Gas Dynamics
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Module - 17
Lecture - 41
Rayleigh Flow, Numerical Example: Non-Isentropic Flows-. Various Choking Mechanisms in Compressible Flow, Supersonic Combustion Flow, Ram Jet Flow

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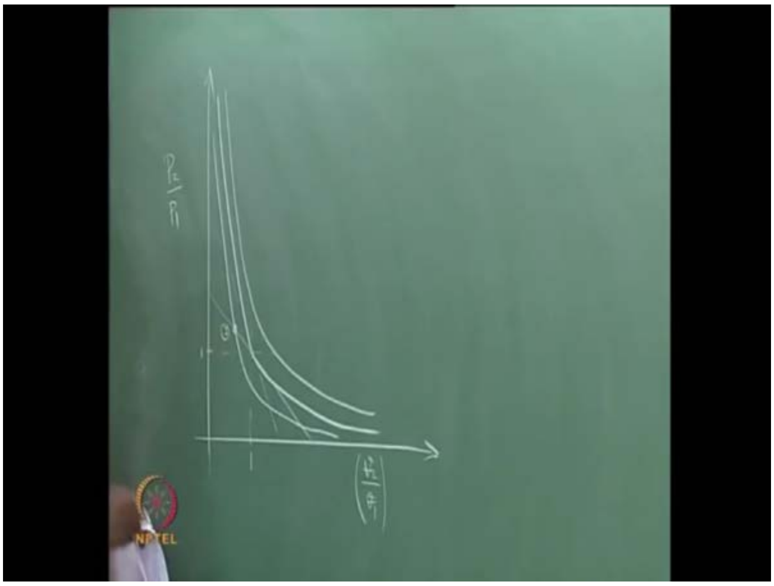

Hello every one, welcome back. We were discussing Rayleigh flow in p v diagram. We derived the expression for Rayleigh line and Hugoniot curve and I showed you the p v diagram for those. We said that these are starting point P 1, V 1; where the ratios will be 1 and we said if I have a Rayleigh line for a given mass flow rate, it will be given something like this, if mass flow rate increases, the slope will become much higher and it will look something like this. That is if my m 1 increases my slope is going to go from this one to a even more tilted one more vertical, that is what will happen? And we said if I have Q equal to 0, then I am going to have a curve through this something like this and if my Q increases, that is f I go Q positive, I am going to say it is going to go have curve like this or if I cool it, that is my Q is negative then my curve will go this side.

This is where we stopped last time and we found that the actual solution for the problem will be the position 2. We started at 1 and we have to go end with 2 the P 2, V 2 will be the intersection of these lines; Rayleigh line and the Hugoniot curve, if I cool with this particular Q value, then I will end up with this particular point state 2 for that particular beginning mark number m r. If I heat it, I find that I am not going to have a solution for that particular mark number. We will just see we will figure out what is happening in here in detail as we go.

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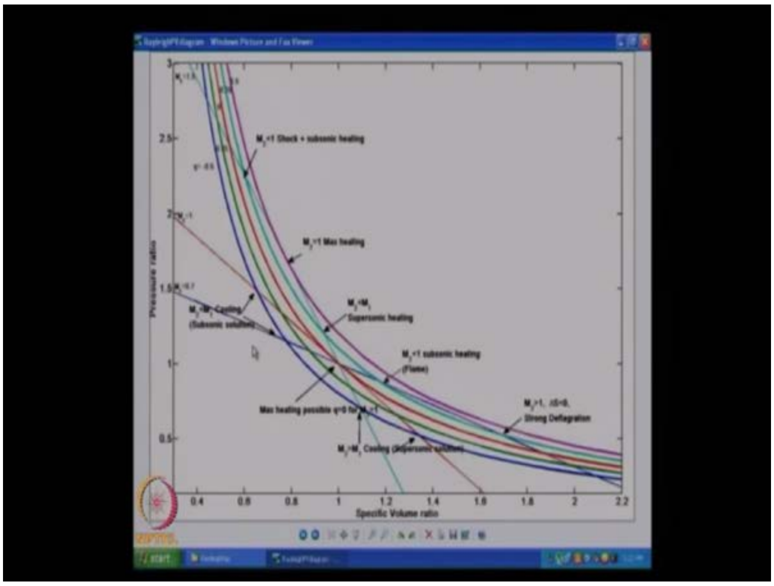

Now, we will go to the screen where I am showing some case, I am showing, so many things on this curve. Let us just look at things one by one. First let us look at these straight lines, these three lines I have, I am drawing it for three different mark numbers M 1 equal to 0.7, M 1 equal to 1 and M 1 equal to 1.5. I am drawing it for 3 and you can see that all of them pass through this point where pressure ratio and volume ratio are 1.

Because, these are starting point from here, the solution is going to go along this line in that way or along the line, this way one of these two it is going to be. Now, let us look at these curves, that we have these are your Huguenot curves for different q values. I am plotting it for q equal to minus 0.5 minus 0.250 that will be the centre and then plus 0.25 and plus 0.5. So, these are just some numbers we just need to think about it as q increasing or decreasing that is all. Now, if I look at the curve, let us say I want to start at this point and I say q equal to 0 lines. I am finding that the solution, that can happens to be if I think about a Rayleigh line for M equal to 1, then there is no other solution other than this what does that mean the flow is already at 1 and V 1 cannot go to any other P 2, V 2. It can just stay at P 1 and V 1 and nothing else.

That is all, it says if I do not add heat or remove heat there is no solution for M 1, M equal to 1, flow mark 1 flow does not like to change that is what, this says there is no solution for this is one special case. Now, let us look at M 1 subsonic, this blue straight line, if I look at that case if I think about the bottom curves, where I am cooling compared to no flow case and here, if I let us first pick no q case q is 0. This red curve along with this blue line, if I think about it, there is one solution that is at P 1, V 1, P 2, V 2 can also be at P 1, V 1 that is a possibility. That is trivial solution, there is no change in the flow or I can have another solution that is sitting somewhere here, which is a case that corresponds to M 2 greater than 1, while my M 1 is less than 1 and it. So, happens that this particular case has entropy change negative and that is not possible. This is corresponding to what we saw in our original b z t flows.

No, we said somewhere that we have strong sorry, sudden expansion there as it is like a expansion shock and in our flow, where p equal to rho r t is our gas law it is not going to be valid for us or delta S will be negative. That particular situation and. So, that, particular solution of the subsonic Rayleigh line cutting with this red curve for q equal to 0 is not possible for us, that is one thing. And on a supersonic side it does not go at all, because that is on the other side. It does not go at all there is only one possibility it says for q equal to 0. Now, let us pick up the same Rayleigh line that go to cooling conditions, simple enough to think about the solution goes towards higher pressure and lower volume. That is, it is getting more compressed, higher pressure and lower volume means it is getting more compressed that is, I am cooling and the gas is getting denser.

That is what is happening here and it. So, happens that these are corresponding to my subsonic solution and I am cooling, this if you go around Rayleigh curve, I am going away from m equal to 1, that is happening along this line if I keep on increasing my delta q it is going to go this way more and more and more and more cooling. It is go more and more far away from m equal to 1 and you can say that m 2 is less then m 1 and that is the cooling situation that will start happening that is one case. Now, if I go the same line on heating side, that Rayleigh line is going and cutting on slight heating somewhere here, where my pressure decreases and volume increases that is the gas has expanded. I have added heat and the gas expanded, this is our standard flame this corresponds to your flame solution typically they call this in combustion world, the deflagration this is your deflagration solution and there is one more solution out here.

If you and do the entropy calculations, you will find that it will be a strong deflagration as per combustion terms and that is your delta S less than 0 condition. Again that is not possible for our situation unless you have a expansion shock, these kind of things will not be possible, there will be a point where I can keep on heating and I will go to a point between this curve and the next curve there is a particular q value for which, this is tangential to it. That is the maximum heat, I can add to this system starting from a subsonic condition that is beyond there is no solution. If I add a heat higher than that for this magenta curve, I find that there is no solution possible, that is the system has reached it maximum t naught star and it cannot accept any more heat.

It has gone to that particular stage. Now, we discussed this particular subsonic initial conditions curve for now next we will look at supersonic initial condition m 1 equal to 1.5. This sine a curve, we will look at that curve, we will again start with the q equal to 0. Huguenot curve along with that Rayleigh line m 1 equal to 1.5. we find that, this particular curve can give a solution here p 1, v 1 equal to p 2, v 2 that is a possibility, which means it is a trivial solution there is nothing changing in the flow, no heat added nothing is changing in the flow, that is a solution or I can have another solution out there which is again, this is the condition. That corresponds to your shock normal shock, if you think about it that point happens to be your normal shock solution no heat added, there is just a sudden jump in solution, it is going to go m 2 less than 1 I am having m 1 greater than 1 and this will give you m 2 less than 1 solution.

That is your normal sub solution, that is possible here, that is your case there. Now, we will go from here to cooling condition again. If I cool this is going to be a green curve or the blue curve along with this sign wherever it meets, that means at this point or at this point or at this point, if I think about these conditions I am going to look at from here it is going to this particular point or at this particular point I am going to say that, if it is at this solution the mark by this arrow you are seeing that m 2 is greater than m 1. I started with m 1.5. Now, it is going to go above 1.5 this is going more supersonic I am going far away from m equal to 1, because of cooling. I am going away on the supersonic curve of my Rayleigh curve this time, what is happening in this condition and similarly, if I heat more it is going to go from this mark number to even higher mark number that is what is happening along this line.

Now, I will go to the other side where it will give me subsonic solutions, I add a little heat and I am going and sitting. It is going to give lesser mark number solution I do not want to say subsonic solution it is going to give me lesser mark number solution I add a little heat for m 1 equal to 1.5 I am going along this line and I added a little heat and I find that m 2 is less than m 1 but still supersonic this is I am going towards m equal to 1 from m equal to 1.5 along the Rayleigh line towards m equal to 1. So, happened that, I was lucky enough to get this tangential condition here for my q values. So, I just kept this number and this is the point where it is just barely tangential for that q value of 0.5 for m 1 equal to 1.5. I am getting almost a tangential situation that basically says that is the maximum heat possible and that particular point you will get m 2 equal to 1. That is, I am reaching the star condition on the Rayleigh curve that is going to happen for this particular q value for m 1 of 1.5 that is a special case here.

Now, I will go along this curve, there is another solution sitting here for a lesser heating, that corresponds to have a shock and I have subsonic heating, that will be the other condition. I have a shock followed by a subsonic heating that will give me this particular solution and these set of solutions. The top half of this set of two solutions on this curve and line if you find these set of solutions are what they call the detonation solutions this is just a shock with no heating. This is shock with some heating and if I add more and more heat, it is going to go to m 2 equal to 1 here, that is what you will end up with finally, if I add more and more heat it is going to go along this the solution will keep going along this curve. And finally, end up here, that is what you will get in this case. Now, there is one thing which I did not talk about but I already gave you the idea basically.

If I think about m 1 equal to 1 condition, this particular Rayleigh line at q equal to 0. I told you it is already tangential and there is no other solution for heating when I cool it. I can go either this direction and I am going to get m 2 less than m 1 the subsonic solutions along this direction or I can go that side and I can get m 2 greater than m 1. The supersonic solutions, that is I am starting at the star condition m equal to 1 condition right m 1 equal to 1 was this line when I start with m 1 equal to 1, I can go either direction. Now, I can go through a supersonic solution or a subsonic solution on my

Rayleigh curve basically, you have to keep in mind. The Rayleigh curve, when I am talking about this one then you can match these two things together, that is the basic idea of looking at this curve this is called the Rankin Huguenot plot and we can look at this as just simple p v diagram.

This gives you some set of information and we have t s diagram, which again gives you another set of information, both are actually useful, if you think about it, we looked at t s diagram where we said that, every solution goes towards m equal to 1. Now, we can also look at p v diagram, which we just did Rankin Huguenot plot where I will say I can look at it from different points of view. There are different solutions possible, there is subsonic solution, supersonic solution, some solutions are not possible etcetera there are. So, much variety and this gives you a little flavor for what is happening, when flow is heated of course, in all these I am not telling exactly at what mark number is the heat added to the system.

I am not telling very clearly where the heat is really added, I am just going to get this solution if I add. So, much of heat into this duct, any point inside the duct all I know is duct starts at 0.1 and ends at 0.2 and somewhere in the middle, the heat was added that is all I know when you look at this solution on the plots. We have, where we said there is a supersonic flow, there is a shock followed by subsonic heating I said it need not be that actually.

It can be a heating followed by a shock, also I do not know where heating is really happening. It is going to give that solution, if I give this much heat, that is a possibility, that is all I can say now and I have not really checked, whether this statement is true by doing numerical examples but I will give that as an exercises to you again that is heating followed by shock and shock followed by heating. I believe, I will give you the same answer for q is less than q star q max currently. I will just go for 1 numerical example, I do not have enough time in the whole course to give you more examples, I just give you one example for a simple case and I will give you more complicated problems in the exercise.

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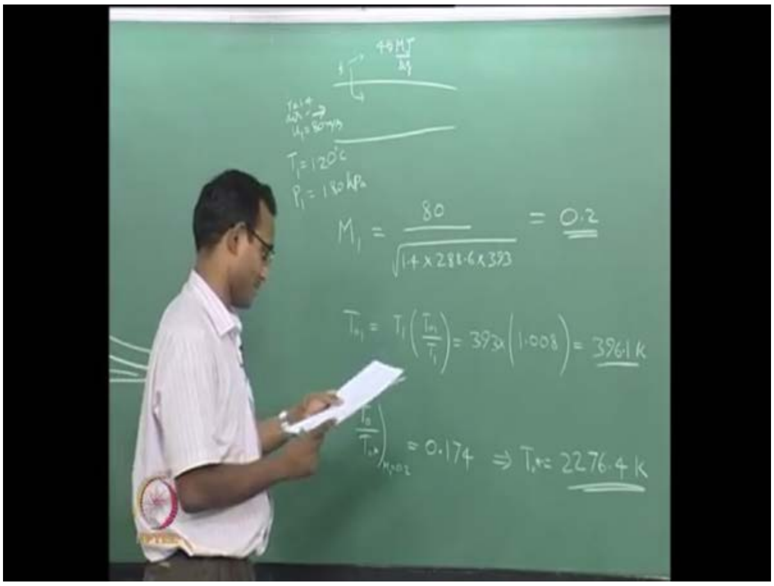

So, I am going to say we will start with combustors, I am having some combustor. It is having u 1 of 80 meter per second, T 1 of 120 degrees Celsius, P 1 of 180 Kilo Pascal, actually I am not going to use the pressure value does not matter for me. And I am having some fuel injected inside and it is burnt. Now, I am going to tell that, the fuel has a heating value of 45 mega joules per kilogram of fuel, if I burn 1 kilogram of fuel it is going to produce 45 mega joules and I am going to say this is air going in gamma equal to 1.4 air and I am going to assume that, because of combustion. The gamma does not change as I said in the beginning of Rayleigh flow assumptions itself. I am going to assume that in here, even though we know carbon dioxide has a different c p value than air, we will assume that it does not change much. So, we want to find how much fuel can I maximum burn in this particular flow situation. I cannot change the incoming conditions, I want to see how much can I burn inside this. Assume a constant area duct currently even though most combustors are not constant area duct, we will assume a constant area duct for this problem.

Then only I can apply all my Rayleigh flow equations here currently. So, how will I start the problem, I just have to find T naught star, I want to find maximum heat added, that is q q max I have to find which is related to T naught star minus T T naught 1. So, I need to find T naught stars for that. I need to know some parameter at the inlet easiest thing for us is mark number. So, we will find the mark number here, M 1 will be u 1 by square root of gamma r T 80 divided by square root of 1.4 into r is 288.6 into 120 Celsius is 393

Kelvin roughly. So, this is going to give me an answer of 0.2. I picked number such that, it gives nice number for now anyways. So, I need to find the T naught 1 from here.

Because, you want t naught star. So, t naught 1 is equal to t 1 times t naught 1 by t 1 is equal to 393 into 1 plus gamma minus 1 plus 2 m square or I will just go look up my isentropic tables for that mark number what is t naught 1 by t 1 that comes out to be 1.008 for gamma equal to 1.4 and this is going to give me an answer of 396.1 Kelvin that is my t naught 1 value. So, after this its problem again become very simple suddenly I am just going to find t naught star from here t naught star from here, I will have to go and look at Rayleigh flow tables for m 1 equal to 0.2 Rayleigh flow tables and find T naught by T naught star for M 1 equal to 0.2 T naught by T naught star for m 1 equal to 0.2 for gamma equal to 1.4 happens to be 0.174.

So, this is going to give me a T naught star value of 2276.4 Kelvin. So, the remaining thing is just finding out how much fuel can be burnt per mass of air, because we do not know the absolute mass flow rate since they did not give me area and the duct, if I know the area I can find the mass flow rate given this information I know density, I know u. I just need area, then I can find mass flow rate, then I can find the mass flow rate of fuel required I did not give you area. So, we would not calculate that right now.

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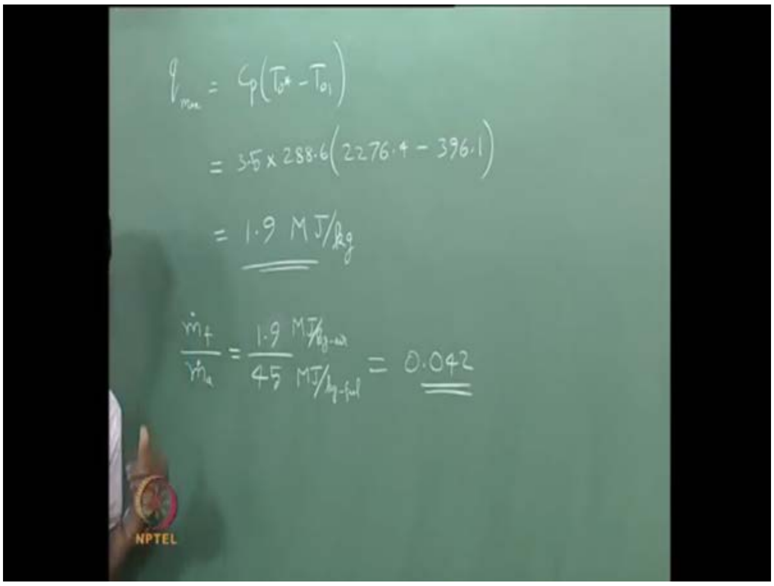

So, I just need to find q max T naught star minus T naught 1. So, you know c p is gamma minus 1 gamma by gamma minus 1 times r gamma by gamma minus 1 is 3.5 for gamma equal to 1.4 into 288.6 into those two numbers, 2276.4 minus T naught 1 was 396.1. So, this gives me an answer, I do not want to write the big number I will just write 1.9 mega joules per kilogram. Once, I know there is I need to find how much mass of fuel will give me this much of but there is one problem, what is this mega joules per kilogram? What is this kilogram weight? What this is weight of air? Now, I want to find how much fuel I can add, I cannot find the fuel unless I find the air. So, what I can really find is m dot fuel by m dot air.

This is all I can find really, if I think about it. This is going to be I want to have kilogram of fuel, I want to have that much heat produced. So, I will divide by the heating value 1.9 divided by 45. I will put the units. So, that it makes things clear kilogram of air here mega joules per kilogram of fuel. Now, you can see that it is coming out to be kilogram fuel by kilogram air units automatically, that is also one more check you need to think about and this number comes out to be 0.042. This is the maximum fuel to air ratio, that you can have in your combustor without having choking condition, that is you are having thermal choking coming up suddenly, because I cannot heat any more if I heat anymore what happens, I am going to have m equal to one forming and suddenly the flow rate decreases everywhere and it jumps to a different curve. Did I talk about that part maybe I would miss that. So, I will just go and do that one little thing just a little detail.

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T versus S curve that is a final a curve like this is for a particular mass flow rate, if I have a different mass flow rate, if I have a lesser mass flow rate, it is supposed to be an envelope outside, this it will be something like this. So, if I say that for a particular mass flow rate I have so much T naught q q max and I actually added more heat than this. Then the solution will jump to another solution and sit here naturally. So, I say, I started here my M 1 was initially here. Let us say and I added more fuel than this q max value, then immediately what happens is the whole flow field adjusts such that the flow at the inlet itself is decreased it goes to the next curve, and then now it goes along this curve to reach this point.

This is your final state, it reaches M equal to 1 it is going to be chocked but it starts with a lesser mass flow rate this will start happening this is the effect of chocking. I am decreasing the mass flow rate because I added too much heat to the system. This is one extra thing this is along the lines of what we did discuss in fan of flow. So, I just went through it a little fast in this particular situation. So, I can give you another example, where there is shock inside but that takes iterations and it is going to take the remaining time and class. So, I have said, I will just put it in an exercise anyway I am going to put up exercise solutions also. So, I decided not to do that in class. So, we will go for the next thing which is just a small discussion where I want to link all the concepts of chocking you learned till now. Typically, this is not given in all the books there are a few books which give this.

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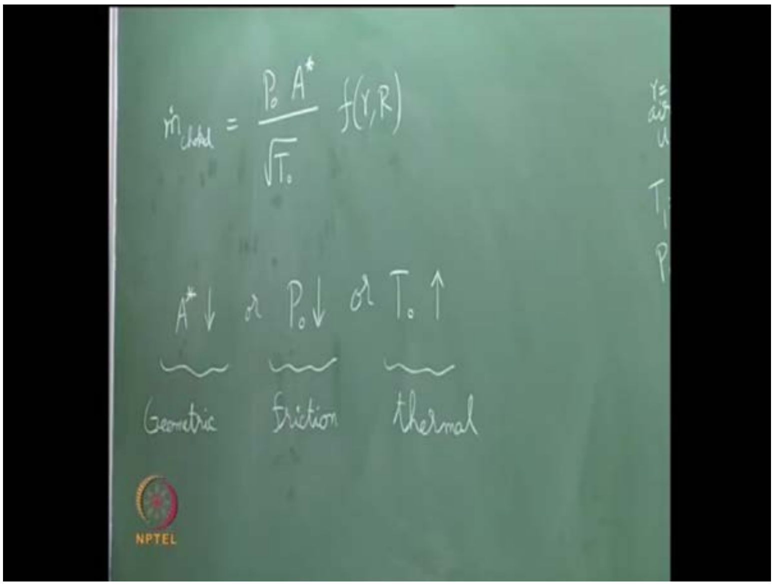

So, I will go back to this particular expression choked mass flow rate, we had an expression, which was I can write this expression. It is going to be square root of gamma by r times gamma plus 1 by 2 to the power gamma plus 1 by gamma minus 1 that whole thing I do not need to write it here, but it is just a function of gamma and r that is all we will keep it like this of course, it is the mass flow rate, choked mass flow rate depends on the gas. Let us say, we would not worry about the gas. Now, if it is more compressible it will be having little more mass flow rate etcetera. That is, there we saw that already in each of those flows, if it is more mass flow rate, more flow can squeeze through that tube. That kind of discussion we have that is still there.

That is one aspect. Now, I want to think about it in different ways each of these terms is important. Now, I am going to say if I increase my T naught, I find that my m dot decreases if I decrease my P naught my M dot decreases, if I decrease my a star, my m dot decreases. Of course, I am keeping gas constant if I have to think about what is the effect of gamma inside here, we will not worry about that right now of course, the r is in the denominator of this function 1 by square root r is the function inside for r, if you think about that, if I increase my molecular mass my mass flow rate increases, that is just because it is heavier molecules going through. So, there is more mass going through you do not worry about that aspect. We want to think about only compressibility, that is related to gamma in here and we already discussed that in detail separately in each of those cases, I would not discuss that in here. I will just look at these individual values.

So, if I have to go for choking, I have to decrease a star or P naught should decrease or T naught should increase, that is I can have a restriction in the flow area. That is I am changing the flow geometry or I can decrease P naught by several methods one of the methods is by introducing friction of course, every flow has friction, we are just neglecting friction most of the times and adding it now. When we want that, is on. So that can be introduced in thinking about that way or I can think about some extra mixing happening or some other crazy geometry. That there is more drag in the flow, I put some protrusions in the inside my duct and that is going to cause P naught loss or maybe there is shock forming inside. That is going to have P naught loss lot of P naught loss mechanisms inside they are all going to go out take the flow towards choking condition even choked. I am thinking about a flow through a duct still and in the middle, I am having some P naught loss mechanisms.

Or I can heat the gas and that will take you to choking condition in spite of all. I can do one more thing, keeping the whole of this section constant if I add more mass in my duct somehow, I added one more tube and I put more mass into it. I will go to a point where it will reach it is maximum mass flow limit for the given area that is another way of choking it. That is mass solution based chocking it. So, it happens, that if I add mass I also have to think about mixing and that will decrease P naught, that will accelerate it towards chocking a little earlier also that is one more extra aspect you want to think about but I just want to give names for each of these decreasing area and the flow goes to a choking is your geometric choking. This typically called friction choking, it need not be just because of friction, it can be mixing based choking also, if I have different gases they are mixing or I have suddenly something evaporating and. So, flow energy decreases those all get into this area.

I can have condensation evaporation those kind of things can come in this area or I can have here this is your thermal choking. I can have geometric chocking friction, choking or thermal choking by the way in a given flow, it can all be happening and when you are close to M equal to one all of them will be very critical, that is why transonic flow is very difficult to solve, you cannot neglect any of these parameters everything will take you to M equal to 1. So that is a little more you have to be a little more careful about it. How do I avoid choking, these are all the mechanisms, that take you towards choking. So, I will do a straight opposite things, I have to think about area increasing, that is a possibility I can think about P naught loss minimizes you cannot increase P naught just like that in a flow unless you add extra energy to the system.

So, I will try and minimize friction, I will try and minimize P naught losses I do not want to have normal shocks. I want to have oblique shocks instead that kind of stuff we want to think about, if I have protrusion in my duct I do not want, if this is a duct I do not want to protrusion straightened but I may want to have a protrusion, that is slant, that will have lesser P naught loss, that will help a little bit those are all things which will take you to choking condition anyway because P naught loss but it will be lesser P naught loss. It will postpone the choking point or I can think about cooling very useful thing to do if you want to avoid choking, cooling is a very nice thing to do. So, by the way if I think about a complicated situation as a supersonic combustion all of this comes into play. It is a very critical situation we will just deal with that a little bit just half or twenty minutes class. We will think about this a supersonic combustor I am just thinking about the combustor part.

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I am not talking about the full scram jet but if this is the combustor inside a scram jet let us assume, I am having a duct and I am having M 1 greater than 1 incoming this is my current situation. Now, I want to actually add fuel into this typically, it is a liquid fuel. So, it has to evaporate which will take some energy from the flow itself and then it is going to think about mixing will remove some P naught and eventually I have to light it and I have to hold the flame next.

When I hold to think about holding the flame typically, people use either cavities or some other metal objects inside the flow. I already told you, it has to slant other ways, I have more P naught losses people do not inject. It always like this, I just gave a typical configuration people may have a cavity in the wall of the duct and they inject it somewhere here. Wherever depending on each configuration different mark numbers, it can be any of these places, they will inject and this flow that is re-circulating will mix that flow with this fuel and then take it out into this region, there will be a shear layer forming here which will be oscillating which will send out fuel in there. This is 1 configuration or I can have a configuration where there is a strut, which is just a metal rod sitting inside the duct and I will send fuel through this and some holes in here will inject fuel this way or in the side or outward anywhere somewhere along the direction.

Somewhere it will inject from inside here and now you think about how to mix this better along with the flow.

People think about this one more than this one, because this one typically, the fuel will stay only along the walls, which will heat the walls more, because when the combustion happens, heating happens only near the wall, maybe the walls will get hard one of the problems, which can get this. Now, we want to think about, if I want to use this kind of situation. Now, I have P naught loss more, because I have an object sitting in the supersonic flow shocks will be there we put slant objects. So, that shocks are lesser but I have to inject, if I inject along the flow then there is a problem of they are all going together velocity difference is less shear is less it is not going to mix very well. So, they have to think about perpendicular injection or against the flow injection typically.

When I do that, I am fighting the flow if I inject against it. So, the P naught loss will be a little higher, I am trying to link all the things that you have learnt in gas dynamics till now in this 1 application. So, I am resisting the flow more. So, the energy of the flow will be lost more p naught will be lost more that is going to happen but after sometime it is going to of course, form a shock against this. The flow will come like this turn around and go this flow will turn around and go there will be a shock sitting like this in front of each of the jets there will not be just one jet there will be so many of them sitting in this whole region. Now, as they go this way there is flow around this also and they are all going to mix. Now, I have to think about mass addition I just added mass and the fuel evaporated, because the temperature incoming is already hot enough for me.

It is evaporated and once it evaporated. Now, I have to think about that is also going to occupy this space. So, already if I have a constant area duct, I will have more congestion more people are running in the same area. So, there is going to be more congestion. I am getting towards choking already just by adding fuel. Now, that is not enough I have decreased P naught, I have put shocks inside I have put a metal rod in the middle injected fuel mixing everything decreases P naught and. So, I am going to have lesser P naught, which is again pushing towards M equal to 1 in all. I want to light this mixture and burn it. So, I am going to think about from here, I am going to light it and as it is travelling I want it to burn inside here. So, when it is burning again I am adding heat to the system if I am adding heat to the gas. I am again sending going towards M equal to 1, another reason for thinking about thermal choking. Now, this is thermal choking, other things were P naught decrease. So, it is typically friction choking or mixing based choking or mass addition based choking.

So, what are the ideas people do to decrease the problems? they will typically use the area expansion, they do not ever have a constant area duct they will have area increasing sometimes they will have semi-nozzle, if you have seen some supersonic scram jet vehicles, you will see that only side the nozzle will be there, other side there will be a free jet going like this. It is also there part of the thing, what matters is only the pressure on the wall. So, the thrust will still be there anyways, this is one way of handling this. There is one more problem with supersonic combustion is the flow is going extremely fast and combustion is slow. Now, I have to think about the combustor should be long enough to release all the heat of the fuel before this fuel admixture gets out of my area of interest, that is near my engine, near my scram jet if I think about.

Before that it has to finish the entire job, that is the idea and of course. I do not want it to be exiting at M equal to 1, because I am flying supersonic. It is a scram jet and I want it to be exiting at M equal to 1. I have to think about having a nozzle here and a free expansion on this side to make the mark number slightly higher than or equal to the incoming mark number that is what I am thinking about. Now, I close to the incoming mark number as possible I want to think about all that. So, in this whole sequence, I am starting with a supersonic flow, I added a lot of things which decreased my P naught and I added heat finally, which took me to M equal to 1 closer by all these means I did not talk about friction in this whole thing.

Now, if I think about friction also there is friction on this rod metal to the gas contact here or along the wall to the gas contact friction is there, everywhere there is friction and that will also take it towards M equal to 1. That is why, this whole problem becomes a little more tricky and by mistake, if you added a little extra fuel than the choking pin, the whole flow chokes there will be a shock running straight ahead and the whole flow becomes un static, the combustor is called un static, what happens is the flow incoming will become subsonic. It jumps and takes a subsonic solution and they call. It is no more a supersonic combustor, it is burning subsonic. So, they call it as un static condition that will start happening, if I by chance do that and then now I have to think about how do pull the shock back in? I have to increase P naught of the flow somehow, increase the P naught of the flow or decrease my back pressure really low.

So that, the shock goes downstream think about our nozzle problem, where we keep on decreasing, the back pressure the shock goes more and more downstream something like that you have to think about then that shock will be going passed in this and I can go back to starting condition. It is very difficult, when I am flying using this engine and the engine is un static, I cannot accelerate very well and go to that condition, that is where things go wrong this is one case, if I think about a subsonic combustion but supersonic vehicle a simple ram jet just a ram jet, I am flying supersonic but near the combustor it is subsonic how do I do it.

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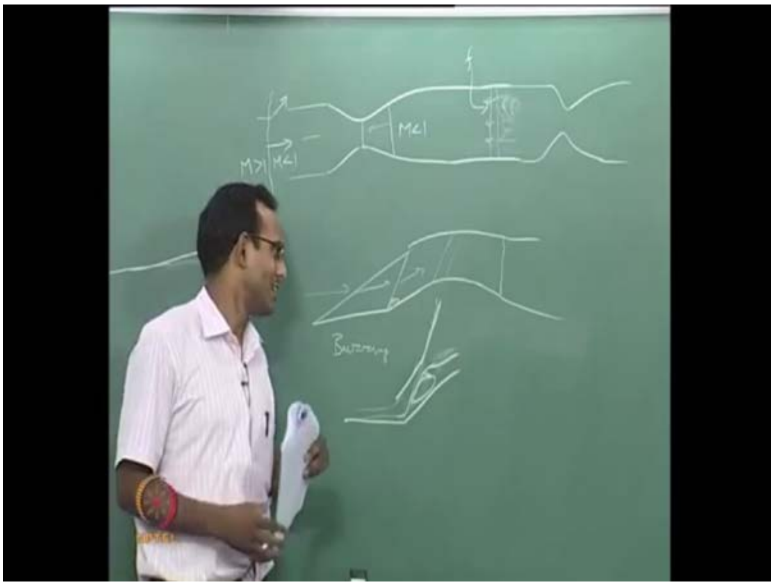

Typically there will be and this is where I am going to add fuel and burn inside, then I will have another nozzle to create thrust further, this is going to be my system and thinking about there is incoming supersonic flow. It is going to have choking here and it is going to subsonic solution. Of course, you should remember your nozzle flow conditions and you should think about, if this is a double throat nozzle, we discuss sometime back this is like imagine there is one more duct here and there is a nozzle which made it supersonic flow it goes through a second throat and it is going subsonic if that is the case, it is as if shock is sitting here. This is what really happens shock is sitting here M is greater than 1. It goes close pack to M greater than 1 jumps across to this condition and then from here, I added fuel I am having subsonic condition of course. Now, I have to think about similar thing I need some flame holder and the injector etcetera. It is going to be fuel added to the system and there is supposed to be a flame holder and there will be burning in here something like that after the burning. Now, it is subsonic.

So, it is a little easier flow is going slow combustion can happen within this length and after that, the hot gases are supposed to be expanded from here. If I think about, it is like a rocket nozzle problem, we did in an example. There is a chamber, where there is high pressure, high temperature gas produced and that is going out through a nozzle expanded out and this is how the thrust is produced in this particular situation. Now, what happens if I chock this if I chock this point and I add a little more heat of course, it has to be chocked for me to get back to supersonic mark numbers here, otherwise I am taking the flow incoming supersonic and sending out subsonic, it is a waste and its going to be a drag we want it to be a thrust. So, I have to think about it a little bit, it is going to be accelerated back. So, here it will be typically choked, if it is choked here and I add a little more fuel to this happens first thing mass choking or if I do not think about mass choking there could be combustion more heat release thermal choking.

Though in all this I did not talk about friction choking, that is also there every choking possibility is always happening, there after all this if there is choking what happens in this region. It is subsonic flow, I added some mass to tend to choking condition mass flow going out is less than what is coming in, that means there is accumulation in this region pressure increases, there is more people getting crowded here, when that happens, what happens immediately pressure here, rises means there will be a compression wave. That is going to travel in this way, there is a compression wave travelling in this way that is going to strengthen the shock. The shock goes more upstream by the way it does not go to mark one here. It goes to a supersonic in here, because I am choking there.

That is typically, the way they design it. Now, the shock goes and sits more and more upstream there will be a point where when the shock reaches this thinnest point. That is a critical condition, if I go anywhere more upstream when I sent more compression wave. Then this shock suddenly it keeps moving like this, after this point you know that it is unstable in this converging duct. So, what happens is suddenly it jumps out of this whole thing and sits here, basically I introduced too much fuel but compression waves came and pushed this shock ahead of this whole thing if it is sitting here. Then what happens is flow suddenly finds that there is a normal shock in front of it and. So, it becomes subsonic and then it goes through this. Now, there is a possibility of spill edge some of the mass goes out because there is choking there and there is extra mass added there air cannot go through in this path.

So, some air goes out that direction that is how you got spill edge in the system. Now, this can start happening and added to this if there is some pressure oscillation in side here which is characteristic. In these kind of ducts with partial closed ends, if there is a pressure pulse it is going to be reflecting up and down inside here and that happens the pressure inside the system is going to be going up and down coupled with this, when the pressure increases flame burns better, because molecules are closer, if such a thing happens then combustion heat release is going to be going up and down. If the things, if the heat release increases we know it chokes better. So, there is a pressure wave created heat, release increase causes increasing pressure, increasing pressure causes the wave to go up, that whole sequence causes a coupling and that causes acoustic instability thermo acoustic instability they call it, because it is linked with the combustion also.

If such a thing happens, then there is a possibility of if I am working on the edge then the shock can be jumping out, coming back, jumping out, coming back typically nobody works on that region. Typically people works safe from the inside that is one thing, you have to think about and one more problem. I just wanted to introduce, because I am working on it if I have external compression intake again a ram jet problem typically, instead of having this kind of supersonic flow incoming and that nozzle they can have a situation, where there are oblique shocks which are decreasing the mark number slowly. And then it goes through a situation, where the area decreases and increases slightly and goes and sits with a normal shock, and then your combustor starts there. This is a replacement for this nozzle in here. That is just a replacement for this nozzle sitting in here which is decreasing the supersonic flow to subsonic inside the combustor, if this is the situation.

Now, there are more things that can happen in here. I will just tell you, this is not in any way part of the scope of the course I just want to go a little beyond this. We have these 5 minutes. So, I am going to say, because of this sudden jump in pressure boundary layer can. Now, suddenly face an adverse pressure variant and it may separate need not separate it may separate there is a possibility, that it separates typically in this one instead of I will just draw that region instead of having a shock like this, because of this pressure variant the boundary layer typically must be rising like this instead of this, it may do something like this with a recirculation bubble sitting here something like this is a possibility, if such a thing happens. Now, the flow has to turn a little more. So, the shock comes ahead and that changes the shape of the shock.

It goes a little more ahead when such a thing happens they have designed it to the point. That shock goes and hits this corner, if they are done in that way and the shock slightly shifts up, what is going to happen. It is going to be more normal, there is going to be more P naught loss, it is going to have easier choking inside if it easier choking inside the compression wave will be pushed more out and I will have the shock going out more but when the shock goes out more this kind of situation happens, if shock goes out of this edge, this is called the curl. If it goes out of this edge, then I am going to have spill edge and the mass going in decreases. The mass going in decreases and there is no extra mass added inside what will happen slowly? The mass inside decreases pressure decreases. So, it is like the system is experiencing a lower back pressure.

If it experiences at lower back pressure slowly, the shock will be pulled in when the shock is getting pulled in suddenly, the oblique shock is more oblique the lesser P 2 by P 1, if it is lesser P 2 by P 1. This boundary layer tripping need not be very strong, the bubble decreases in size and when the bubble decreases in size there is more mass flow going in, because it is a opposite of it. Now, we went through a whole cycle we started with nothing there was a bubble formed. It grew and now it is decreasing. Now, again it goes to a situation where if there is any disturbance can again form this bubble. Now, what happens is this thing starts oscillating up and down like this is called the buzzing right this is called the intake buzz in supersonic intakes. This is also a possibility in this system if I think about these problems, whatever I discussed in the last ten to fifteen minutes they are all complicated examples, which can be solved by whatever we deal with in the whole course till now.

But it is a little more complex, because now I have to think about there is friction, there is also heat emission, there is also expansion, there is a there is also a mass addition just becomes a little more complex to deal with it is not one at a time, we deal with only things one at a time. We said, when there is friction, there is no heat addition if there is heat addition, there is no friction, there is no area change ever and when there is area change there is no friction, no heat addition, that is the way we deal with one at a time but in real life applications, it is all mixed up everything happens with the same time, that is a little more than this course scope. So, we will not going to that. The next class onwards we will think about experimental methods, experimental techniques as in how to create a supersonic flow or a compressible flow even subsonic high subsonic how to create such flows and how to do experiments in there. Probably next five, six classes I will be dealing with that and then I will go into the probes various probes, that can be used. And we will deal with some computational methods after that see you people in next class.