that shock is running through it cannot stop half way, it has to go all the way till it finds somebody adamant who will replace them. So, they will keep on running again. What happens here the flow was going straight. I have to draw the angle this vector that is going up is now going, to see this expansion which is going to tell pull it that way.

So, it will become parallel again, going straight flow it is going to see the shock and it is going to turn down, that will happen here. So, my jet boundary will come in again. This will happen there. From now on I would not draw anything on the bottom picture, I will just keep the topic picture after this, what should happen shock goes and hits the boundary, expansion should start, if I look at it that same thing happened here, shock went and hit the boundary and immediately expansion started.

So, what happens is this whole sequence from 3 to. I did not mark this region, this is 6 and this is 7, 3 to 7, the whole thing that whole region, I am going to capture and paste it again there, take and paste the whole thing there. So, I will have that whole cell forming here, if I look at what is happening inside, it is a whole bunch of expansion fans turning back to compression, forming a shock and crossing to that side, same thing here. Whole bunch of expansion turning back to compression forming a shock and going to that point that whole sequence happens again. If I want I can label them again it. It so happens that if we are in very ideal world, the pressure at 3 and pressure at 7 will be the same, If I do not have any other loses, it will be exact repetition and it just keeps on going like this.

It just goes up, comes down, goes up comes down, goes up, comes down, if you think about it is like some new driver driving a car, they want to suppose to be drawing going along one straight line. If they got 1 disturbance, they will correct for it if you going here, they over shoot go that side and then they correct for it go this side over shoot this side, they just keep over shooting.

When they are very learned, they will start applying brains, when it is going closer that is not happening here, it always if you look at the center line, 3 is higher, it becomes atmospheric pressure somewhere inside this expansion, becomes lower jumps to higher becomes, lower jumps to higher, just keeps doing this. If I look at any other line I have drawn so many vectors here, if I drawn all of them connected together, it is going to like this. It is going down, coming back out, going in coming back out and it just going to some wavy fashion.

If you look at it here, it is going to come straight go in, go straight, go out, out, out, go parallel, go out, go parallel, go parallel up to here, jump in, come back straight and it just keeps doing this. If I look at this in those points there will be a small region, where the pressure is exactly correct, that is the pressure it had to achieve outside pressure it has achieved it even at 2. If I go along the centre line it, really never achieves. It just jumps up and down above that point expect through inside this set of expansions, somewhere near it has to cross it slowly, but every other point it just jumps up and down that is what really happens there will be a time when I will ask you a question, where I am going to put a pressure transducer as somewhere here and I am going to change my P naught in my nozzle, that is a beautiful problem to solve I am just leading you into that direction right now, it is a beautiful problem to solve. If you solve that problem you can solve problem of a cycle tube being punctured by the pin and put a pressure transducer outside. What will you see more practical problem to solve. So, much things can be done anyways.

So, we have come to a point where we have discussed to a reasonable extent, over expanded jets that is the cases were exist pressure is too low compared to the outside pressure, too much expanded, over expanded case and now, you can tell what happens if it is more special case of slightly less than P critical 2 only, then I will have a case like this, again the same thing happens here there will be an expansion fan and that will go turn around into a compression waves and form another shock and they will again have this jump typically and it goes through the whole sequence again. It will again have an expansion all that, I have not drawn the jet boundary.

Here If I draw the jet boundary it will be something like this and then it will turn down again like this. It is not looking very correct at the beginning but other things are all correct, just at the beginning it looks like this it is going straight, it should actually be coming from much higher heights, its roughly correct from here. So, if you look at it again starting from expansion till the shock, the whole sequence repeats after that only thing that does not repeat is the first shock portion, this particular thing is called the expansion shock cell, the same structure repeats again and again. They call it the shock cells, if we think about the temperature of the gas along the centre line. I will go back to this picture it is nice, if I think about the temperature of the gas along the centre line, 1 is high mock number, 3 is low mock number, 5 is high mock number, 7 is low mock number expansion versus shock.

So, I can tell if it is high mock number, it is low temperature. So, here it is low temperature, here it is high temperature, low high, low, high it just keeps going oscillating, what is happening because of that, if I have a hot gases coming in, the temperature becomes too high here that the gas starts glowing, this is the kind of glows you will see as diamond shaped glows behind your supersonic jets take off.

We will see that S R 7 typical pictures will be available on the web, if you want just go look at it taking off, you will see this diamond like structures just behind it which are glowing hot. Typically, they will be glowing orange, yellow, this portion will be glowing hot then the region 7 will be glowing hot, then 8, 9, 10, 11 will be glowing hot like that it just keeps going, in other regions will be cold. If you have such a case then it will be glowing differently, this you can see if you have if you ever seen a rocket take off. If you see a rocket take off, you will see this kind of situation where you will see this flat portion and then a glow behind it, again the same thing will repeat for 1 or 2 more times, this is what you will see if you are observant, you will also see one more thing this whole jet will keep on shrinking in size in real aircrafts. We will see that in next class. For now we will stop here under expanded jets, we will deal with it tomorrow and then we will talk about shear layers. See you people next class.